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ABSTRACT

This document presents the Maryland Collaborative for Teacher Preparation (MCTP) faculty's reviews on instructional issues of different disciplines. Contents include: (1) "The Maryland Collaborative for Teacher Preparation"; (2) "Guiding Principles: New Thinking in Mathematics and Science Teaching"; (3) "Introduction: Parallel Journeys of Risk and Reward" (Maureen B. Gardner); (4) "Elementary Geometry" (Karen Benbury); (5) "Interdisciplinary Science and Mathematics: Geometry and the Round Earth" (Kenneth Berg and James Fey); (6) "A Constructivist Approach to Plate Tectonics" (Rachel J. Burks); (7) "A Mathematical Modeling Course for Elementary Education Majors" (Don Cathcart and Tom Horseman); (8) "Adaptation of a Traditional Study of Enzyme Structure and Properties for the Constructivist Classroom" (Katherine J. Denniston and Joseph J. Topping); (9) "The Air We Breathe: Is Dilution the Solution to Pollution?" (Thomas C. O'Haver); (10) "Constructing the Stream Community: The Ecology of Flowing Waters" (Joanne Settel and Tom N. Hooe); (11) "The Challenge of Teaching Biology 100: Can I Really Promote Active Learning in a Large Lecture?" (Philip G. Sokolove); (12) "A Shift in Mathematics Teaching: Guiding Students to Become Independent Learners" (Richard C. Weimer, Karen Parks, and John Jones); and (13) "A Tale of Two Professors: Faculty Profiles." Appendices include: "References for Reading," "Highlights of National Recommendations," and "MCTP Advisors and Participants." (Contains 49 references.) (YDS)

JOURNEYS OF TRANSFORMATION

A Statewide Effort by Mathematics and Science Professors to Improve Student Understanding

Case Reports from Participants in the Maryland Collaborative for Teacher Preparation

Funded by the National Science Foundation Division of Undergraduate Education

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Mathematics and Science Professors to
Improve Student Understanding

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Maryland Collaborative for Teacher Preparation

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Journeys of Transformation,
visit the MCTP World Wide Web site at
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FOREWORD

Forty years ago, on October 4, 1957, the Soviet Union launched the first artificial earth satellite, Sputnik 1, and American science, mathematics, engineering, and education were changed forever. Spurred by military and political competition with the Soviets, we began rapid escalation of our investment in scientific research and development and in the educational infrastructure needed to provide brain power for those efforts.

The investment in both science and education paid admirable dividends. We soon matched and then outstripped Soviet accomplishments in space and became world leaders in all major aspects of scientific research. We revitalized school and university science and mathematics programs and produced outstanding students headed toward careers in science, mathematics, and engineering.

As Cold War national security threats diminished over the past 15 years, they were replaced by new concerns about world-wide economic competition. The challenges of new high-tech industrial and business competition increased demands for scientific literacy and technical skills in broader segments of our population. Public schools and universities have again been asked to enhance science education, but success has not been as easy to achieve.

The Problem

Although schools have increased enrollments in academic science and mathematics courses for all students, reports of national and international assessments indicate disappointing progress of American students. The number of students continuing past high school into undergraduate study has increased dramatically over the past several decades, but many of those students face extensive remedial work in mathematics before they can begin work toward degrees. An emerging body of research on undergraduate science and mathematics education shows that even students who are apparently successful in collegiate science and mathematics courses have disturbing gaps and misconceptions in their understanding of those subjects. The recent National Science Foundation review of undergraduate education concluded that:

> *America has produced a significant share of the world's great scientists while most of its population is virtually illiterate in science . . . Undergraduate science, mathematics, engineering, and technology education in America is typically still too much a filter that produces a few highly-qualified graduates while leaving most of its students "homeless in the universe."*
>
> (Advisory Committee to the National Science Foundation, 1996, pp. 3–4)

The challenges and shortcomings of contemporary science and mathematics education have led to dozens of major conferences and policy advisory reports that outline directions for reform at the school level (National Council of Teachers of Mathematics, 1989, 1991, 1995; American Association for Advancement of Science, 1995; National Research Council, 1995) and at the undergraduate level as well (Mathematical Sciences Education Board, 1991; Advisory Committee to the National Science Foundation, 1996). As a result, significant experiments with new curricula and teaching in K–16 science and mathematics are using calculators and computers to explore new approaches in traditional science and mathematics courses and to create new interdisciplinary configurations of knowledge. These experiments are drawing on insights from research on human learning to design new models for teaching, and are testing new ways of accurately assessing student skills and understanding.

The Response

Every major proposal to improve mathematics and science education describes teachers as the critical agent in the change process. Thus, changing the content or pedagogy of courses in elementary, middle, secondary, or undergraduate mathematics and science education requires increasing the knowledge and classroom skills of teachers. In recognition of this fact, the NSF initiated a program in 1992 to support Collaboratives for Excellence in Teacher Preparation (CETP) that would significantly change teacher preparation programs within a state or region and serve as national models of comprehensive change. The basic premise of the CETP program was that:

> *The content and presentation of science, mathematics, engineering, and technology that prospective teachers learn as part of their undergraduate and pre-certification experience will determine the quality of their own teaching efforts; their interest in integrating science, mathematics and technology in their classroom activities; and their ability to adopt and adapt creative effective teaching methods validated by recent research on teaching and learning.*
>
> (Straley, 1996, p. vii)

In response to the NSF request for proposals, the teaching and research institutions of the University System of Maryland joined with Baltimore City Community College, Morgan State University, and three major Maryland public school systems to form such a teacher preparation collaborative. Our Collaborative's plan to design, develop, implement, and evaluate a new kind of teacher preparation program for teachers of mathematics and science in the middle grades was funded in the first round of NSF-CETP proposals.

Over a five-year period of funded work, the Maryland Collaborative for Teacher Preparation (MCTP) engaged more than 120 school and university faculty in professional development activities that led to the creation and implementation of 89 new or modified university science, mathematics, and teaching methods courses. When we developed those courses, our first aim was to help prospective teachers develop a confident understanding of the fundamental concepts, principles, and reasoning processes at the heart of science and mathematics, especially those that underlie the school curriculum. Thus, we engaged in extensive cross-disciplinary discussions to articulate our views about the fundamental ideas of mathematics and science and the connections across traditional disciplinary lines.

The dominant lecture mode of undergraduate instruction conveys neither an accurate image of the way science and mathematics are created nor of the ways that the subjects are most effectively taught and learned. Therefore, our second aim in developing and revising science and mathematics courses was to create learning environments in which students could actively investigate problems that help them construct personal understanding of key ideas.

While there is remarkable commonality in diagnoses of the problems and prescriptions for improvement in school and undergraduate mathematics and science education, implementation of the reform proposals is far from a routine task. It is very hard to identify a set of scientific and mathematical principles that provide a necessary and sufficient foundation for teaching; it is even more difficult to create engaging instructional activities that bring about understanding of those principles. In the face of those challenges, participants in the MCTP experienced some early failures and some subsequent remarkable successes. This publication reports these experiences, which we hope will encourage and inform others who are interested in improving undergraduate science and mathematics, especially for prospective teachers.

Credits

The accomplishments of the MCTP project resulted from contributions by science, mathematics, and education faculty and key administrators in schools and universities across Maryland (see Appendix III). Our National Visiting Committee (see Appendix III) has provided us with timely and insightful advice on goals and specific activities at all stages of the project. Financial support from the National Science Foundation and the University System of Maryland has allowed us to explore a variety of intriguing new ideas in teacher preparation.

Since the beginning of our work in 1993, the MCTP project has been guided by the energetic and insightful leadership of our executive director, Susan Boyer. She understands science and mathematics education and teacher education, and is respected by educators throughout the State of Maryland. The successes reported in this volume are a credit to her ability to translate the ideas of our initial proposal and subsequent operational plans into first-class activities that engaged and transformed everyone involved in the Collaborative.

The papers in this volume were contributed by MCTP faculty from a variety of disciplines. Selection of papers was guided by an editorial committee including Rebecca Berg, Joseph Hoffman, Joan Langdon, and Gilbert Ogonji. Coordinating and editing these diverse contributions has been no small task. As managing editor, Maureen Gardner has done a remarkable job not only in helping the authors tell their interesting stories in engaging ways, but also in overseeing all phases of publication development. Donna Ayres' exceptional skills in editorial assistance, copy editing, and production management were vital both to the quality of the document and to its completion on deadline. In addition, other MCTP staff members—Karen Langford, Carolyn Parker, and Amy Roth-McDuffie—deserve acknowledgment for their technical and editorial support of the production effort.

As principal investigators for the project, we have been challenged by the task of creating a productive collaborative from institutions, disciplines, and individuals with a history of competition rather than cooperation. Nevertheless, the experience has been consistently stimulating and rewarding. In this publication, you will find both the spirit and the substance of the work of the Maryland Collaborative. We hope the stories within will give both stimulus and direction to innovative efforts of your own.

MCTP Principal Investigators

James Fey

Genevieve Knight

John W. Layman

Thomas O'Haver

Jack Taylor

References

Advisory Committee to the National Science Foundation. (1996). *Shaping the Future: New Expectations in Science, Mathematics, Engineering, and Technology.* Washington, DC: National Science Foundation.

American Association for Advancement of Science. (1995). *Science for All Americans (Summary).* Washington, DC: AAAS.

Mathematical Sciences Education Board (1991). *Moving Beyond Myths: Revitalizing Undergraduate Mathematics.* Washington, DC: National Academy Press.

National Council of Teachers of Mathematics. (1989). *Curriculum and Evaluation Standards for School Mathematics.* Reston, VA: NCTM.

National Council of Teachers of Mathematics. (1991). *Professional Standards for Teaching Mathematics.* Reston, VA: NCTM.

National Council of Teachers of Mathematics. (1995). *Assessment Standards for School Mathematics.* Reston, VA: NCTM.

National Research Council. (1995). *National Standards for Science Education*. Washington, DC: NRC.

Straley, T. H. and Woodin, T. (1996). Foreword by workshop organizers. In Millar, S. B. and Alexander, B.B. (Eds.). *Teacher Preparation in Science, Mathematics, Engineering, and Technology: Review and Analysis of the NSF Workshop, November 6–8, 1994*. Madison, WI: National Institute for Science Education.

THE MARYLAND COLLABORATIVE FOR TEACHER PREPARATION

The heart of this publication is a set of case reports and profiles of Maryland college and university professors who have made substantial changes in the way they teach mathematics and science. Their work to create new courses and revise existing ones, for the sake of improving student understanding, is one of several facets of a statewide program called the Maryland Collaborative for Teacher Preparation (MCTP). This section summarizes the MCTP's goals, program components, and accomplishments.

The MCTP is an innovative, interdisciplinary undergraduate program to prepare future teachers of grades 4–8 who are confident in teaching mathematics and science and can provide exciting and challenging learning environments for all students. The program has sought to:

- introduce future teachers to standards-based models of mathematics and science instruction;
- provide courses and field experiences that integrate mathematics and science;
- provide internships that involve genuine research activities;
- develop the participants' ability to use computers as standard tools for research and problem solving, as well as for imaginative classroom instruction (through training on how to incorporate calculators, microcomputer-and calculator-based laboratories, and the Internet into their instructional practices);
- prepare prospective teachers to deal effectively with the diversity of students in public schools today; and
- provide graduates with placement assistance and sustained support during the critical first years of their teaching careers.

Building a Collaborative

In the first year of the initiative (1993–94), project staff recruited 85 mathematics and science faculty members from 10 collaborating colleges and universities. The faculty became familiar with the project's goals through professional development activities; designed new mathematics and science courses that incorporated hands-on, cooperative learning activities; and developed teams within each institution. They also participated in sessions to raise awareness about diversity and equity issues. The use of technology has been emphasized throughout the program in course development and, through the project's listserv and Web site, as a central mode of communication.

During its second year, 20 new MCTP courses were offered and the first group of pre-service teachers was recruited. The project continues to recruit freshmen and sophomores at collaborating institutions who are interested in becoming elementary or middle school teachers. The project also enlisted a cadre of community college faculty to provide insights into how to recruit students who transfer into the University System of Maryland. This is especially important, as a high percentage of Maryland's teachers begin their college education in community colleges.

By the start of the third year, the Collaborative had reached a new, more multifaceted level of operation. A clarity of mission and a sense of camaraderie were evident among the participants. In addition to ongoing work on recruiting faculty and students and on developing courses, key program activities were under way, including student research internships, mentor teacher training workshops, and teacher education research.

During the fourth and fifth years, faculty members formed working groups to tackle remaining needs such as the development of culminating "capstone" courses, an induction program for graduates, and faculty professional development plans.

New Courses

The MCTP has grown to include more than 120 faculty members (listed in Appendix III) in 13 Maryland colleges and universities (listed at the end of this section). These professors have made fundamental changes in 89 mathematics, science, and methods courses, having shifted to a more hands-on, interactive, student-centered approach to teaching. In contrast to the traditional lecture format, these faculty members employ cooperative learning strategies and create environments in which students explore mathematics and science questions and discover the answers themselves. Although MCTP's central goal has been to improve the science and mathematics education of future teachers of grades 4–8, its reach extends to all students who take courses taught by these "reformed" instructors—which amounts to approximately 4,000 students per semester.

Research Internships

In the summer of 1995, 11 MCTP students took part in a pilot program of full-time research internships in the "real world" of science and mathematics. The internship sites included local museums, informal science centers, and zoos, as well as research laboratories and federal agencies. A quote from one student, who was an MCTP intern at NASA, helps to show the kinds of transformations these students undergo as a result of the internship experience:

> *I learned that research is not cut and dried . . . there's a lot of trial and error involved. I also learned a lot this summer about my own learning. It involves so much more than reading what someone else has found to be true. It involves making connections, experiencing, doing, trying, and sometimes making mistakes. It's very important when teaching that I remember this—that my students can be involved in what they're learning and that will be meaningful for them.*

Based on the success of the pilot year, 24 additional interns were supported in the summer of 1996 and 18 more in 1997.

Mentors for New MCTP Teachers

Another important component of the MCTP is the preparation of mentor teachers who will guide MCTP students during their field experiences and student teaching, as well as during their first year of teaching. During the past three summers, some 64 upper-elementary and middle school teachers have been prepared to be mentors. They participated in two-week, intensive workshops to enhance their knowledge and skills in areas such as coaching and mentoring pre-service teachers, using technology in the classroom, and integrating science and mathematics in lessons.

More than 40 MCTP students are expected to graduate in the spring of 1998; many of these are among the first to complete a full, 4-year program of MCTP courses as well as summer research internships. (Already, 30 students with fewer than four years of MCTP experiences have graduated, and many are already employed in school systems in the region.)

Evaluation

Evaluation of the program is performed by a combination of internal evaluators and the project's own research group. The formative evaluation of the MCTP activities is carried out by the staff of CoreTechs, a private consulting firm run by the former director of the Center for Educational Research and Development at the University of Maryland, Baltimore County. A recent CoreTechs survey of 33 faculty members shows a marked shift in how frequently they used certain teaching strategies after joining MCTP. For example, compared to the use of these strategies prior to MCTP, there was a two-to ten-fold increase in the number of faculty members who regularly used cooperative learning groups, hands-on learning activities, constructivist methods, alternative assessments by students and peers, learner-centered approaches, project-oriented learning, technology in the classroom, and other "reform" strategies.

From the perspectives of faculty and students, the MCTP Research Group continually documents the unique elements of the program, particularly the instruction methods that model active, interdisciplinary teaching. Data collection strategies include regular surveys of students in MCTP classes; audio-taped and videotaped interviews of MCTP faculty and students; observations of selected MCTP classes; and collection of course materials. To follow are the main areas of research and some findings to date:

- *Student Attitudes and Beliefs about Mathematics and Science.* Compared with other teacher candidates, MCTP students hold more positive attitudes towards mathematics and science as well as more positive beliefs about the nature and teaching of mathematics and science.
- *Mathematicians and Scientists' Views of Each Others' Disciplines.* This study, which explored how these views impact classroom efforts to connect disciplines, found that MCTP mathematics content faculty tend to refer to science as a discipline similar to mathematics in that it requires a sustained, focused study, while MCTP mathematics methods faculty tend to view science as a context for doing mathematics. Moreover, MCTP science content faculty tend to view mathematics as a tool that enables them to solve problems in science, while MCTP science methods faculty tend to view mathematics both as a tool used in doing science as well as a separate discipline independent of science.
- *Benefits of Student Discussions on Pedagogy in "Reformed" Content Classes.* A study of how faculty attempt to model exemplary teaching practices, and how their students perceive those efforts, found that MCTP teacher candidates benefit from regular opportunities to discuss reform-based pedagogy while taking mathematics and science content classes. Discussions can occur in those classes or in concurrent seminars.
- *Student Content Knowledge and Process Skills.* Preliminary findings from a current study indicate that students who have taken MCTP science and mathematics classes perform better than non-MCTP teacher candidates in assessments of science and mathematics content knowledge, science process skills, and depth of approaches to teaching science and mathematics topics.

For More Information

The MCTP has an award-winning World Wide Web site created by co-Principal Investigator Thomas O'Haver. The site provides a project summary, essays on constructivism and education, types of technologies and software used by the project, a list of project courses, and much more. Readers are encouraged to visit the site for more information about the MCTP project: *http://www.wam.umd.edu/~toh/MCTP.html.*

Participating Institutions

Listed below are the institutions of higher education that participate in the Maryland Collaborative for Teacher Preparation. Also listed are the public school systems and research institutions that have been involved in shaping the program.

Higher Education Institutions

The University of Maryland, College Park
The University of Maryland, Baltimore County
Bowie State University
Coppin State College
The University of Maryland, Eastern Shore
Frostburg State University
Morgan State University
Salisbury State University
Towson University
Baltimore City Community College
Anne Arundel Community College

Catonsville Community College
Prince George's Community College

Public School Systems

Baltimore City Public Schools
Baltimore County Public Schools
Prince George's County Public Schools

Research Institutions

The University of Maryland Biotechnology Institute
The University of Maryland Center for Environmental Science
The University of Maryland School of Medicine

GUIDING PRINCIPLES: NEW THINKING IN MATHEMATICS AND SCIENCE TEACHING

Compiled by James Fey, MCTP Project Director

Based on a Collaborative-Wide Effort to Define a Framework of Guiding Principles Led by Genevieve Knight and John Layman, MCTP Co-Principal Investigators

If young people whose adult lives will be spent entirely in the 21st century are to be active and influential participants in the emerging social, political, economic, and scientific world, their education must provide broader and deeper knowledge of scientific concepts, principles, reasoning processes, and habits of mind than students typically acquire today. Unfortunately, there is convincing evidence that large numbers of students leave secondary and collegiate education with inadequate information and understanding about science and mathematics and little inclination to apply or even value the methods of those disciplines in the solution of problems or in reasoning about important personal and societal questions. A recent National Science Foundation review of undergraduate education concluded that:

> *Too many students leave science, mathematics, engineering, and technology courses because they find them dull and unwelcoming. Too many teachers enter school systems under-prepared, without really understanding what science and mathematics are, and lacking the excitement of discovery and the confidence and ability to help children engage science, mathematics, engineering, and technology. Too many graduates go out into the workforce ill-prepared to solve real problems in a cooperative way, lacking the skills and motivation to continue learning.*
>
> (National Science Foundation, 1996, p. 4)

Faculty who are drawn to *Journeys of Transformation* are already sensitive to the problem of providing more sophisticated scientific and mathematical education to a broad and underachieving population. The central question is: "If I want my students to develop a deeper understanding of science and mathematics, where do I turn for new ideas?" In grappling with the same question, leaders and participants in the Maryland Collaborative for Teacher Preparation (MCTP) found a number of credible sources of guidance.

Over the past decade, mathematics and science educators have engaged in spirited critical examination of current practice and have undertaken creative research and development activities. While the greatest energy has been focused on elementary and secondary education, a significant number of college and university faculty are now engaged in basic research and applied curriculum development projects aimed at improving undergraduate science and mathematics education. Their critical and creative work is producing remarkably consistent recommendations and intriguing resources.

For the Maryland Collaborative as a whole, the challenge was sorting through the recommendations and deciding which to adopt as a package that could be called "the MCTP approach." For the individual instructors, a greater challenge was deciding which innovations to try in their own classrooms. This section summarizes the underlying principles and recommendations that have guided their journeys of transformation. It describes: (1) curriculum issues, including content coverage, connections among disciplines, and materials emphasizing scientific and mathematical investigation; (2) instructional issues, including constructivism, active learning, hands-on experiences, collaborative learning, and writing to enhance learning; (3) new approaches to assessment; and (4) technology as an impetus for changing course goals and classroom activities and for enhancing communication among faculty and students. (See also Appendix II for highlights of national recommendations that guided MCTP participants.)

Curriculum

For most scientists and mathematicians concerned with improving education, the first target of attention is usually the content and organization of topics in school and collegiate curricula. Quite naturally, they ask themselves and others whether current instruction focuses on the most important facts, concepts, principles, and methods of the disciplines and whether those topics are presented in the most effective sequences for students with different interests, aptitudes, and prior achievement (e.g. Leitzel, 1991).

Less is More. Given the explosive growth of scientific knowledge and the application of that new knowledge to a wide range of human activities, it is natural to expect that recommendations for reform would focus on the addition of topics to existing courses and an acceleration of the pace at which those topics are covered. In fact, there are strong arguments for quite different answers to questions about appropriate curriculum. For example, a report from the American Association for the Advancement of Science (AAAS) Project 2061 argues that:

> *Present curricula in science and mathematics are overstuffed and undernourished. . . . They emphasize the learning of answers more than the exploration of questions, memory at the expense of critical thought, bits and pieces of information instead of understanding in context, recitation over argument, reading in lieu of doing.*
>
> (AAAS, 1990, p. xvi)

The sentiments in that influential AAAS proposal are echoed in many other recent discussions of K–16 curriculum issues. Scientists and mathematicians have urged critical reexamination of their disciplines to identify the truly fundamental ideas and reasoning processes that most students must master and to cut away details that are important only for specialists. Lynn Steen (1988) has spoken eloquently about an evolving view of mathematics as the science of patterns, and he has proposed a framework of structures, actions, abstractions, attitudes, behaviors, and attributes that are useful in describing and reasoning about patterns of many different kinds. The Project 2061 recommendations include similar themes—systems, models, constancy, patterns of change, evolution, and scale—that are useful in thinking about science, technology, and mathematics in the worlds that we experience and seek to understand.

While students undoubtedly will need some specific factual knowledge and skills as a basis for learning the proposed broader concepts and "habits of mind" (Cuoco, et al., 1996), a common thread in recent curriculum advice suggests that students would be better off if we would "organize curricula around profound exploration of a few basic ideas, rather than basic exploration of many profound ideas" (Stanley, as quoted in Millar & Alexander, 1996, p. 65). This point of view is often expressed with the catchy phrase, *less is more.*

Connections. The growth of scientific and mathematical knowledge has also been accompanied by increasing specialization in research fields. Science and mathematics curricula in secondary school and undergraduate education tend to be organized in ways that honor those specializations. On the other hand, recent developments have demonstrated that progress on major scientific problems usually requires integration of principles and methods from several traditional disciplines. For example, problems in environmental science often require concepts and strategies from the biological and physical sciences and mathematics as well as significant insights from economics, public policy, and law.

The case for better-connected science and mathematics curricula rests on pedagogical grounds as well. For example, recent critiques of school and undergraduate mathematics have pointed out that typical syllabi and textbooks consist of hundreds of exercises "detached from the life experiences of students and seen by many students as irrelevant" (Mathematical Sciences Education Board, 1991, p. 17). A solid body of research in cognitive science demonstrates that learning with understanding requires learning how concepts, principles, and procedures are connected (Hiebert & Carpenter, 1992; Redish, 1994). These connections can relate ideas within a subject area, across other subject areas, and to real-life situations in which the scientific or mathematical principles are at work.

Students can develop such interdisciplinary perspectives through theme-based curricular materials such as *Teaching Integrated Mathematics and Science (TIMS)* at the elementary level, *Event-Based Science* in the middle grades, and even the *Applications Reform in Secondary Education (ARISE)* and *Systemic Initiative for Montana Mathematics and Science (SIMMS)* projects at the high school level. (See references to follow for publisher information on curricular materials.) Not surprisingly, as one gets into advanced secondary school and undergraduate curricula, specialization by traditional discipline becomes more common. However, most of the recent developments in calculus and linear algebra curriculum materials give a prominent role to modeling of scientific and economic situations (Tucker & Leitzel, 1995; Carlson, et al., 1997). Moreover, at the college level, NSF has sponsored the development of curricular materials that honor the less-is-more philosophy and provide modules that exemplify current views of teaching and learning. One such project is *Powerful Ideas in Physical Science*, published by the American Association of Physics Teachers (College Park, MD). This project had a major influence on how MCTP structured its summer faculty development programs. Another example of theme-based materials at the college level is *Chemistry in Context* (Schwartz, et al., 1994), described by Dr. Thomas O'Haver in his contribution to this publication.

Scientific and Mathematical Thinking. While curriculum design has traditionally focused solely on the selection and sequencing of topics to be 'covered' in a course, there is growing support for the principle that *how* we teach is as important as *what* we teach. The National Council of Teachers of Mathematics (NCTM) articulates this notion in its *Curriculum and Evaluation Standards:*

> *Students' ability to reason, solve problems, and use mathematics to communicate their ideas will develop only if they actively and frequently engage in these processes. Whether students come to view mathematics as an integrated whole instead of a fragmented collection of arbitrary topics and whether they ultimately come to value mathematics will depend largely on how the subject is taught.*
>
> (National Council of Teachers of Mathematics, 1989, p. 244)

That NCTM position has been echoed in many recent comments on science curriculum and teaching as well. For example, at a 1994 conference on the preparation of science and mathematics teachers, Jaleh Daie suggested:

> *Science is best learned as a way of knowing, not as a collection of facts . . . (C)ertain scientific facts are . . . needed before larger concepts can be understood and ideas can be constructed. (But) learning the process of science (logic, methods, quantitative skills, and cause and effect relationships) is more important than having a collection of facts. This approach emphasizes attainment of intellectual skills (rather than routine memorization) to reinforce student interest and increase motivation.*
>
> (Daie, 1996, p. 70)

This point of view implies that curriculum materials should emphasize investigation and problem solving more than reading and imitation of examples, and that students should have an opportunity to experience authentic scientific research environments.

Instruction

When content goals and curricular structures have been agreed upon, it is natural to turn to considerations of learning and instruction. How do students with various interests and aptitudes acquire the understanding we aim for? What kinds of instructional materials and activities stimulate that learning? Consistent themes have emerged from a substantial body of research on these questions, including much work directly related to undergraduate science and mathematics education.

Constructivism. The traditional pattern of K–16 mathematics and science teaching includes teacher explanation and demonstration of new ideas and skills followed by guided and then independent student work on routine exercises. Some students are able to learn from this pattern of interaction with their teachers and curriculum materials, but many are unsuccessful. Teacher-focused class meetings induce student inattention and, even when teacher explanations are clear and complete, students often report frustration when they face homework tasks away from the teacher's immediate guidance.

In response to the well-known difficulties that students have in learning science and mathematics, extensive research has attempted to clarify the mechanisms of learning in students of various ages and aptitudes. Over the years, this research, from a combination of content discipline and psychological perspectives, has led to a number of general theories about learning and those theories have then been used as bases for models of instruction. The theories that currently hold most promise for explaining and facilitating learning with understanding in science and mathematics are described by the general label of *constructivism*.

With primary roots in the research and thought of John Dewey, Jean Piaget, and Lev Vygotsky, modern constructivism has several key tenets:

- Knowledge is actively created, not passively received.
- Students construct new understanding by reflecting on and modifying their prior knowledge structures.
- Knowledge is personal, an amalgam of individual interpretations of experiences and observations that are shaped by prior conceptions and social interactions.
- Learning is a social enterprise in which scientific ideas are established by members of a culture through shared observations and social discourse involving explanation, negotiation, and evaluation.

From a constructivist perspective, the goal of learning is the formation of internal representations of objects and relationships. Those representations can then be manipulated mentally to explain and make predictions about the structure of modeled situations. While there is little direct evidence of how representations are stored in the brain, there is general consensus that students will develop effective representations of mathematical and scientific concepts and principles only if they actively examine those ideas in varied forms, on a continuum from tactile to symbolic.

Active Learning. Constructivism is basically a theory of knowledge and how knowledge is acquired and used. However, it has been translated in various ways to give guidelines for mathematics and science instruction as well. The fundamental premise of constructivist learning theory is that knowledge is acquired only through direct involvement of the learner. Theories of teaching built on that principle have emphasized some of the following objectives:

- Instruction should engage students in experiences that challenge their prior conceptions and beliefs about mathematics and science.
- Instruction should encourage student autonomy and initiative. The instructor should be willing to let go of control over classroom discourse.
- The instructor should encourage the spirit of questioning by posing thoughtful, open-ended questions and encouraging discussion among students.

- Instruction should not separate knowing from the process of finding out.
- The instructor should allow student responses to drive lessons and seek elaboration of students' initial responses.
- The instructor should allow students some thinking time after posing questions.

A comprehensive listing of "Learner-Centered Psychological Principles" developed by the American Psychological Association can be found in Appendix II.

Of course, it is one thing to set these admirable goals and quite another to create the desired classroom learning community. It seems fair to say that development has just begun on instructional materials (problems, laboratory investigations, etc.) and classroom strategies that will constitute a "wisdom of practice" comparable to the patterns of traditional instruction that have been passed from generation to generation of teachers. Further discussion of constructivist teaching and its foundation in theory and research on learning appears in a number of contemporary research and expository journals and books (for example, see Brooks & Brooks, 1993; NCTM, 1990; Simon, 1995; Driver, et al., 1994; Redish, 1994).

Hands-On Laboratory Experience. Interpretations of constructivist learning theory also generally infer that the most effective path to conceptual understanding is one that proceeds from active engagement with concrete embodiments to progressively more abstract and efficient representations. The implication for education is that science and mathematics instruction should make extensive use of interactive physical materials and "real-world" data from primary sources. While laboratory experiences have been standard features in secondary and collegiate science instruction for years, there have always been challenges to the authenticity of those experiences. They tend to be exercises in demonstrating or confirming principles learned from classroom lectures, rather than opportunities to discover answers to genuine scientific puzzles. Until very recently, mathematics classrooms have only rarely engaged students in genuine investigation of data or modeling results from experiments.

Over the past decade, creative science educators have demonstrated ways to make laboratory investigations the central component of instruction in physics. The pervasive influence of computers and calculators on mathematics has transformed many school and college classrooms into laboratory environments as well. Furthermore, calculator-and computer-based laboratory equipment has facilitated a blending of science laboratory and mathematical modeling/analysis activity. Many innovative instructional materials and case reports of laboratory-style classes are now available, particularly for courses in physics, statistics, and calculus. Much of that work began at the Technical Education Research Center (TERC) under the leadership of Robert Tinker, and descriptions of the development are in reports from physics educators (see Thornton & Sokoloff, 1990; Laws, 1991; Krajcek & Layman, 1992). Moreover, evidence that these methods really work is building (see Redish, et al., 1997).

Collaborative Learning. The dominant public image of a scientist or mathematician is that of a solitary figure in a private world of laboratory experimentation or hypothetical reasoning. Indeed many stunning examples of scientific and mathematical discoveries have developed from one individual's sustained deep thought about complex problems. However, progress in science and mathematics is also cumulative—the work of any individual builds on the observations, conjectures, and reasoning of many others with similar interests. Furthermore, the power of teamwork in problem solving has been demonstrated not only in science and mathematics but also in our increasingly complex and technical environments in business and industry.

In addition to the payoff of collaborative work in professional science, mathematics, and engineering, recent research on learning and teaching has demonstrated the effectiveness of engaging students in structured cooperative learning activities. Consistent results suggest that student learning will be impressive if the classroom is organized to put students in small groups working on challenging problems. Common guidelines for teaching through cooperative problem solving include (from Johnson, Johnson & Smith, 1991, and Davidson, 1990):

- *Simultaneous Interaction*. Students should interact in team structures that work simultaneously to optimize their engagement during classroom time.
- *Positive Interdependence*. Activities should be structured to require contributions from all team members.
- *Individual Accountability*. While learning takes place in a team environment, students must demonstrate individual achievement.
- *Social Skill Development*. Since learning is socially negotiated from multiple perspectives, students must develop the social skills necessary for effective group interaction. Those skills must be taught and monitored along with academic objectives.
- *Reflecting*. At the conclusion of an activity, groups should be brought together to share their findings and reflect on their meaning.

Studies show that when these guidelines are effectively implemented, students have higher achievement, increased retention, increased motivation to learn, increased ability to consider multiple perspectives, more positive relationships with others, more positive attitudes toward learning, better self-esteem, and improved social skills.

If one is interested in acquiring skill in teaching that employs cooperative small-group problem solving in science and mathematics, advice is readily available (see, for example, Artzt & Newman, 1990; Davidson, 1990). Furthermore, new curriculum materials generally include a variety of group problem-solving activities that stimulate positive interdependence, allow multiple solution approaches, and pose reflection questions that help groups to articulate important scientific and mathematical principles represented in the problems.

Writing. When educators ask representatives of business and industry about skills they look for in future employees, they often mention the ability to work effectively as part of problem-solving teams. But representatives of technical fields also frequently mention the importance of the ability to communicate clearly in speaking and writing.

One of the truisms of education asserts that one never truly understands a subject until required to teach it to others. Thus it is not surprising that active participation in collaborative problem-solving activities facilitates learning. It also appears to enhance the development of student communication skills. Furthermore, one of the standard aspects of laboratory and small-group problem-solving instruction is the writing of reports that summarize and reflect on group work. Experimental K–16 science and mathematics curricula are now including substantial writing tasks, and they seem to help students to solidify and become more articulate about their knowledge (see, for example, Countryman, 1992).

Many science and mathematics teachers have begun using regular journal writing as a tool for communication with their students. On a daily or weekly basis, students are asked to write about their understanding of ideas in science or mathematics courses—what they are confident about and what they are still puzzled about—and their reflections on class activities. For many students this sort of opportunity to write about their learning is a powerful tool for developing understanding as well as a way to make personal contact with their teachers.

Assessment

Closely related to questions of learning and instruction are questions about techniques for assessing students' skills and conceptual understanding. In K–16 science and mathematics classrooms, the most common strategy for assessing student learning is through competitive, timed, written quizzes and tests that require individual students to answer a collection of specific short questions or to perform routine calculations to solve well-defined problems. Some students do very well in this sort of testing, but for many others, the conventional testing paradigms do not give accurate readings of their knowledge. Furthermore, even students who are "successful" on standard tests often have embarrassing gaps in their understanding of key scientific and mathematical ideas.

As curriculum developers have focused more on developing student skills and conceptual understanding and less on memorization and routine procedural skills, they have been compelled to devise assessment approaches that reflect the same shift in goals. For both mathematics and science, many prototypes for new assessment strategies are available (see Hestenes, Wells & Swackhammer, 1992; Mathematical Sciences Education Board, 1993; Schoenfeld, 1997).

To make student assessment more authentic, the tasks used in testing are increasingly set in realistic, open-ended contexts; may involve small groups of students; and allow multiple solutions or multiple paths to solutions. Responses to these assessment tasks are being scored using a range of new techniques, including looking at the work holistically, rather than by analyzing it as a collection of many discrete "right/wrong" responses. Assessment of portfolios of student work, which show the development of understanding over time, can also play a role in a more complete evaluation of each student's progress.

Advocates of group and portfolio assessment strategies often emphasize their interest in learning what students do know as much as what they do not know. They also stress the importance of making assessment an integral part of instruction, not simply a sorting tool to identify winners and losers in the game of science and mathematics learning.

As with other new ideas in mathematics and science teaching, the opportunities for innovative assessment are described in numerous publications. The NCTM has published a *Standards* volume focusing on assessment in mathematics (NCTM, 1995), the *National Science Education Standards* (NRC, 1996) contain similar guidance to options in science assessment, and there are practical suggestions in dozens of books (e.g., Stenmark, 1991), journal articles, and Web sites.

Technology

Curriculum, learning, teaching, and assessment are long-standing concerns in mathematics and science education. But consideration of new approaches to those problems is influenced today by fundamental changes in the technology available for doing and learning about science and mathematics. From calculators and computers to video disks and the World Wide Web, science and mathematics educators can employ many new tools in their teaching practice. These tools influence the choice of content goals in mathematics and science courses, strategies for organizing classroom and laboratory instruction, and options for communication with students and colleagues about course materials and assignments.

Changing Course Goals. When calculators and computers are available as standard tools for mathematical problem-solving, it makes sense to rethink the goals for student learning in mathematics. Curriculum development projects at every level are designing new mathematics courses that assume access to arithmetic and graphic computing software—reducing attention to training students in paper and pencil execution of routine procedures and increasing attention to strategies for intelligent use of electronic tools.

The explosion of information resources available on CD-ROM and World Wide Web networks raises similar questions about the balance between conceptual learning and acquisition of specific facts in science courses. When one can search the libraries of the world from a home computer terminal, what sort of broad understanding is needed to guide the retrieval of information from those resources, and what knowledge must still be retained "locally"? It is still too early to tell how science and mathematics education will use these information resources most effectively, but a great deal of activity is under way.

Changing Classroom Activities. Hand-held electronic technologies of various kinds are reshaping the possibilities for classroom instruction in science and mathematics in fundamental ways. The popular calculator- and computer-based laboratory instruments (CBL) are supporting exciting new kinds of investigations in which data are collected in real-time and then represented and modeled in numerical, graphic, and symbolic forms. These electronic tools for data collection and analysis are helping to integrate science and mathematics more deeply than ever before. Mathematical concepts are developed through modeling of real-life activities and scientific experiments are analyzed mathematically with a variety of convenient statistical and algebraic tools.

For example, motion detectors can be used to monitor the movement of people or objects and transform and record that information, usually in real time, directly into computers or calculators. The computers or calculators then display the data in tabular or graphic formats. Students can then analyze the data to study position, velocity and acceleration for these experiments. In addition, devices are being used with computers and calculators that measure force, temperature, pressure, voltage, current, and kinetic energy for a wide variety of "real-time" experiments. Laboratory material is available for these devices (see Thornton & Sokoloff, 1990).

When mathematics students have access to hand-held calculators with powerful numeric, graphic, and symbolic capabilities, they can investigate algebraic expressions, functions, and geometric shapes in search of interesting patterns. The mathematics classroom can become an experimental laboratory in which students construct their own understanding of key ideas and then share results with other students and the teacher as co-investigator. The use of multiple representations for mathematical ideas opens doors to the subject for students who are more adept at visual or numeric reasoning than the conventional symbol manipulation. These attractive options are being built into a range of new K–16 curricula.

Communication. Electronic communication via e-mail and the World Wide Web has made the world seem physically smaller but intellectually larger. Recent projects have also explored the power of electronic information technologies for creating scientific communities that join individuals from many schools and geographic areas—sharing experimental data and mathematical problems across state and national borders. Although work has only begun on projects to provide access to rich data-bases and on-demand assessments, the promise is great. Many school and university faculty are already using e-mail to communicate with their students and colleagues, as well as using the World Wide Web as an information resource and as a medium for publishing class materials and student projects.

The Challenge and the Opportunity

It is easy to identify the problems of teacher education in mathematics and science. But reaching agreement on ways to proceed toward solutions for those problems is a more imposing challenge. It took science, mathematics, and education faculty participating in the Maryland Collaborative for Teacher Preparation nearly two years to reach a comfortable consensus on the principles that would characterize MCTP courses. The key changes from traditional practice that we agreed would be required to reach our goals are summarized well by the following table, adapted from Johnson et al. (1991, p. 7) and Wright & Perna (1992, p. 35).

Science, mathematics, and education faculty from across Maryland accepted the challenge of creating courses that reflect these desired departures from traditional practice. Working together across disciplines and institutions, they have developed, tested, refined, and implemented dozens of new courses. Their case reports describe both successes and failures along the way. They also illustrate ways that such collaboration can facilitate faculty professional development by forming an *invisible college* of interacting scientists, mathematicians, and educators who stimulate and support each other in change.

Traditional Courses	MCTP Courses
Science and Mathematics for Some	Science and Mathematics for All
Science and Mathematics as Separate and Distinct Subjects	Science and Mathematics as Part of an Interdisciplinary World
Many Topics Covered with Little Depth	Few Topics Covered in Greater Depth
Focus on Factual Knowledge	Focus on Conceptual Knowledge
Behaviorist Learning Theory	Constructivist Learning Theory
Teacher Imparts Knowledge and Students Receive and Store it	Teacher is a Facilitator of Learning and a Learner, Too
Passive Students	Active Students
Text-Based Instruction	Hands-on/Minds-on Investigation
Confirmatory Investigations	Problem-Solving Investigations
Teacher Demonstration	Laboratory and Field Experiences
One-Way Communication	Networks of Communication in a Learning Community
Limited Use of Technology	Full Integration of Appropriate Technology
Competitive Learning	Cooperative Learning
Testing to Assign Grades	Multi-dimensional Assessment Integrated with Instruction

References

American Association for the Advancement of Science (AAAS). (1990). *Science For All Americans.* Washington, DC: AAAS.

Artzt, A. F. & Newman, C. M. (1990). *How To Use Cooperative Learning in the Mathematics Classroom.* Reston, VA: National Council of Teachers of Mathematics.

Brooks, J. G. & Brooks, M. G. (1993). *In Search of Understanding: The Case for Constructivist Classrooms.* Alexandria, VA: Association for Supervision and Curriculum Development.

Carlson, D., Johnson, C. R., Lay, D. C., Porter, A. D., Watkins, A., & Watkins, W. (Eds.) (1997). *Resources for Teaching Linear Algebra.* Washington, DC: The Mathematical Association of America.

Countryman, J. (1992). *Writing to Learn Mathematics.* Portsmouth, NH: Heinemann.

Cuoco, A., Goldenberg, E. P., & Mark, J. (1996). Habits of mind: An organizing principle for mathematics curricula. *The Journal of Mathematical Behavior, 15,* (4), 375–402.

Daie, J. (1996). Response to Elizabeth Stage. In Millar, S. B. & B. B. Alexander (Eds.). *Teacher preparation in science, mathematics, engineering, and technology: Review and analysis of the NSF workshop, November 6–8, 1994.* Madison, WI: National Institute for Science Education, 69–71.

Davidson, N. A. (1990). *Cooperative Learning in Mathematics: A Handbook for Teachers.* Reading, MA: Addison-Wesley.

Driver, R., Asoko, H., Leach, J., Mortimer, E., & Scott, P. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher, 23*, 5–12.

Hestenes, D., Wells, M., & Swackhammer, G. (1992). Force concept inventory. *Physics Teacher, 30*, 141–158.

Hiebert, J. & Carpenter, T. P. (1992). Learning and teaching with understanding. In D. A. Grouws (Ed.). *Handbook of Research on Mathematics Teaching and Learning.* New York: Macmillan.

Johnson, D.W., Johnson, R.T. & Smith, K.A. (1991). *Active Learning: Cooperation in the College Classroom*. Edina, MN: Interaction Book Company.

Krajcek, J.S. & Layman, J.W. (1992). Microcomputer-based laboratories in the science classroom. In Research matters to the science teacher. *NARST Monograph, 5*, 101–108.

Laws, P. (1991). Calculus-based physics without lectures. *Physics Today, 44* (12), 24–33.

Leitzel, J. R. C. (Ed.). (1991). *A Call for Change: Recommendations for the Mathematical Preparation of Teachers of Mathematics.* Washington, DC: The Mathematical Association of America.

Mathematical Sciences Education Board. (1991). *Moving Beyond Myths: Revitalizing Undergraduate Mathematics*. Washington, DC: National Academy Press.

Mathematical Sciences Education Board. (1993). *Measuring Up: Prototypes for Mathematics Assessment*. Washington, DC: National Academy Press.

Millar, S. B. & Alexander, B. B. (Eds.). (1996). *Teacher Preparation in Science, Mathematics, Engineering, and Technology: Review and Analysis of the NSF Workshop, November 6–8, 1994*. Madison, WI: National Institute for Science Education.

National Council of Teachers of Mathematics. (1989). *Curriculum and Evaluation Standards for School Mathematics.* Reston, VA: NCTM.

National Council of Teachers of Mathematics. (1990). Constructivist views of the teaching and learning of mathematics. *Journal for Research in Mathematics Education*, Monograph No. 4.

National Council of Teachers of Mathematics. (1995). *Assessment Standards for School Mathematics.* Reston, VA: NCTM.

National Research Council. (1996). *National Science Education Standards.* Washington, DC: National Academy Press.

National Science Foundation. (1996). *Shaping the future: New expectations for undergraduate education in science, mathematics, engineering, and technology (executive summary)*. Washington, DC: NSF.

Redish, E. F. (1994). Implications of cognitive studies for teaching physics. *American Journal of Physics, 62*, 796–803.

Redish, E. F., Saul, J. M., & Steinberg, R. N. (1997). On the effectiveness of active-engagement microcomputer-based laboratories. *American Journal of Physics, 65*, 45–54.

Schoenfeld, A. (Ed.). (1997). *Student Assessment in Calculus.* Washington, DC: Mathematical Association of America.

Schwartz, A.T., Bunce, D.M., Silberman, R.G., Stanitski, C.L., Stratton, W.J., & Zipp, A.P. (1994). *Chemistry in Context: Applying Chemistry to Society.* Dubuque, IA: Wm. C. Brown.

Simon, M. A. (1995). Reconstructing mathematics pedagogy from a constructivist perspective. *Journal for Research in Mathematics Education, 20*, 114–145.

Steen, L. A. (1988). The science of patterns. *Science, 240*, 611–616.

Stenmark, J. (1991). *Mathematics Assessment: Myths, Models, Good Questions, and Practical Suggestions.* Reston, VA: National Council of Teachers of Mathematics.

Thornton, R. K. & Sokoloff, D. R. (1990). Learning motion concepts using real-time microcomputer-based laboratory tools. *American Journal of Physics, 58*, 858–867.

Tucker, A. & Leitzel, J. R. C. (1995). *Assessing Calculus Reform Efforts.* Washington, DC: Mathematical Association of America.

Wright, E.L. & Perna, J.A. (1992). Reaching for excellence: A template for biology instruction. *Science and Students, 30* (2), 35.

References (Curricular Materials)

Applications Reform in Secondary Education (ARISE). Cincinnati, OH: Southwestern Publishing.

Event-Based Science. Menlo Park, CA: Addison-Wesley.

Powerful Ideas in Physical Science. College Park, MD: American Association of Physics Teachers.

Systemic Initiative for Montana Mathematics and Science (SIMMS). Needham, MA: Simon-Shuster Custom Publishing.

Teaching Integrated Mathematics and Science (TIMS). Institute for Mathematics and Science Education. Chicago: University of Illinois at Chicago.

INTRODUCTION: PARALLEL JOURNEYS OF RISK AND REWARD

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"We teach the way we were taught," the adage goes. This is no longer true for dozens of mathematics and science professors in Maryland who have taken part in the Maryland Collaborative for Teacher Preparation (MCTP), a statewide experiment to improve student understanding. These faculty members had the courage to take risks, to transform their teaching practices, to try new and vastly different methods of instruction.

Breaking long-held traditions has been demanding for the faculty and their students alike. But it has also been rewarding—many students are grasping mathematics and science concepts in deeper, more meaningful ways than they ever have before. For the professors, who care profoundly about their areas of expertise, this payoff has made the extra effort—or what one even called "the agony"—of changing their teaching approaches worthwhile.

In their own schooling days, these faculty members learned through lectures, drills, and step-by-step laboratory exercises. Figuring that these methods "worked for them," they taught that way themselves, some for 20 to 30 years. But what "worked for them" wasn't working for many of their students. The professors were disturbed by their students' lack of interest, meager participation in class, and inability to connect concepts across disciplines. Too many students just weren't "getting it" and didn't seem to care. As one mathematics professor put it, "the overall atmosphere of my classroom bordered on 'siesta time.'"

Now these professors have shelved their lecture notes, preferring to have students develop concepts through hands-on, problem solving activities done in small groups. They might cover less material, but do so in more depth. Generally they refrain from answering student questions directly; rather, they guide students to finding their own answers through discussions and investigations. No longer "siesta time," classrooms buzz with activity and discovery. Instead of simply testing students' abilities to recall memorized material, the professors assess students' progress by having them apply knowledge in new situations. Recognizing that learning takes time and reflection, they have students write in journals to express their understandings, misunderstandings, and thoughts on their learning.

The net result has been a quiet revolution of instructional change in Maryland, involving more than 120 science and mathematics faculty members in 13 institutions who have modified 89 courses in the past three years. Their individual journeys of transformation have taken different twists and turns, but there are many parallels in the risks they took and the rewards they reaped.

Journeys of Transformation captures the stories of 17 of these professors. This introductory section previews some highlights of these journeys, pulling together the common difficulties and the payoffs. It also describes the scope of this movement in Maryland and its national roots, why many of the professors joined this innovative program, how they were introduced to the new concepts, and why they stuck with it when times got tough.

For any mathematics or science professor who is concerned about students' understanding, and who has the courage to depart from tradition, *Journeys of Transformation* will provide practical advice as well as inspiration.

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Until the MCTP program came along, many mathematics and science faculty in Maryland probably did not know where to turn for advice in improving their students' depth of understanding. Fortunately, the groundwork for reform in Maryland was laid in the preceding years by movements at the national level that seeded this program and provided guidelines for its cultivation.

Action at the National Level

At the national level, the problem of "students not getting it" fueled a growing concern about undergraduate education in mathematics and the sciences. In particular, poor US rankings in international mathematics and science tests of grade school students called into question the college preparation of K–12 teachers in these subjects. Too few teachers, especially at the elementary and middle school levels, had more than a cursory exposure to mathematics and science as part of their undergraduate work. Too few teachers had college courses that connected the science disciplines and mathematics, or engaged students in the excitement of the science process, or incorporated technology such as computers and graphing calculators into lessons. And too few teachers were prepared to help an increasingly diverse population of students to become critical, independent thinkers. The NSF responded by initiating large-scale programs such as MCTP to reform the ways in which college mathematics and science are taught to teachers-to-be.

Also at the national level, mathematics and science education communities mobilized in recent years to develop standards for teaching these subjects at the K–12 levels. Key elements of the new standards call for teachers to actively engage students in their learning, to connect mathematics and science in "real world" problem solving, and to integrate technology into instruction. These standards and other recommendations from the mathematics and science education communities became guidelines for the MCTP faculty as they revised their courses and teaching strategies. (For more details see the section "Guiding Principles" and Appendix II.)

Maryland Breaks the Cycle

Like most school systems nationally, Maryland's educational leadership wants its K–12 teachers to be guided by the new mathematics and science education standards. So a central goal for MCTP was to encourage college and university faculty members to adopt these "standards-based" teaching methods as well, particularly when they taught future teachers. This way, the old cycle of "teaching the way we were taught" would be broken, and replaced with a new one that revolved around active learning.

To help faculty members make this change—a drastic one for many—the project held summer workshops for three years, starting in 1993. Faculty members took part in many hands-on sessions on topics such as integrating mathematics, science and technology in lessons; cooperative learning strategies; alternative assessment techniques; and other "reform-style" teaching methods. Through readings and discussions, the participants were introduced to the philosophy of "constructivism" that underscores the new methods. The philosophy recognizes that students do not learn passively but instead actively construct knowledge, filtering new information through earlier learning experiences, values and attitudes.

Not all faculty members bought the "whole package" of reform-style teaching, at least not at first. Each needed to sort through the new information and decide which elements to incorporate into his or her instructional strategy. Over time, though, many of them made significant shifts in their teaching methods. Here are some examples from contributors to *Journeys of Transformation:*

- At Frostburg State University in the mountains of western Maryland, cooperative learning has replaced lecturing as the standard mode of operation in the mathematics classes of professor Dick Weimer and his colleagues. No longer just note-takers, students actively explore mathematical concepts by working in small groups on hands-on activities.
- At Coppin State College in inner city Baltimore, chemistry professor Pallassana Krishnan resists the urge to answer student questions. Instead, he opens the questions to classroom discussions, from which the answers "evolve." "It takes a little time," he says, "but then this *learning* takes place, which is exciting."
- At suburban Towson University, geosciences professor Rachel Burks reverses the traditional method of introducing the topic of plate tectonics. Instead of telling students the major land mass movements and giving supporting examples, she has created activities in which students discover and construct key concepts themselves. For assessment, Dr. Burks has the students apply their new knowledge to explain related phenomena that they've never discussed in class.
- At the University of Maryland, Baltimore County, biology professor Phillip Sokolove incorporates small group activities into his lecture classes of 240 students, having them develop responses to question prompts. No longer nameless and voiceless in a lecture hall, his students wear name tags so that all can be identified, and use wireless microphones to contribute to large group discussions.
- At Bowie State University, students in Karen Benbury's elementary geometry course communicate mathematical ideas not only with numerals and other symbols, but also by writing in journals. Her students often have "aha" experiences upon writing their reflections, while Dr. Benbury herself gains unprecedented insights from journal entries in which students convey both their frustrations and their breakthroughs in comprehension.
- On the eastern shore of the Chesapeake Bay, professors Don Cathcart and Tom Horseman resist the natural tendency to correct students instantly when they make faulty generalizations in a mathematical modeling course. Instead, these Salisbury State University professors take the time to devise new activities that allow students to recognize their misconceptions themselves.

Having made these and other remarkable changes, the professors tend to stick with them. A 1997 survey of 33 MCTP faculty members shows that they have not only markedly shifted their instructional strategies, but they have also retained the changes over the three years or so since revising their courses. Many even employ some of the new methods in their upper level courses for students majoring in science and mathematics. The professors have "made a commitment to the new way of providing instruction," according to project evaluator Gilbert Austin, who conducted the survey. He adds, "It's a very impressive finding."

A 1997 survey of 33 MCTP faculty members shows that they have not only markedly shifted their instructional strategies, but they have also retained the changes over the three years or so since revising their courses.

In the Classroom: Adjustment Pains

When the first MCTP courses were offered in the fall of 1994, the new courses posed many challenges for professors and students alike. For the professors, it generally took more time to plan activities that actively engaged students, and to figure out ways for students to discover things on their own instead of just "telling them." Responding to student journal entries and devising new methods of assessment took additional time and thought as well. A common source of tension was the urge to cover the traditional amount of content despite the greater time needed for activities that permit students to develop deeper understandings. As stated by Tom Hooe and Joanne Settel, biology professors at Baltimore City Community College:

> *We realized early on that we were not going to be able to cover all the content we had originally planned. . . . We came to the realization that simply "covering" material does not improve student learning. Instead, we adopted the 'less is more' concept, which is hard for many professors to accept. But we believe that when assessments show that students aren't learning effectively when you just 'cover' the information, then you must search for new ways to facilitate student understanding.*

Students, too, must make their own journeys of transformation in these new courses. At first, most students expected professors to respond immediately to questions; few were used to taking the initiative to find answers themselves. Some found it very difficult to adjust when professors basically handed the questions back to them. It was not uncommon to hear comments such as, "I would just kill for a formula." A few students even responded with hostility, asserting that they were not getting what they (or, more often, their parents) paid for.

As semesters progressed, however, the students began to accept responsibility for their learning. Having shifted their expectations, they typically became active learners and willing participants. In later MCTP courses, many became role models for reluctant students with no prior experience in active learning classrooms.

The Payoff: Discovery and Deep Understanding

As MCTP professors gained proficiency in new methods, and as the students gradually accepted responsibility for their learning, wonderful things began to happen. "Aha" experiences occurred during hands-on activities and discussions that could not have happened when lecture format was used. Students gained understanding of science and mathematics concepts, often building the confidence to overcome deep-seated fears about the subjects. Through reflective writing in journals, students gleaned insights into how they learn, an invaluable experience for future teachers. Some quotes from student journals:

> *I am beginning to lose some of the anxiety I first had about venturing into the unknown. The labor involved in our pursuit is where the real learning occurs and this seems far more valuable to me as a future educator than merely obtaining the actual "answers" to this assignment.*—Frostburg State University mathematics student

> *Before taking this course, the only way I could identify a rock or mineral was because I had seen it before and remembered what it looked like. Now I can look at a rock I've never seen before and find identifying characteristics in it. To me, it's so neat to be able to do that. And if I'm excited about it, and find it fun, when I get into the classroom I can pass that excitement on to my students.*—Towson University physical sciences student

> *After completing the paper on constructivism, I feel that it is the best possible way to teach math whenever possible. Sometimes there is more than one way to reach a solution, and by letting the student try by trial and error, it builds their confidence and critical thinking skills. I think that is a part of how this course was taught, and it worked! It has helped me over a large part of my 'math phobia'!"*—Bowie State University geometry student

Student responses such as these, many of which are included in *Journeys of Transformation*, serve as strong reinforcement to professors who have taken the risk to try something new. Support has also come from studies conducted by the MCTP's research group, which is co-directed by science education professor J. Randy McGinnis at the University of Maryland, College Park and mathematics education professor Tad Watanabe at Towson University. The group has found that, compared to other teacher candidates, those who have taken MCTP courses hold more positive attitudes towards mathematics and science as well as more positive beliefs about the nature and teaching of mathematics and science. Preliminary results from new studies indicate that MCTP science and mathematics courses do, as expected, enable students to develop deeper content understanding as well. (Visit the MCTP Web site for updates on MCTP research: *http://www.inform.umd.edu/UMS+State/UMD-Projects/MCTP/WWW/MCTPresearch. html*)

Re-Writing the Textbook

Thanks to their professors' student-centered methods, some MCTP students even developed enough confidence in their content understanding to make improvements in a college laboratory text. At Towson University in 1995, in an introductory course that integrated biology and chemistry, students struggled with some enzyme experiments that did not deliver clear-cut results. Instead of stepping in with a standard protocol to save the day, professors Katherine Denniston and Joe Topping, who team-taught the course, had the students discuss the problems in depth. The students were able to recognize flaws in their abilities to observe, describe results, and keep records, which led them to devise a much more reliable and efficient method.

Even more remarkable, the students were able to draw upon their own newly developed, but solid, understandings of chemical structures to suggest that a different chemical be used to replace one that they suspected had clouded the initial experiments. The students' modification to the experiment was so successful that Dr. Denniston discussed it with the editor of their text, and it is now incorporated into the accompanying lab manual. Says Dr. Denniston, "This was very important reinforcement of their sense that they have the ability to contribute significantly to the sciences."

Courage and Community Support

Although joining the MCTP program offered professors hope for improved student understanding, it also guaranteed transition difficulties. So why did so many professors join MCTP, and why did they persevere? As mentioned previously, many were dissatisfied with the status quo, with their students not "getting it." Others had resigned themselves to the lack of student participation, but joined MCTP after being coerced by colleagues or perhaps lured by the prospect of a summer stipend. Some professors signed up a few years later, after noticing excited, engaged students in a neighboring classroom taught by an MCTP participant.

Whatever the motivation to join, sticking with the program and making changes in long-held teaching practices was risky. It took courage for these professors to try something new and drastically different, and to continue in the face of uncertainty and initial student resistance. The urge to give up and go back to the "old ways" was often strong and compelling. Fortunately, the MCTP program offered solid support from a community of kindred spirits.

Chemistry professor Pallassana Krishnan, for example, said it took him one entire, difficult semester to adjust to a student-centered approach after more than 20 years of lecturing at Coppin State College. "The first time I taught an MCTP course it was a disaster," said Dr. Krishnan. "If the professor is confused, the students sense that so easily, and that causes a lot of disturbance in the students." When asked why he didn't just "bag it" when times got tough, he replied, "'Bagging it' flew through my mind several times, but bag it and do what? If you go back to the old way, that isn't any better; it's equally bad."

Dr. Krishnan persevered, and the following semesters got better and better. Now he says, "Even if someone were to question it, I still would not go back to the lecture. The students are learning and excited; that's all I need." He said he survived his tumultuous start because "MCTP was the backing; I know at least that somebody was behind me to help me out." His institution's formal support of this program and this new style of teaching was essential. Beyond that, the "somebody to help out" included five other science and mathematics faculty members at his own institution who participated in MCTP, as well as dozens of other participants in his field and other disciplines from across the state.

In the early project years, as all the faculty members delved into the job of re-structuring their courses, they came to each others' aid in myriad ways, offering both practical assistance and moral support. Although professors from different disciplines and institutions initially held each other suspect, this distrust eventually gave way to mutually beneficial relationships that have endured since. Many conversed on the project's listserv, helping each other design interdisciplinary courses, locate resources, and sort out reactions to class activities. Some decided to form partnerships for team-teaching. When statewide "course de-briefings" were held at the end of each semester, they shared inspiring stories of their challenges and triumphs.

> *"In the long run, one of the most marked measures of the success of this project is this collaboration. It really has panned out—people in different institutions now know each other as colleagues, and not just in a passing way but in a working way."*
>
> *—Dr. Gilbert Austin*

It took time, but a community with unprecedented cross-disciplinary and cross-institutional ties formed. A sense of solidarity took hold. "In the long run, one of the most marked measures of the success of this project is this collaboration," according to Dr. Austin, the project evaluator. "It really has panned out—people in different institutions now know each other as colleagues, and not just in a passing way but in a working way. I think that will remain and continue to be fostered."

Better Undergraduate Science and Mathematics Education—For All

The MCTP program came into existence to improve teacher education in mathematics and science, but its effects will extend far beyond its initial intent. In the coming years, the program will meet its goal of producing hundreds of new teachers for elementary and middle schools who will know first-hand the thrill of discovery, the connections between mathematics and science, and ways to enhance learning with technology. Their confidence and expertise will benefit countless school children, enabling them to understand their world by seeking their own answers and, as they grow, to participate more fully in a society increasingly influenced by science and technology.

Beyond this vital goal, the program will benefit thousands of undergraduate students who do not intend to teach, but who still need better instruction in science and mathematics. A recent NSF report, *Shaping the Future*, calls for colleges and universities throughout the nation to improve the way mathematics and science are taught to *all* students. Noting the pressing need for a more scientifically literate public, the report urges science and mathematics professors to "model good practices that increase learning" (Advisory Committee to the National Science Foundation, 1996, p. iv). The report's recommendations align directly with the teaching strategies now used by MCTP professors not only in their classes for future teachers, but also, in many cases, in their classes for other undergraduates.

Thus, the MCTP program has given Maryland an enormous head start in meeting the national goal of improving undergraduate education in mathematics and science for all students. In the years to come, more and more students will benefit from deeper understandings, as MCTP professors today are spreading the word to their colleagues about the risks, the rewards, and the wisdom of no longer "teaching the way they were taught."

Reference

Advisory Committee to the National Science Foundation. (1996). *Shaping the Future: New Expectations in Science, Mathematics, Engineering and Technology.* Washington, D.C.: National Science Foundation.

ELEMENTARY GEOMETRY

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When Bowie State University decided in 1994 to require a geometry course of all elementary and early childhood education majors, I created "Elementary Geometry" under the auspices of the Maryland Collaborative for Teacher Preparation (MCTP). The course was first offered in the fall of 1994; as of this writing I have taught it three times. This paper describes the course content, the difficulties and rewards I have encountered in changing my teaching approach, and student reflections on their experiences.

Course Content and Evaluation

In developing the course content, I consulted the NCTM *Standards* (NCTM, 1989) as well as my colleagues in the MCTP program, who had many helpful suggestions. The outline of the new course included critical thinking and logical reasoning, basic ideas of geometry (points, lines, planes, triangles, polygons, etc.), some theorems from Euclidean geometry, symmetry, tessellations, geometry in 3D-space, measurement, motions, similarity, topology, and some non-Euclidean geometries. In addition, since one MCTP goal is to incorporate technology wherever possible, I planned to include a little LOGO and Geometer's *Sketchpad.* (As described later, not all topics were covered, and difficulties with technology at our institution at the time allowed us to do only a little with it.)

For evaluation, I decided to base half of each student's grade on assignments done in and out of class, individually and in groups. Assignments included logic puzzles, a work sheet entitled "What is a Math Fact?" (in which I tried to communicate the idea that mathematics is almost alone in requiring formal proof to establish a statement's validity), geometric constructions using compass and straight edge, a symmetry unit, and a unit on Eratosthenes' measurement of the Earth's circumference. Students also wrote a short paper on constructivism, and applied what they learned to produce a lesson plan for a mathematics topic for a grade level of their choice. Since most students had not yet taken their mathematics methods courses, the point of the lesson plan was entirely to demonstrate the salient features of a constructivist approach. In addition, the students kept journals, which I read a few times during the semester. I purposely required a lot of writing, since many prospective teachers seem to feel comfortable with that mode of expression, and also because I felt they needed experience expressing mathematical ideas and relations.

The other half of the grade was based on the student's performance on tests. Two in-class, one-hour tests covered material from the text and handouts. I tried a new assessment strategy in which 25% of each exam was done as a group. The groups were comprised of students who finished the individual part of each exam at roughly the same time. Although I had concerns that this arrangement might result in the brighter students automatically working together, in practice this did not happen. The final was a take-home, cumulative exam, which included some essay questions.

Approach to Teaching

Like many college professors, my main exposure to teaching has been in the form of lectures. Some of the best lecturers I have heard use a question-and-answer format in which students are naturally led to asking the appropriate questions or noting similarities to previous ideas. I have always tried new approaches with this type of presentation in mind.

Before I joined the MCTP project, I had a little training and experience in group learning and some types of active learning. I had been to workshops in which group work and learning styles were explored; these were often led by experienced people who made it look easy. The workshops gave the participants—faculty members like myself—the experience of working in a group that really *does* cooperate. They did not, however, provide the experience of *facilitating* such work among students, who are not necessarily cooperative.

When I had tried these methods in the classroom, I found it considerably harder to induce students to work together on a sustained project. The same factors that caused failure in other situations—missing classes, not performing assigned tasks, and lack of respect for the opinions of their peers—led to problems with group performance. Also, to many of the students, working in groups felt partly like cheating, and partly unfair. (One common complaint went along the lines of: "If the genius were in my group, I would get a better grade also.") At first, my own inexperience in facilitating group learning was a drawback, too. With practice, however, and with contact with other MCTP faculty who had been very successful with cooperative learning, I started to get better at it. As described later, depending on the mix of students in my classes, I eventually achieved a good deal of success with group work.

A decision to try a new approach is not an easy one.

Through MCTP I also gained exposure to teaching in the constructivist vein. What I finally attempted, however, was only partially constructivist, at least as I understand the term. I decided to start new material either with a class discussion to elicit what students already knew or with a work sheet to stimulate thinking in the new direction. This was followed by reading, possibly some explanation (explanation was better if given by the student), and more work in class to consolidate and test understanding. Finally, out-of-class work was given, with the following rules: (1) collaboration on figuring things out was encouraged, but (2) each individual was to write his or her own answers, and (3) explanations and solutions were expected, even when the question had a "yes or no" answer.

In practice, the first class was quite small, which meant that class discussions tended to include everyone. Although I tried to avoid lecturing to this small group, I did lecture on occasion, partially in response to the students' feelings about what I "should" be doing. Another traditional classroom activity in which I indulged was having them answer questions from the book or from the activities.

Much of what ordinarily would have been lecture, however, was given over to my asking leading questions to guide student discussions (and sometimes their thinking), and having them work on projects in groups or as a class. They liked the group work, especially on the exams; it reduced their anxiety. A later class was appalled when I told them that some students do not like group work.

For me, the consequences of abandoning lecture presentation are many. Lecturing allows a planned amount of material to be presented over a planned duration of time. Most mathematics courses do not allow much class time for student exploration if the syllabus is to be completed. (This is a recurring problem; it is my belief that not everything needs to be taught, but many professors and students disagree.) Another problem is that most faculty teach a fairly heavy load, with little time available for developing new presentations of ideas. When we lack time, we revert to our old ways. Finally, the students themselves are accustomed to lectures, and resent the frustration inherent in figuring things out instead of being told "the answer." A decision to try a new approach is not an easy one.

Student Age and Math Anxiety

During my first semester with the course, my students were older than the traditional college student. This had some distinct advantages, in that they were serious about learning to teach and wanted to be prepared to do a good job. They also accepted the idea that they needed to understand the mathematics.

A disadvantage with this group, however, was that math anxiety was prevalent. At least at the beginning, some students "froze" as soon as they were presented with anything challenging or out of the ordinary. Over the years, I have noticed that the math anxious are often perfectionists. A person without math anxiety might be happy with an 85 on a test, but many math anxious people are not happy with anything less than 100. For example, one assignment for this class involved graphing some measurements. In plotting the graph, which turned out to be linear, one student found that one of her points was less than an eighth of an inch off. She was so upset about this that she redid the exercise.

Math anxious students also tend to be unhappy with questions having multiple, approximate, or incomplete answers. I tried to bolster the confidence of these students by giving them a lot more time on assignments than I would normally give, then waiting for them to achieve an understanding. Some points had to be covered several times, and many had to be explained in detail more than once. I encouraged the students to work together on assignments outside class, as long as each person wrote his or her own responses. My goal was to model what their task as teachers will be; I certainly am not used to waiting so patiently for results.

Course Chronology

Almost everything took more time than I had allotted for it, so we did not complete the syllabus. Since this course had never been offered before, this may also have been a miscalculation on my part. In contrast to my original plans, non-Euclidean geometries were touched on only briefly, rather than in any detail. The topics of motions in geometry and similarity were not covered at all, nor was topology. Because technology was a problem at the time in my institution, we were not able to do as much as I would have liked with the computer.

On the plus side, however, we did cover units on the nature of geometry; critical thinking and logic; some theorems and proof concerning lines, triangles and other polygons; straight-edge and compass constructions (from the appendix of O'Daffer and Clemen's [1992] text); symmetry; tessellations; measurement of the circumference of the Earth; measurements (the metric system, areas, volumes); Platonic solids; and an introduction to non-Euclidean geometry. To follow are summaries of the key units interspersed with excerpts from student journals.

Critical Thinking. In the "critical thinking" (logic) part of the course, the students were assigned a work sheet to do out of class. Collaboration was allowed. They were to decide whether certain conclusions were justified given the hypotheses, and write both their answer and their reasoning. These were everyday situations, some of which were taken from the text.

We then discussed the propositional calculus in class, together with truth tables. We did some "knights and knaves" problems from Smullyan's *What Is the Name of This Book?* (1986). (These problems are based on the interaction between the truth or falsity of statements and the type of speaker making each statement; knights always tell the truth, knaves always lie, and normals could do either. For example, only a normal can say "I am a knave." Both knights and knaves must say "I am a knight.")

The students were also given work sheets of similar problems; they had some trouble with this, but we went over some of the problems in class, and other problems were collected and graded. Finally, the last assignment was to go back over the first work sheet, and change any answers they now thought were wrong. They were asked to hand in their final answer, together with a short statement of what had changed in their reasoning as a result of our discussions in class. We also discussed quantifiers, with special attention to the negations of universally and existentially quantified statements. In the following journal excerpts, students express a range of reactions to this unit:

I'm having a hard time grasping what this [critical thinking] has to do with math. My impression of math has always been of a discipline where one answer is correct, and there are rigid procedures to follow step-by-step to achieve the result.

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Still on critical thinking—I'm getting a grasp on it thanks to the "knights and knaves" work sheet. . . . [Dr. Benbury] clarifies and simplifies the ideas and makes it fun (for math, anyway!)

∞∞∞

The knights and knaves activities were enjoyable. I have always had difficulty with these types of puzzles. It was thrilling to finally understand how to do them.

Role of Logic in Mathematics. After the critical thinking section, we spent some time discussing the role of logic in mathematics. Since they had little prior knowledge of this, I tried to find out what they knew by having them consider some questions about facts. In groups, they were asked to list three facts from different fields of knowledge, such as history, geography, biology, or whatever they came up with. Then they were asked how these facts had been validated (how do we "know" they are facts?). They were then asked to do the same for math (they all wrote, for example, 1+1=2). We were then able to discuss definitions, postulates, and theorems.

Basic Geometry. Next we studied the basic ideas in the geometry chapter in the text. Students enjoyed doing the straight-edge and compass constructions, probably in part because they are tactile (although some students had never used a compass and encountered difficulties at first). Some remarked that going over these helped them with their understanding of geometric objects. The following journal excerpts demonstrate how this hands-on approach helped to build the students' confidence in basic geometry:

Making a figure really gives you a feel for it.

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I felt very clumsy with the compass at first, but once I got the hang of it, I really enjoyed doing them. Therefore, I was surprised to have trouble with some of them.

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I did not know how to use a compass before coming to class. . . . It took me three times . . . to bisect a line segment using the compass and straight edge. However, I did it! It was a great feeling to be able to do something with the compass

When students tackled some of the later constructions that lacked step-by-step instructions, they had difficulty. It seemed beneficial to have students do some of these harder problems in groups so that the students could brainstorm together to arrive at a solution.

Symmetry. We next studied symmetry, using the text and a draft module created by another MCTP faculty member for reference. The text covers the different types of symmetry for plane and solid figures. We discussed figures that exhibit certain types of symmetry and how to complete a figure so that it would have certain symmetries. The MCTP module had students compute the symmetry groups for a rectangle and an equilateral triangle. This led into symmetry groups in a natural way, so we continued with a brief discussion of groups and gave some arithmetic examples of groups as well (for example, the integers modulo 3 and the groups related to "clock arithmetic"). One of the points I tried to have them discover was that geometry and algebra are related in some ways that they had not previously known.

During this unit, one student wrote the following journal entry, which encapsulates a problem that persisted for many students in other units as well:

Each of the questions on the rectangle asks you to justify your answer. I have discovered that with some of these activities I can do them and know I'm right, but don't have a clue as to why I'm right.

I find that students often have trouble expressing mathematical reasoning; part of the problem is lack of familiarity with expressing mathematical concepts. When I talk with students, their response is "Oh, I didn't know I could write *that* as a reason." Often, the problem is more subtle in that they are not paying attention to their own thinking processes. They arrive at an answer, but are not sure how. Sometimes I can straighten things out by talking about it, and sometimes I do not seem to be able to help.

Tessellations. The material on tessellations came from the text, and also some related topics using excerpts from Marvin Gardner's *The Riddle of the Sphinx* (1987) and *Ah Ha Gotcha!* (1982).

The value of this unit to a future teacher is shown in the following journal excerpt by a student who had been doing observations in an elementary classroom:

I watched during the school year as students did beautiful tessellations and I was clueless as to how they did it. After this chapter I feel that I can have a conversation with these students and I have developed an understanding.

Globe Module. The best material in the course was the "Where Are We?" module, developed by Ken Berg and Jim Fey for MCTP (included in this volume). It is carefully developed to lead the student through Eratosthenes' estimate of the Earth's circumference. In so doing, students learn the significance of longitude and latitude, and gain a clearer picture of how the Earth rotates about its axis and revolves around the Sun. Most of these students did not previously understand these things. Some of them made remarks like: "We covered this in geography, but I had no idea what the professor was talking about."

The first part of the exercise involves finding longitudes and latitudes for various cities. One of the globes we used had a built-in device that gave the longitude and latitude of an illuminated spot on the globe. The students who used this particular globe discovered that the device was not working, as it gave Tokyo's coordinates in degrees West as opposed to East. Although they had to redo some of their work, the fact that they used their own powers of reasoning to determine that the globe was broken underscores the value of this kind of hands-on, investigative activity.

Then the module asks students to supply evidence for the ideas that the Earth is spherical, that it rotates, and that it revolves about the Sun. They had some trouble distinguishing between evidence for rotation (like sunrise and sunset) and evidence for revolution about the Sun on a tilted axis (like the seasons). They also had difficulty identifying the geometry theorems used to derive the circumference of the Earth, even though they are provided in the module. The struggle was worthwhile, however, as indicated in the students' journal excerpts below:

> *. . . the fact that they used their own powers of reasoning . . . underscores the value of this kind of hands-on, investigative activity.*

I understand the reasons for the seasons better now. I never really thought how useful geometry was for geography and astronomy. I also liked the way the unit gave background information on the people who made these mathematic/geometric discoveries.

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We worked together on the 'Where Are We?' handout. I really enjoy working with others. I took Geography over the summer. . . . I feel that working on the handout has helped me understand about the globe better.

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I wasn't prepared for a geography-type lesson. Math is everywhere!

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The globe module is an interesting application of geometry and angle measures. I never really knew how latitude/longitude were used or how they were really calculated.

In my opinion, this module (or something like it) should be a part of every elementary education major's course work. The surprise the students almost uniformly showed when exposed to these concepts leads me to believe that their understanding of many phenomena is weak at best. Moreover, this kind of unit helps them to recognize that even though we cannot observe directly the workings of some portions of our world, we can still model and predict them, and in this sense, understand.

Measurements. The last part of the course focused on measurements. We covered some of the standard area and volume measures and, briefly, the metric system. The students found conversion of measurements very challenging. They were also asked to explore how doubling or tripling the side of a square (or the radius of a circle) affected the area and how doubling or tripling the side of a cube (or radius of a sphere) affected its volume. Students were often uncomfortable when asked to state a general principle that they had discovered.

Platonic Solids and Geometry of a Sphere. During the first semester, we only had time to touch on Platonic solids and the geometry of a sphere. During the summer of 1996, however, we had time for the students to write brief explorations on "great circles"—the curves on the surface of a sphere that are the "straight lines." This caused considerable consternation, as many of the students had never heard of such a concept before. But some good papers resulted, which reinforced my view that future teachers in particular benefit from expressing mathematical ideas. The following journal quote captures one student's frustration as well as recognition of the value of doing the paper:

This was a nightmare for me. . . . Finally, I realized that I understood what was being said but [writing the paper] forced me to be able to articulate it. . . .

Paper on Constructivism. At the end of the course, each student submitted a paper on constructivism as well as a lesson plan. To complete the project, the students needed to discover the educational resources for teaching elementary mathematics available at the campus library. (There is a considerable collection, but many of the students were unaware of this at the outset of the course.) While some students at first hunted until they found "the book" they thought I wanted them to use, most were comfortable with multiple sources once they explored the available material. Each presented his or her lesson plan to the class as a whole. A surprising and wonderful outcome of the paper and lesson plan assignment was that most of the students felt that they could now learn and figure out how to present at least some mathematics on their own. The following journal excerpt shows how one student gained confidence in constructivism as a teaching philosophy, and more importantly, in herself as a learner:

After completing the paper on constructivism, I feel that it is the best possible way to teach math whenever possible. Sometimes there is more than one way to reach a solution, and by letting the student try by trial and error, it builds their confidence and critical thinking skills. I think that is a part of how this course was taught, and it worked! It has helped me over a large part of my 'math phobia'!!

Reflection

Probably my biggest surprise was the extent to which the students' confidence increased as a result of doing the lesson plan. They found that the educational resources in mathematics available in the library were not overwhelming, but instead comprehensible. This may have been their first experience reading and understanding mathematics (no matter what the level) on their own.

My next biggest surprise was the extent to which the elementary education majors are willing to work. (I have since found that some of them are not so energetic; my first class was not completely typical.) I was quite dismayed at the lack of knowledge in some of the students, particularly when we studied the measurement of the Earth's circumference, but was pleased at the time and energy they put into answering the questions and, in the main, the understanding they were finally able to exhibit.

Although the students often struggled with material, through their journal entries I learned that they appreciated my efforts to make mathematics relevant to them. For example, journal reactions to the first material (what is geometry, where do geometric objects appear, etc.) indicated surprise that geometry had any relevance to anything. So far I have taught the class three times, and each time the students have had this same reaction. (Those who took a standard high school geometry course seem most prone to this response.) In addition, one student appreciated that the text took "into account that many cultures had an impact on what we know as geometry today." For some types of learners, relevant non-mathematical content must be included in the course.

The first class was so good about keeping their journals that I did not realize the extent to which students need to be guided. They wrote about their frustrations and their breakthroughs of comprehension; they often pasted in relevant news articles and commented about them. They commented frequently about rote learning versus thinking, and related this to their own experiences in the course. Unfortunately, I caused some brief interruptions in the recording of these experiences because I had to collect their journals to read and comment upon them. The second time, we used e-mail, so that feedback was more immediate, but they were less reflective, and I was not sure what to do about it. I think that this was mainly the problem of the younger students, and I did not recognize for some time that I had to give them more leading and focused questions. The third time, we were back to notebooks again because e-mail was once more not available; once again the class was a bit more mature, so the journals offered more insight.

Much of the group work in the first elementary geometry class seemed to go more smoothly than with my other students (both general education and math majors). I believe that the students in this class were older and more responsible. My second class seemed less responsible than average, and the groups were less successful. The third class said that they had always heard that group work was better, but that this was the first time that working in a group seemed natural to them. It seems that a certain type of student really likes collaborative learning (I've found that math majors, in the main, do not); I think many of the more mature elementary education majors fit this profile.

The grades in this class were better than usual in a lower level mathematics class, probably because I tried to give the students more time when they appeared to need it, and explained some concepts many (three or four or more) times in class. I made a conscious choice to do whatever possible to decrease their anxiety, since without confidence and knowledge, they will not be able to cope with mathematics in the classroom. Several of my students have started the course in a state of terror, and have finished it with a fair degree of confidence. One of them, for example, went on to apply and participate successfully in an MCTP summer research internship. Considering that she literally shook with fear at the beginning of the course, this is something I doubt she would have considered without having gained confidence in herself through the course.

Although the students often struggled with material, through their journal entries I learned that they appreciated my efforts to make mathematics relevant to them.

For future semesters, I plan to use portfolios as part of the assessment, and manipulatives for the section on Platonic and semi-semi-regular solids. There are ways that folding papers (including origami) can illustrate geometric concepts that I would like to explore. I also will be incorporating technology in a more consistent way.

In closing, I'd like to note that one of the often-overlooked aspects of learning is the time between classes. For a student who is willing to work consistently on material, this time is perhaps the most critical, for it is in these periods that the concepts come together. I have found that, even though I have more of a tendency to "tell them" than a true constructivist should, I still had to wait for the knowledge to be assimilated. Students' understanding too soon slips away, particularly if we go on to different material; the first "ah ha" is not enough.

References

Gardner, M. (1987). *The Riddle of the Sphinx*. New Mathematical Library, Volume 32. Washington, DC: Mathematical Association of America.

Gardner, M. (1982). *Ah Ha, Gotcha!* New York: W. H. Freeman.

Henderson, D. (1996). *Experiencing Geometry on Plane and Sphere.* Upper Saddle River, NJ: Prentice Hall.

National Council of Teachers of Mathematics. (1989). *Curriculum and Evaluation Standards for School Mathematics.* Reston, VA: NCTM.

O'Daffer, P. and Clemens, S. (1992). *Geometry, an Investigative Approach* (2nd ed.). Reading, MA: Addison-Wesley.

Smullyan, R. (1986). *What is the Name of this Book?* New York: Simon & Schuster.

INTERDISCIPLINARY SCIENCE AND MATHEMATICS: GEOMETRY AND THE ROUND EARTH

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It's hard to imagine doing important science without using some mathematics, and mathematics would certainly be a much less important subject without its applications in the sciences. But, in traditional science and mathematics courses, the connections between these subjects are poorly represented. Mathematical ideas and techniques are generally taught with little reference to their uses in scientific problem solving. A typical mathematics course might often use scientific formulas as contexts for practice of mathematical calculation, but would seldom show how important mathematical principles are suggested by abstraction of patterns observed in scientific phenomena. Conversely, science educators typically think of mathematics only as a toolbox to which they turn for techniques of data analysis and problem solving—once scientific principles have led to well-defined plans for calculation.

Over the past several decades, the increasing mathematization of all sciences has been accompanied by the emergence of a new point of view about the relation between mathematics and science. Instead of thinking about mathematics as only a collection of convenient computational techniques, it is increasingly seen as a source of *models* for describing and reasoning about all sorts of structural patterns that occur in the natural world. Mathematical modeling helps scientists to find patterns in data and explanations for those patterns, as well as predictions of the ways that changes in conditions of an experiment will lead to changes in results. This modeling point of view about the relation between mathematics and science has also stimulated intense interest in using scientific experiments and data as starting points for the study of important mathematical structures.

With the objective of conveying to liberal arts students and prospective elementary school teachers some breadth of understanding about the relation between mathematics and the physical, life, and management sciences, the University of Maryland, College Park requires a fundamental studies course titled Elementary Mathematical Models. Even with the modern title alluding to mathematical modeling, the standard offering of MATH 110 is commonly a pretty traditional finite mathematics course that trains students in calculations required by familiar applications in linear programming, probability, game theory, and mathematics of finance. To give students a more authentic experience with the processes of mathematical modeling, we used support from the MCTP project to develop new materials and instructional approaches in that course.

In designing the new version of the modeling course, we wanted students to analyze problems by:

- beginning with data from experiments or realistic situations;
- producing numeric, graphic, and symbolic representations of significant data patterns;

- using mathematical models to make predictions;
- interpreting those predictions in the original problem contexts;
- examining the models and their implications for sensitivity to changes in modeling assumptions; and
- looking for cause-and-effect explanations of model results.

We wanted students to experience use of the technological modeling tools like the data plotting, curve-fitting, and random number generating routines of graphing calculators. Furthermore, we wanted students to gain insights into mathematical modeling through student-centered classroom activities, not lectures.

We chose to include material that would lead to function models (primarily linear and exponential) in both iterative ($y_{n+1} = y_n + k$ and $y_{n+1} = ky_n$) and closed forms ($y = kx + b$ and $y = ak^x$) and probability models (using simulation and formal analysis). But we also chose to extend the standard list of finite mathematics topics by including a substantial unit that demonstrated the usefulness of geometric models.

. . . we wanted students to gain insights into mathematical modeling through student-centered classroom activities, not lectures.

The report that follows describes the unit on geometric modeling that we developed and have used in nearly a dozen sections of MATH 110 over a number of semesters. We've included the full student text, which is essentially a narrative and a series of problems to be solved by students in collaborative groups, and some sample assessment probes. We've also interspersed some commentary on our objectives and experiences in using the unit.

Geometry and the Round Earth

One of the most striking examples of interdisciplinary science and mathematics is the long history of interplay between physics and mathematics for work on astronomical questions. Unable to stand outside the solar system or galaxies to see how the observable pieces fit together into a system, scientists have been forced to make extensive records of visible patterns and then to use analogy, metaphor, and scientific imagination to build physical and mathematical models of the objects and their interaction.

Astronomy today is a deep and complex subject that employs sophisticated mathematics, physics, and chemistry in attempts to explain the origin and evolutionary processes of the entire universe. However, many significant questions about our Earth and solar system can be studied with elementary mathematics and science. In the process, prospective teachers and other students can gain valuable knowledge and insight into scientific method.

Contrary to popular belief, the spherical shape and approximate size of the Earth were determined more than two thousand years ago, though direct physical verification of these facts was not achieved until many centuries later. Unraveling the story of these early astronomical inferences is a fascinating opportunity to review fundamental concepts of geometry (proportionality, similar triangles, and central angles in circles), geography (latitude, longitude, equator, Tropics of Cancer and Capricorn, Arctic/Antarctic Circles, and change of seasons), history (Mediterranean region in the time of Euclid and later when Columbus was seeking support for his voyages of discovery to the Americas), and scientific method (the interplay of empirical and theoretical work and the profound challenges posed by astronomical questions when observational tools and vantage points were limited).

To help our students gain some of the scientific and mathematical insights that underlie those profound questions and their important everyday consequences, we developed plans and instructional materials for an interdisciplinary unit of instruction which we titled "Where Are We?" Our goal was to guide students to construct or refine their personal understanding of several fundamental questions:

- How are latitude and longitude determined on our Earth and why are several latitude lines designated as especially significant?
- How does the Earth's relation to the Sun determine seasons and the length of days and nights?
- How could scientists over 2000 years ago have known that our Earth is a sphere and estimated the circumference of that sphere to a high degree of accuracy?

The answers to these questions are widely known today. In any event, it would clearly be easy to "cover" the facts in a few short lectures. But there is also a growing body of evidence that many educated adults have very shaky and superficial understanding of the "facts" and that listening to a lecture or two (no matter how lucid and well illustrated) will not begin to produce the deep understanding that one would hope a science or mathematics teacher ought to have.

We planned the unit so that it would begin with an assessment of students' prior conceptions on these issues, engage students in active investigations that involved hands-on modeling of important scientific phenomena, encourage students to communicate their questions and findings clearly to each other and the instructor, demonstrate the power of mathematical modeling as a tool in scientific reasoning, and cause students to reflect on the complex paths of reasoning that lead to scientific discoveries.

In a typical classroom launch of the unit, we begin with a short quiz and discussion to assess student prior knowledge and conceptions on the issues raised here. For many students this simple assessment of prior conceptions reveals how little they understand about lines of latitude and longitude. In a subsequent journal entry, one student wrote:

> *I learned this week that I knew virtually nothing about the lines of latitude and longitude, nor the reasons for their placement on the globe/map. I was surprised at how little I knew. So, I guess this was a bit of an eye-opening exercise.*

Geometric Modeling Unit
Student Text

WHERE ARE WE?

In the search for scientific theories that explain our observations and experiences of the world around us, few things have sparked as much interest as the simple question, "Where are we?" Throughout recorded history (and probably long before), people in all places and cultures have puzzled over the size and shape of our planet and the location of the Earth among the planets and stars of the heavens. What do you know or believe about:

- *the size and shape of planet Earth?*
- *systems for locating points and travel routes on the Earth?*
- *the size, location, and motion of the Moon, the Sun, and the other planets of our solar system?*

As fascinating and important as are many facts of life on Earth and in the solar system, it is equally intriguing to ask how and when we came to current understandings of our place in the universe. What do you know or believe about the timing and methods of thought used in the discoveries that:

- *Our planet is round like a ball, not flat like a table top?*
- *The circumference of the Earth is about 25,000 miles, and the distance from the Earth to the Sun is about 93,000,000 miles?*
- *The Earth rotates around a tilted axis and revolves around the Sun to cause days and nights and seasons of the year?*

The answers to these fundamental scientific questions are generally considered part of the discipline called astronomy. However, the methods used by astronomers rely heavily on numerical and geometric ideas from mathematics. This unit explores scientific and historical connections between mathematics and astronomy in four investigations titled:

Latitude and Longitude

Days and Nights, Years and Seasons

Shape and Size of the Earth

Where in the World Is Christopher Columbus?

The goal is to explore the basic ideas and processes that have been involved in the long and fruitful search for mathematical models of our Earth and the solar system.

Latitude and Longitude

This first investigation reviews and extends student understanding of the basic global positioning system based on latitude and longitude. In our experience, most students certainly remember something about these two ideas. However, they've often forgotten which is which, they don't know how the locations of the lines are actually determined, they don't know the connection between latitude and distance of points directly north/south of each other, and they don't know the fundamental and fascinating connection between the latitudes of the Tropics and the Arctic/ Antarctic Circles. In the hands-on activity mapped out to help students reconstruct their knowledge of these things, many students are genuinely challenged by the problem of determining spherical radius or diameter from circumference. The group project work involved in constructing a planar section of a globe works well to get students cooperating, because there are significant roles for several people at each stage. Also, while an instructor could lecture (even with demonstration for the class) through this investigation, we find that watching students work on the problem themselves gives us insight into the conceptions and puzzles of individual students that we would never get in a lecture setting.

In their journals, many students commented on both the mathematical substance and the classroom investigative style of the activities. One student's remarks are particularly vivid:

> *Math and its exactness have always been hard to get used to. It carries a connotative meaning of 'One false move and you're dead' concept. It was a horrible way to come to class. So my idea of learning was that I had to just be right, no matter what I did. Scary. In our class, and with our experiments, I make mistakes all over the place, end up with the right answer after bouncing it off of my group members, and I am not downgraded for that. Our experiment on latitude and longitude gave me the opportunity to say, and even think, that latitude was north to south and longitude was east and west distance, and have that idea changed and changed again before it was correctly stated, and I wasn't going to be condemned to death as a result.*

Student Text

LATITUDE AND LONGITUDE

If you had to tell someone how to locate College Park, Maryland, it's unlikely that you would say, "It's at 77° west longitude and 39° north latitude." But as an international scheme for describing positions on Earth, the (longitude, latitude) coordinate system has proven itself as an invaluable tool for navigation on land, sea, or air. It's a system that we take for granted, but:

- *What do you know about the rules for assigning longitude and latitude coordinates or the specific coordinates locating important places on the Earth?*
- *Do you know when the current system was developed and what sorts of prerequisite knowledge were necessary for building the system?*

It's hard to recreate the human experience of exploration and discovery that led to our current global positioning system. But by analyzing the way that lines of longitude and latitude are drawn on a model globe, we can make some guesses at the origins of this important mapping system. To answer the following questions, and those of subsequent investigations, you'll need a globe map of the Earth, several feet of string, and rulers for length and protractors for angles.

1. To get started, use the globe to find approximate map coordinates for the following major cities around the Earth:

   a) Chicago, Illinois　　b) Honolulu, Hawaii　　c) Tokyo, Japan

   d) Sydney, Australia　　e) Kinshasa, Zaire　　f) Sao Paulo, Brazil

   g) London, England　　h) Cairo, Egypt　　i) Moscow, Russia

2. One natural question about map coordinates is whether you can tell the distance between two points from the difference of their coordinates. Collect some data from your globe to explore this question:

   - Locate the Equator and several lines of latitude in the northern hemisphere.
   - Use a tape measure to find the distance from the Equator to each of the lines of latitude on your globe. Don't worry right now about the actual distance on the Earth; use inches or centimeters to measure the distance on your globe model of the Earth.
   - Make a table and a graph plot of the (latitude, distance) data.

   a) Describe the pattern of data relating latitude and distance from the Equator. How, if at all, does it allow you to predict north-south distance between two points from the latitude coordinates?

   b) Locate the two special lines of latitude in the northern hemisphere—the Tropic of Cancer and the Arctic Circle.

      (1) Measure the distance on your globe from the Equator to each of those two latitude lines.

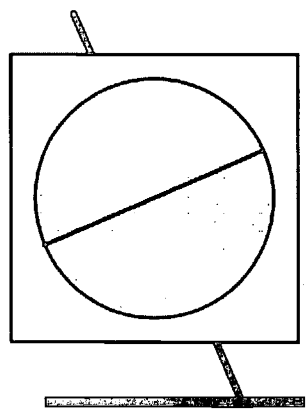
      (2) Use the pattern of (latitude, distance) data from your measurements in (a) to estimate the latitude of the two special lines.

      (3) If you see any interesting connection between the Tropic of Cancer and Arctic Circle latitude numbers, see if you can come up with an explanation of why that relationship

occurs. If you don't see anything noteworthy right now, keep on the lookout in the investigations ahead.

3. You know, or have noticed from the globe, that latitude is reported as a measurement in degrees. That suggests that angles are involved in establishing the lines of latitude. *What angles do you believe are being measured?*

   - Figure out the diameter of your globe (Do you remember the relation between circumference and diameter?).
   - In a piece of poster board paper, cut a circular hole with the same diameter as your globe and slip the resulting circular collar over the globe from pole to pole. It represents a plane passing through the sphere.



   - Around the circular collar, mark the points where lines of latitude touch it. Then take the "planar section" off the globe and lay it flat for analysis.

   a) Think again about the possible angles being measured when lines of latitude are given their degree measures. Record your ideas.

   b) Any more thoughts about the Tropic of Cancer and the Arctic Circle latitudes?

4. The circles on the globe that pass through both North and South Poles are called lines of longitude. Those lines are also measured in degrees.

   a) How do you think degree measures are assigned to lines of longitude?

   b) Do some experimentation to see if you can tell the east-west distance between two points on the globe from their longitude coordinates.

5. Having studied the relation between measures of latitude and longitude and distance on your globe, scale up your findings to facts or principles about distance on the whole Earth.

   a) If one point is directly north or south of another, how can you predict the distance from one to the other, based on knowledge of the latitude of each?

   b) If one point is directly west or east of another, how can you predict the distance from one to the other, based on knowledge of the longitude of each?

6. A family in the northern hemisphere sets out from their home and walks 3 miles due south, then 2 miles due west, and then returns home by walking 3 miles due north. Along the way they see a bear.

a) What color was the bear?

b) Could a family in the southern hemisphere make a similar trip?

Conclusions and Connections—Now that you've reviewed the structure of our familiar latitude and longitude coordinate system for locating positions on the Earth, think about the ideas that had to be developed before the current system could be organized and what problems remained for navigation even with the notion of latitude and longitude developed.

1. What big ideas about the size and shape of our Earth seem prerequisites for defining longitude and latitude, and in what order do you think those ideas were discovered?
2. The system of latitude and longitude coordinates is only one of many locator systems used in a whole variety of tasks. Think about and describe several other coordinate locator systems that you are familiar with. Then compare them with the basic features of Earth longitude and latitude coordinates.
3. What is it about 90°, 180°, and 360° that makes them common in angle measurement?
4. The Equator is the line (circle) of latitude with measure 0; the prime meridian is the line (circle) of longitude with measure 0. Which of these two great circles pretty much has to have a coordinate of 0° and which has that coordinate pretty much by historical accident?
5. How do you think satellite dishes for television are "tuned in"?
6. The U. S. Defense Department developed a global positioning system that uses orbiting satellites and a portable piece of apparatus on the ground that can be carried by an individual. It can pinpoint the carrier's location on the Earth to within 1 meter! How do you suppose it does that?

Days and Nights . . . Years and Seasons

As the title suggests, this investigation moves on to the connection between latitude, the tilt of the Earth's axis, the orbit of the Earth around the Sun, and other related topics. In our experience, these questions are much more foreign ground than the simple latitude/ longitude questions. Many students really don't have much sense of what it means for the Earth to orbit the Sun in such a way that its axis of rotation at any time is always parallel to its position at the beginning of a year. Explaining how the Earth's axis tilt and orbital motion around the Sun cause seasonal changes in daylight and typical temperatures at various places on the Earth is not a trivial problem. For example, one common misconception is that summer in either hemisphere is warmer primarily because that part of the Earth is tilted "closer" to the Sun. That misconception is very resistant to modification.

The interplay between the perceived size of the Sun and Moon and their distance from the Earth is a challenging question of scaling, similar triangles, and other geometry. The question of how people living thousands of years ago could figure out astronomical sizes and distances is a wonderful puzzle to get students thinking about.

For many mathematics instructors, such hands-on activities are often seen to be something appropriate only for elementary or middle school students. However, we've found that appropriate hands-on work is appreciated by undergraduates as well.

In this unit we encourage students to get their hands on models of the Earth and the Sun by providing them with globes, flashlights, and measuring tools. At some points we actually hang a light bulb Sun from the classroom ceiling and have students "walk" the Earth around that Sun. Keeping the Earth axis in the requisite parallel position has been a surprisingly tough task for even our stronger students, highlighting the impressive insights of those who conceived and convinced others of the proper heliocentric models of planetary motion, all from an Earth-bound vantage point.

For many mathematics instructors, such hands-on activities are often seen to be something appropriate only for elementary or middle school students. However, we've found that appropriate hands-on work is appreciated by undergraduates as well. In the process we realize our objective of teaching in ways that our prospective candidates might themselves teach in future K–12 classrooms. The effect of hands-on work with challenging problems is endorsed in these journal reflections by many students. One student wrote:

> *The proportional model of the sun and the earth that we put together helped the people in my group understand how far away the sun really is. It is sometimes hard to comprehend the distances that we use when talking about planets or stars. Using a proportional model helps put things on a smaller scale so that it is easier to grasp the concept.*

Another student wrote:

> *In this class activity, I learned more about the specific motions of our solar system. The use of the flashlight and globe in this experiment was a great way to visualize the mathematical aspect of this project. These models helped me understand the concept much more. It was interesting to study how the sunlight hours are different at each particular season.*

Student Text

DAYS AND NIGHTS . . . YEARS AND SEASONS

In the search for mathematical models of our solar system, one of the toughest problems was figuring out how (if at all) the Earth, the Moon, the Sun, the other planets, and the stars are moving.

- *What do you know or believe about the motion of planets and the Sun in our solar system?*
- *Try to imagine yourself thinking about this question 1000 or even 2000 years ago. What evidence would you have that something was moving, and what clues would you have that would lead to the present understanding of solar system motion?*
- *What practical consequences could there be to understanding motion of the heavenly bodies?*

These are very hard questions, but scientists (and lay people also) conjured many theories and had heated debates about them.

You can get an understanding of the present-day theories by simulating the Earth and the Sun with a globe and a flashlight. Of course, those crude simulation tools only suggest what is going on. You have to imagine the experiments scaled up many times to get a picture of what is really happening.

1. To get a rough idea of the kind of scale model that would be needed to do accurate Earth-Sun simulations, consider these data:
   - The diameter of the Earth is about 8000 miles; the diameter of our Sun is about 865,000 miles;
   - The Sun is typically about 93,000,000 miles from the Earth;
   - Light from the Sun travels 186,000 miles per second.

a) If your globe is 1 foot in diameter, what diameter would you need for a model Sun?

b) How far from your Earth model should your Sun model be placed to have the model be proportional to the real thing?

2. Your answers to question (1) might convince you that a globe and a flashlight will tell nothing about the real Earth-Sun relations. But with some care and thought, you'll see illustrations of many important facts of the solar system. Hold your flashlight several feet from the globe and experiment with movement of those Earth-Sun models to simulate various times of day and night and various seasons of the year.

   It was not until the late 1950's that we were able to observe the solar system from orbits far above our Earth's surface! Think about how an earlier Earth-bound observer might reasonably get the following ideas about solar system phenomena:

   a) That the Sun is revolving around the Earth

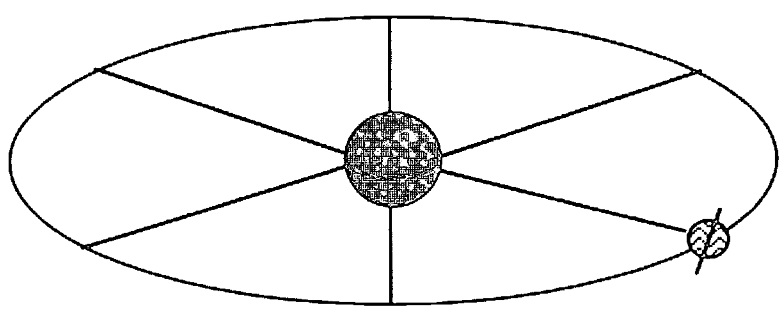
   b) That the Earth itself is rotating on an axis

   c) That the Earth is revolving around the Sun

   d) That the Earth moves around the Sun with its center in a fixed plane

   e) That the Earth's axis is tilted at an angle to the orbital plane

3. Although it took thousands of years for scientists to realize (believe?) that the Earth revolves around the Sun, not the other way around, let's assume some modern knowledge of Earth-Sun relations to figure out why days and nights and years and seasons behave the way they do. The Earth moves in an elliptic orbit and the plane of that orbit cuts through the center of the Sun. At any point in the orbit (any time of year), the Earth's axis of rotation is parallel to its position at any other point in the orbit and tilted to the plane of the orbit.



   Use this model of Earth-Sun relations and your flashlight-globe simulation to study the following questions about familiar seasonal phenomena. Move the globe around to different positions in relation to the flashlight "Sun" and observe differences in the way the Sun illuminates the Earth as it rotates on its own axis. Record your ideas with sketches that help to describe events and their explanations.

   a) At noon on March 21 and September 21 (the spring and fall equinoxes), the Sun is directly overhead at points on the Equator. Where is the Earth in its orbit around the Sun on those dates, and why do all points on the Earth experience equal amounts of daylight and darkness on those days?

   b) At noon on June 21 (our summer solstice in the northern hemisphere), the Sun is directly overhead at points on the Tropic of Cancer. Where is the Earth in its orbit around the Sun on that date and why do some points on the Earth experience 24 hours of sunlight and others 24 hours of darkness?

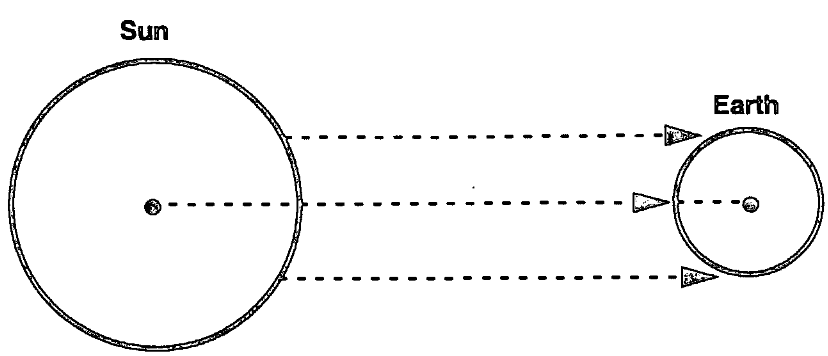
c) At noon on December 21 (our winter solstice in the northern hemisphere), the Sun is directly overhead at points on the Tropic of Capricorn. Where is the Earth in its orbit around the Sun on that date and why do some points on the Earth experience 24 hours of sunlight and others 24 hours of darkness?

d) Why is it that in the northern hemisphere, June, July, and August are generally the warmest months, while December, January, and February are the coldest?

e) How are the latitude measurements of the Tropic of Cancer and the Tropic of Capricorn related to each other and to the tilt of the Earth's axis, and what connection does this relationship have to seasonal variations in daylight and darkness on the Earth? What is the comparable answer for the Tropic of Capricorn and the Antarctic Circle?

Conclusions and Connections—The flashlight and globe experiments use a *physical model* to study the solar system. It gives a general qualitative idea of how the system works. To describe things more precisely and to make predictions, it helps to have a model of the Sun and planets that can be described with geometric shapes and equations.

1. What geometric shapes and measurements play key roles in a solar system model and in explaining days and nights and years and seasons?
2. Because the Sun is so much larger than the Earth and so far away from the Earth, it is hard to make true scale model drawings of the relationship between them. However, the following drawing (inaccurate as it is in some respects) can be used to describe some important aspects of the relationship. Imagine that you are looking at a side view of the Sun and Earth with your eye directed along the orbital plane.



a) On sketches like this, draw in the Earth's axis and Equator as you would see them from such a side view at each of the four key points in the year: the summer solstice, the fall equinox, the winter solstice, and the spring equinox.

b) Explain how the sketches demonstrate the different sunlight hours at different seasons. In particular, how do parts of the northern hemisphere have 24 hours of sunlight at the summer solstice and 24 hours of darkness at the winter solstice.

c) Explain how the sketches show the special properties of the Tropics of Cancer and Capricorn and their relation to the Equator and the Arctic and Antarctic Circles.

Shape and Size of the Earth

This investigation gets to the two big questions that drive the entire unit: How and when did scientists and explorers know that the Earth is a ball? How and when were they first able to make good estimates of the size of the Earth?

Consistent with our focus on student conceptions, we usually begin the investigation with a discussion of student prior notions about these questions. When time is allowed for students to work in groups to formulate preliminary conjectures about the issues, we've found that many groups engage in very lively discourse of the sort that must certainly have typified scientific debates over long periods of time. We believe that this experience, when it is called to their attention, gives students a valuable insight into the nature of scientific work. Instead of simply listening to (and copying) well-polished theories explained by an expert, the students grapple with the questions themselves.

The student text material is written as a series of questions, offering progressively greater guidance or scaffolding to help students formulate ideas that can be used to reconstruct the amazing work attributed to Eratosthenes. In our judgment, the reasoning involved in his estimation of the Earth's circumference is one of the truly impressive examples of mathematical modeling at work to make scientific predictions that could not be confirmed by physical measurement until much later. While few student groups are able to integrate the various pieces of knowledge needed to replicate Erathosthenes' method without several steps through the hints, it is always exciting to hear the, "Oh, I get it—it's alternate interior angles," from students when they have progressed far enough to recognize a familiar relationship that is the key.

Again, we are sure that a clear lecture presentation of the reasoning could be provided in much less than one class period. But we are convinced that until students have struggled with the problem themselves, even the best exposition will not connect with their prior conceptions in a way that produces permanent conceptual change. By teaching through investigations, we see clear instances of the students thinking deeply about the problems, and raising questions as to what they do and do not understand, rather than simply accepting information as the truth. For example, in the following journal entry one student shared how he was having difficulty understanding a concept:

> *Instead of simply listening to (and copying) well-polished theories explained by an expert, the students grapple with the questions themselves.*

> *So why is it that the sun's rays can be considered to be parallel lines striking the earth? I have trouble with the concept. I understand that it works, but it always seems to me that light travels in all directions out from the surface of the sun . . . so why doesn't some light which, for example, let's say it leaves the sun at a minutely small angle—why doesn't this light hit the earth's surface, also at an angle, throwing off the "parallel rays" theory? Is there no angle small enough to accomplish this (meaning that, by the time it had come the distance of the earth, it would have angled too far left/right/up/down)? I just don't know.*

SHAPE AND SIZE OF THE EARTH

The Earth is round. Are you sure? Why do you think so? Why would a resident of Nebraska (one of our flatter states) think so? When and how do you think astronomers, geographers, and explorers came to believe that the Earth is round?

When Columbus proposed his westward trip from Spain to China, via the Canary Islands off the coast of North Africa, his estimate of the distance was not very accurate and there was a large land mass blocking his planned route. However, he was right that the Earth was round. Isabella and Ferdinand of Spain financed the voyage, over the objections of their royal advisors who believed the Earth was round but thought Columbus was mistaken about the distance . . . which he was!

As early as 240 B. C. it was commonly believed that the Earth was round and various people had given estimates, or perhaps their guesses, as to its size. In fact, in 240 B. C., Eratosthenes, the librarian of Alexandria, produced a well-reasoned estimate placing the Earth's circumference at about 25,000 miles (using more modern units).

Eratosthenes' Bright Idea

The city of Alexandria in Egypt was founded in 332 B. C. by Alexander the Great. After Alexander's death nine years later, Ptolemy I emerged from the conflict among potential successors to establish control in Egypt with a government based in Alexandria. A succession of Ptolemys built Alexandria into an enormous cultural center. A center of learning was established where, for example, Euclid taught mathematics. Eratosthenes was the librarian responsible for building a collection of the best thought from around the world. Among the information he collected were some facts that led to his impressive deduction about the size of the Earth.

The questions that follow give a series of challenges and hints that allow you to trace Eratosthenes' reasoning about the size of the Earth and then to move farther back in history to see how one might first reckon the Earth to be round.

1. Imagine that the year is 240 B. C. and you live in Alexandria. You accept the general idea that the Earth is round, so you can imagine it marked up with lines of latitude and longitude, *but you don't know its size.* First bright idea: If you knew the connection between change in latitude and distance on the earth's surface, you could estimate the circumference of the Earth.

   If a one-degree change in latitude corresponds to a known distance d, how would you calculate the circumference of the Earth?

2. Imagine next that someone phones you from a place due south of your home and says, "Whew, is it hot! I just went outside and the Sun is directly overhead." You hang up and go outside to find that the Sun is not directly overhead where you live.

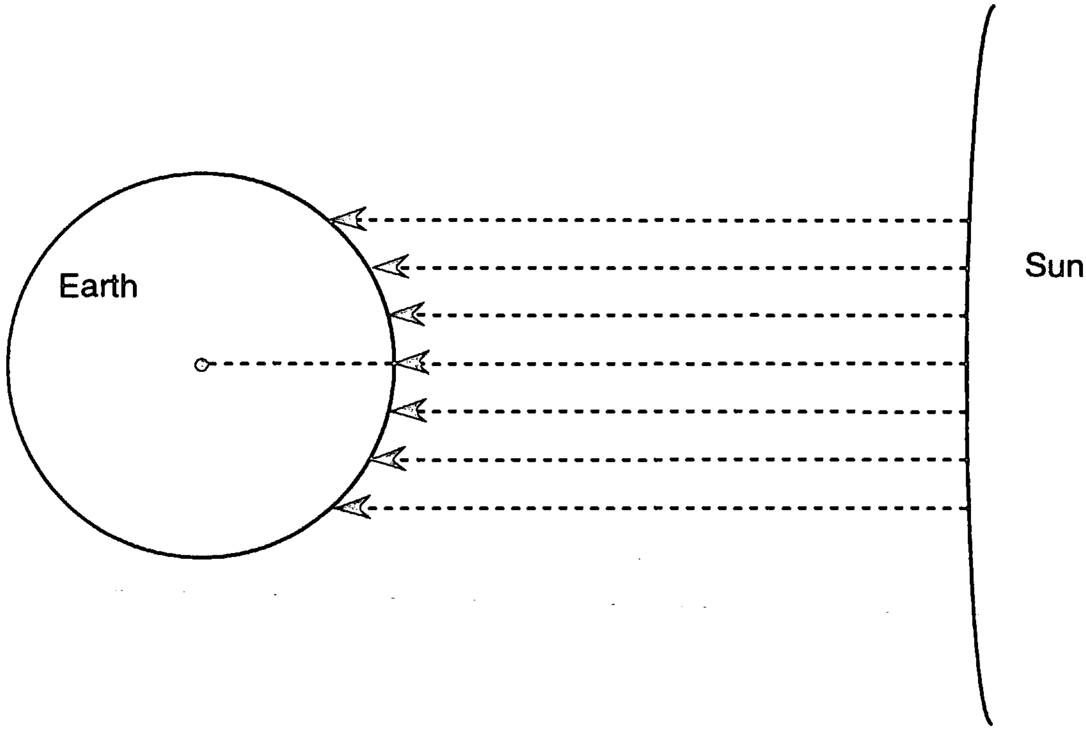
   a) How would your friend know that the Sun was directly overhead?

   b) How would you know that the Sun was not directly overhead where you live?

   c) How could you use the observations by you and your friend to estimate the change in latitude between your homes?

This is a hard problem . . . it's the key to Eratosthenes' discovery. However, if you think about your flashlight Sun shining on a globe and make some sketches of the situation, you might be able to guess (if not prove) the answer. A good guess about the truth is usually the essential first step in finding a logical argument.

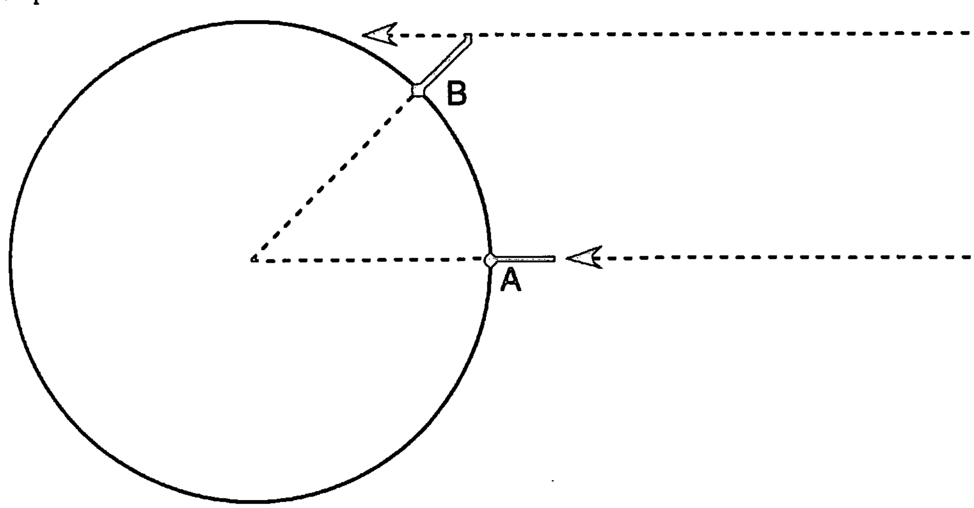
3. One observation that might help your reasoning is the fact that, because the Sun is so large and so far from Earth, its light comes in a beam that can be thought of as parallel light rays.



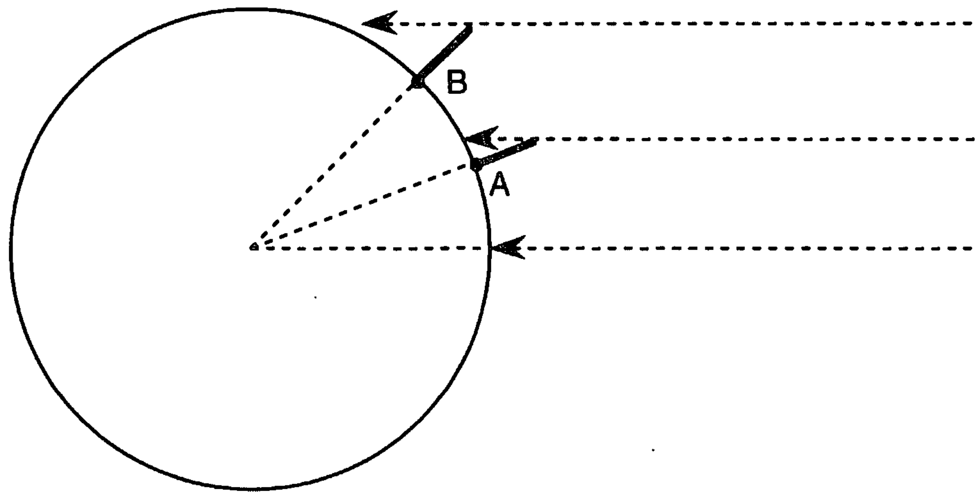
How, if at all, does this assumption change your thinking about using Sun rays to measure change in latitude between two spots on the Earth?

4. The following sketch shows a side view of the Earth with Sun rays falling at two places, one directly north of the other. The Sun is directly overhead at point A, but not directly overhead at point B. Suppose that it is you standing outside in the Sun at point B and your friend at point A.

   a) Do you see anything in the sketch that you could measure to find the change in latitude from point A to point B?



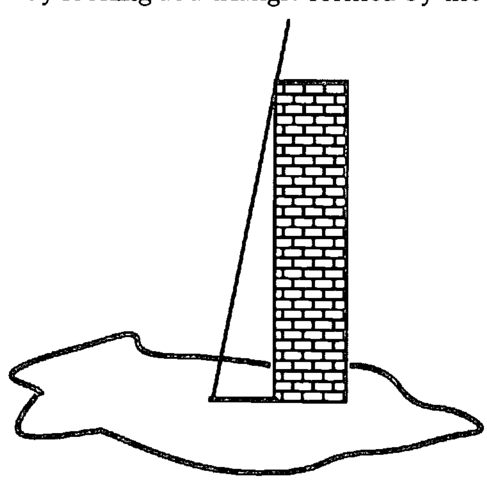
b) The next sketch shows two points, neither of which lies directly under the Sun's rays. Is it still possible to find the change in latitude from point A to point B by suitable clever measurement in this case?



5. Eratosthenes did not receive a phone call! However, he knew some facts that allowed him to reason with much the same information that your phone call from a friend could provide.

   a) Locate the cities of Alexandria and Aswan in Egypt on a map or globe. In 240 BC. the city of Syene was located at the site of present-day Aswan. Residents of Syene noticed that on June 21 of every year at about mid-day the Sun's rays were reflected from the bottom of a deep well. What does that tell you about the latitude of Syene?

   b) On June 21 at mid-day in Alexandria, Eratosthenes measured the angle between the Sun's rays and "straight up" by looking at a triangle formed by the Sun's shadow on a tall building.



He found the angle to be about $7\frac{1}{5}°$. What does that tell you about the latitude of Alexandria, in relation to Syene?

c) Eratosthenes then learned that the distance on land from Alexandria to Syene was a 50-day camel trip and that a camel could cover about 10 miles (in modern units) per day. What does this information imply about the distance from Alexandria to Syene and the distance around the Earth?

6. Now turn to the even older question of determining the shape of the Earth. How could people have become convinced that it is a ball and not a flat disk?

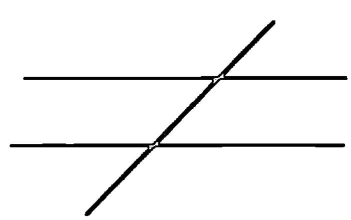
   a) What happens in a lunar or solar eclipse and how would the images seen in such an event suggest that the Earth, Moon, and Sun are round?

   b) Perhaps you are not a stargazer . . . or maybe you are. People spent more time outdoors two thousand years ago. They were fascinated by star patterns. Using your twentieth century knowledge, what might observant stargazers have noticed as they traveled? How would those observations suggest something about the shape of the Earth?

   c) Imagine a ship with a tall mast sailing directly outward from land over a relatively calm sea. If you watch for a long time from sea level, what would you notice? How would this observation suggest a round Earth to people living thousands of years ago?

Conclusions and Connections—The questions of this investigation have been designed to help you follow the course of discovery that led to good estimates of the shape and size of our Earth. Test your grasp of the main ideas by answering these questions:

1. The latitude and longitude of Washington, DC are about 39°N and 77°W; the location of Nassau in the Bahamas is about 25°N and 77°W. How far apart (in miles) are the two cities?
2. Chicago, Illinois is located at about 42°N and 87°W while Managua, Nicaragua is at about 12°N and 87°W. How far apart (in miles) are those two cities?
3. The city of Madison, Wisconsin is located at about 89° west longitude and New Orleans, Louisiana at about 90° west longitude. How could you get friends in those two cities to collaborate with you to make the measurements needed in Eratosthenes' method of estimating the circumference of the Earth, using the fact that it is about 1000 miles on land from Madison to New Orleans?
4. Without access to a modern clock or telephones to communicate, how could observers at Syene and Alexandria know that their Sun shadow observations were occurring at the same time on the same day?
5. Without knowledge of the magnetic compass, how could people have known about directions of North, South, East, and West?
6. On the following sketch of parallel lines cut by a transversal, what pairs of angles are congruent and how do those facts play a critical role in Eratosthenes' method for estimating the circumference of the Earth?



Where in the World is Christopher Columbus (Going)?

In some sense this investigation is the frosting on the cake. It asks students to put together everything that they've learned—latitude/longitude, Sun shadows, estimation of Earth circumference—to reconsider one of the oldest and most common historical/geographic/scientific misconceptions. We have most often used this investigation (at least part 1) as a performance assessment project that students do outside of class. While we don't discourage students from consulting each other, we generally ask for individual written reports. Even when there has been collaboration on the problem, the written reports reveal a lot about points in the unit that remain unclear for individual students. At the same time, those reports offer an opportunity for individual style in expressing ideas. Many students really get into the spirit of writing a report to Ferdinand and Isabella and embellish their scientific ideas with stylistic creativity that demonstrates real engagement with the problem.

Student Text

WHERE IN THE WORLD IS CHRISTOPHER COLUMBUS (GOING)?

A lot happened between 240 B. C. and 1492 A. D. During the Renaissance, the various nations of western Europe, particularly Portugal, Spain, France, and (the city states of) Italy, found trading with China and India desirable. However, between those European nations and their prospective Asian trading partners lay several other countries inclined to block the trade. So, since the Earth is round, why not go west instead of east to reach the same spot?

Of course, there were other possibilities. Working out a friendly and mutually beneficial relationship with the other countries did not seem to be considered. Perhaps it would be possible to sail around the southern tip of Africa and then up through the Indian Ocean. At the beginning of the fifteenth century Europeans were not sure that there was a southern tip of Africa. (If this sounds silly, remember that explorers were later to spend much effort trying to find a Northern Passage over the top of North America. It was perfectly reasonable to think that Africa might extend into the southern polar regions.) But the tip was reached in 1488, and then Vasco de Gama successfully reached India by that route in 1498. Thus it was de Gama who succeeded in doing what was actually intended. Nonetheless, Columbus, in error about the size of the Earth and believing that he was off the coast of Asia when he was really in the Caribbean, changed history. Such is often the way of major discovery and change.

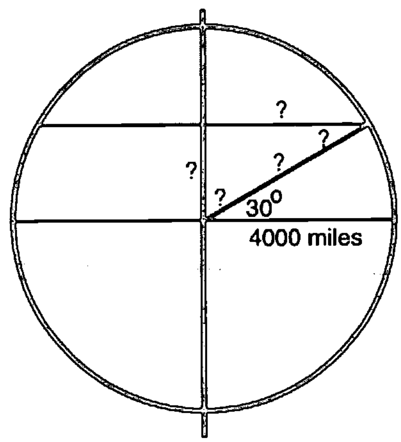
Accounts vary as to exactly how Eratosthenes' excellent estimate of the size of the Earth got reduced to 18,000 miles by Columbus. Columbus also planned to start in the Canary Islands to sail due west at the latitude of about 30°—making the projected trip considerably shorter than it would have been at the Equator. Further, he thought that the eastward distance to the coast of China was longer than it actually was, and this led him to a corresponding reduction in the westward distance estimate. At any rate, Columbus had it figured that Japan was about 2700 miles west of the Canary Islands. Even if, as many Europeans believed, Japan was a fictional place made up by Marco Polo, it wouldn't be much farther to China.

Columbus' proposed trip was controversial. He had been turned down by Portugal, France, and England when he turned to Ferdinand and Isabella in Spain. The royal advisors in Spain were opposed to the trip. Remember, the issue was whether this was a practical way to get to China and India, not whether it was a way to explore a whole new continent.

Advise the King and Queen

Imagine that you are a Royal Advisor to Their Majesties Queen Isabella and King Ferdinand of Spain. The Queen calls you in one day and requests that you design an experiment to discover the true size of the Earth.

1. How could you reproduce the experiment of Eratosthenes without leaving Spain? Use whatever current globe or atlas information you need and write up a careful explanation of your method and conclusions.
2. Use your result from (1) and further reasoning to figure the distance around the Earth at a latitude of 30°. The following sketch might be a helpful guide in calculating the circumference of that circle of latitude.



Again, write up a careful explanation of your method and results.

What Do You Know?

As mentioned above, the previous investigation is often used as a performance assessment for the unit. But we have also included questions about the unit on more conventional quizzes and examinations. A few typical questions follow.

Student Text

WHAT DO YOU KNOW?

1. Latitude, Longitude, and Distance on the Earth

   The cities of New Orleans, Memphis, and St. Louis are all located very close to the 90° west line of longitude.

   a) New Orleans is at 30° north latitude and Memphis is at 35° north latitude. What does that imply about the distance in miles from New Orleans to Memphis?

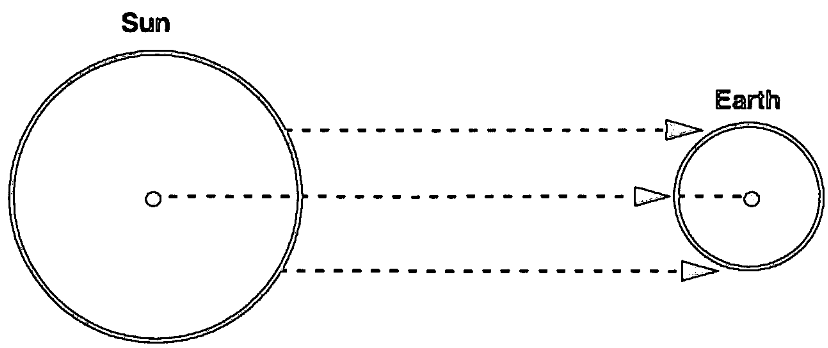
b) St. Louis is 250 miles north of Memphis. What does that imply about the latitude of St. Louis?

c) At noon on June 21 two friends observed their shadows cast by the Sun, in Memphis and New Orleans respectively. If the friends were the same height, what difference would be noted in their shadows?

2. Angles, Circles, Sunlight, and Seasons

Imagine that you are looking at a side view of the Sun and Earth with your eye directed along the orbital plane.

a) Make two sketches like this. On one draw in the Earth's axis as you would see it from such a side view on June 21. On the other draw in the Earth's axis as you would see it on December 21.



b) Explain how the sketches show that parts of the northern hemisphere have 24 hours of sunlight at the summer solstice and 24 hours of darkness at the winter solstice.

c) What are the latitudes of the Equator, the Tropic of Cancer, the Arctic Circle, and the North Pole?

d) How are those special latitudes related to each other and to the inclination of the Earth's axis of rotation?

At the center of our campus is a very special kind of sundial that shows, in addition to time of day, the shadow length expected in each month of the solar year. We have used this extended sundial as the basis of another major performance assessment project in the course final exam.

We usually initiate the project with a class visit to the sundial for orientation to the problem and some initial measurements of shadow lengths and angles. Despite the fact that the problem posed is really a straightforward application of the method of Eratosthenes, we've found that recognition of this fact and the ability to visualize the mathematical model embodied in the sundial is a genuine challenge to the students.

Student Text (continued)

3. As you know, lines, angles, circles, and spheres can be used to construct geometric models of the solar system, including detailed positioning systems on our own planet Earth. Using these models, you can develop scientific explanations of fundamental phenomena like days and nights or seasons and years, and to estimate distances on and around our Earth.

   At the center of our campus mall is a large sundial with an arm extending northward on which markings are labeled with dates in each month of the year. Apply what you know about Sun shadows and latitude and distance to develop answers to the following questions:

   a) How can you use the sundial arm and the date marks for the summer or winter solstice to estimate the latitude of the campus, given these facts: Tropic of Cancer is 23.5° north latitude, Equator is 0° latitude, Tropic of Capricorn is 23.5° south latitude.

   b) Suppose that another sundial was located exactly 700 miles south of our campus with similar appropriate markings for shadow lengths at various times of the year. How could you use measurements from the two sundials to estimate the circumference of the Earth?

Write up your conclusions in explanations that could be understood by someone with knowledge of high school geometry. Use sketches as needed to help clarify the ideas.

Summary and Concluding Comments

The "Where Are We" unit has been well received by varied groups of students—with some local modifications by individual instructors. Students are genuinely interested to understand some facts of life on Earth that they had only vaguely comprehended before. They do seem to gain insight into both the history of science and scientific methods as well as the interplay of science and mathematical modeling.

When we have the patience to let students really grapple with open questions in the unit (instead of succumbing to the urge to "cover" more material) we find spirited discussions break out frequently. Students who've never thought of themselves as mathematically capable are excited to figure things out and really understand some big ideas. One student expressed the feelings shared by many students when she summarized her learning experience in this unit:

> *I was just thinking today about the way I've been learning in class. I think that it is working well the way we need to figure things out by thinking about them. It is also cool the way the questions in a section lead up to more difficult things as they go along. I might not know anything about the subject we are talking about, but with thinking about the questions and bouncing ideas off other people in the group, I learn. I like this way of learning by figuring out things for myself rather than just being told the answer. It does get frustrating at times when the answer does not come quickly, but I don't think that I will forget it as easily. I've been learning a lot about models and how to use them as a tool. As with many people in the class, I did not see how math*

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really entered into anything when we first started the class, but now I do.

Of course, not all students retain (or even gain) complete and confident grasp of the mathematical and scientific ideas involved in the problems of the unit. In fact, most faculty teaching the unit find themselves questioning prior inadequate or incomplete understandings themselves! This can be a disquieting experience for faculty accustomed to mastery of the material they teach, but if one becomes comfortable with a genuine response of "That's an intriguing question; I'll have to think about it myself," there are many days on which deep student questions add an exhilarating spontaneity to class sessions.

A CONSTRUCTIVIST APPROACH TO PLATE TECTONICS

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I have twice taught the course "Physical Science II" for the MCTP program at Towson University. The first year I team-taught with Joe Topping, a chemist, and the syllabus reflected a blend of geological and chemical topics. The second year I taught it solo and revised the curriculum to include about two-thirds earth science and one-third topics from physical optics (my most recent syllabus is attached as Appendix A). My choice of subjects within each field was guided by both the *AAAS Benchmarks* (AAAS, 1993) and the *National Science Education Standards* (NRC, 1996), as well as those topics which lend themselves particularly well to a "constructivist" pedagogy. In truth this selection represents my favorite topics in the courses in physical geology and the physics of light and color that I have taught in an increasingly constructivist manner at TU for several years.

Most of the activities I used in Physical Science II have been somewhat modified from what I do in my other courses, where the earth science content is more in-depth. In the following text I present a sample of one such activity. After presenting this "module," I close this chapter with some personal observations of my MCTP experience and some excerpts from the students' final journal entries, in which they reflect on their learning experiences throughout the course.

Primary Goal: Student Discovery

This unit focuses on the essential principles of plate tectonics, the most significant unifying theory of modern geology. The primary goal of the unit is to provide students with an opportunity to discover and construct for themselves the rudimentary elements of plate tectonics movements that have created the earth's present-day surface. This approach essentially reverses the traditional method of presenting this material, in which students are told what major movements have occurred over the last 200 million years since the break-up of the great landmass of Pangaea, and are then shown specific examples that illustrate the relative motions.

Given the opportunity to observe resources such as detailed maps (especially the Heezen and Tharp ocean floor map) and globes (such as the National Geographic Physical Globe), my students have been able to formulate some of the fundamental relationships between geologic features, such as mid-ocean ridges and coastal mountain belts, and the processes that form them. They have also been able to calculate general movement rates and to gain an appreciation for the enormity of time required for such large-scale movements.

Creating opportunities for discovery for my students required that I choose from among a number of physiographic areas that show evidence of plate movements. For example, the relatively straightforward illustration I chose for a central activity in this unit is the symmetric seafloor spreading of the mid-Atlantic ridge, which has been occurring since the opening of the north Atlantic Ocean approximately 100 million years ago. Dated rock core samples from specific locations in the Atlantic seafloor enable students to measure spatial distance of the cores from the ridge axis, where basaltic rock material is presently forming. Dividing this distance by the time elapsed since the rocks' formation (i.e., the age) generates the rate of movement of that segment of oceanic plate from the ridge. Since the other side of the plate is also moving away from the ridge, the total movement rate is twice this value. Such data are readily available from numerous locations across ridges on the seafloor (Brice, Levin, & Smith, p. 52–53).

Although my students often struggled during these activities, their journal entries have shown recognition that, as one student wrote, " . . . the beauty is that when you figure it out with some effort, you understand it better." Moreover, students who plan to become teachers have drawn conclusions such as, "When I see my kids frustrated, I will guide them to discovering the answer because it is more rewarding to solve a problem than to have the material dictated."

. . . as one student wrote, " . . . the beauty is that when you figure it out with some effort, you understand it better."

Overall, the plate tectonics unit was designed to engage students in the following:

- observing the distribution and geometric relationships of major physiographic features of the earth's surface;
- applying previous knowledge of basic geography to the development of broader themes;
- manipulating scale, involving measurement of both enormous spatial dimensions as well as inexorably slow rates of motion; activities include:
    - constructing a scaled representation of the 4.6 billion years of geologic time (plotting specific events on this scale requires real comprehension rather than memorization of the use of exponents);
    - determining movement rates and conversion of these quotients to meaningful expressions, generally on the order of centimeters per year;
    - utilizing measuring skills, as students express the distances between locations where rock samples have been dated; and
- performing authentic assessments of knowledge through meaningful analysis of new data sets and comparison with their previous results.

In designing the unit with these goals, it became essential for me to integrate instruction in mathematics. The students' facility with exponents was addressed in several guises: labeling of a time scale with billion- and million-year divisions, converting rates for kilometers per million years to centimeters per year, and construction of the Richter scale.

Context for the Plate Tectonics Unit

This unit is designed to follow several student-centered investigations wherein they discover the essential characteristics of minerals and rocks from their own observations, and ascertain that the earth's surface is divided into continents and ocean basins. One of these preliminary activities involves the determination of densities of materials from the continental crust, oceanic crust, and mantle. A hypothesis students may develop to explain the density relationships between these materials is that the earth may be layered, and the lighter layers "float" on the heavier layers. Class discussion of this may lead students to speculate about the earth's core, which would be comprised of the heaviest material. Since of course we do not have samples of this, a small polished piece of a iron meteorite, presumably from the core of an ancient planetary body, usually amazes students at this point.

Students then develop hypotheses for heat transfer from the molten outer core outward through the mantle, the process that drives large-scale plate tectonic movements of earth's plates. From this point, using the unit described in this paper, students investigate fundamental processes and plate movement directions and rates, eventually verifying their hypotheses and uncovering for themselves evidence for the enormity of geologic time. Students then begin to explore aspects of seismic waves as a transition to the physical optics section of the course.

Pedagogical Considerations

In developing and teaching this unit with a constructivist approach, I took the following key factors into consideration:

Engagement. To spark students' interest and start them thinking about physical changes on a large spatial scale, I presented them with cutouts of some of the major continents, especially Africa and South America, and allowed them time to explore. (Photographic slides of satellite views of parts of the earth can also illustrate this.) After some minutes of manipulation, the students "discovered" that some of the coastlines fit together.

Prior Knowledge. On the first day of this unit, I had the students fill out an anonymous questionnaire where they can record their preconceptions about the earth's surface and interior (see Appendix B). I have found that most students have sufficient geographic knowledge to identify the landmasses, and have heard of "continental drift," which is the antiquated forerunner of modern plate tectonic theory. Our class discussions elicited connections between tectonic movement and geologic processes like earthquakes and volcanoes. A likely area of frustration involves students' manipulation of exponents, required both in the constructions of the geologic time scale and in the expression of tectonic movement rates.

Monitoring Beliefs. By encouraging continual class discussion and questioning, I have found that students have ample opportunity to express skepticism and sometimes awe at the magnitude of the physical changes recorded on the earth's surface. I have also found that letting students "discover" plate tectonics gradually in this manner, rather than first lecturing on it as a "fact," allows those students with more fundamentalist religious backgrounds to appreciate and understand this geological theory with more open minds.

Concept Development. I encourage students to develop multiple working hypotheses as they wonder about the origin and nature of the various features they encounter in examining a detailed physiographic map of earth's surface, both continental and ocean floor (Dolgoff, 1996, p. 256–257). I created a "travelogue" (Appendix C) to guide their observations as they cruised along mid-ocean ridges from Iceland all the way around to the San Andreas fault in California. Photographic illustrations of features such as volcanic island arcs can supplement student investigations of these landforms.

Making Connections. This unit gives students the opportunity to recognize that a geographic pattern of "disasters" can be seen as they connect localities they have heard of in the news with their geologic positions relative to active plate boundaries. To facilitate their making these connections, we explore several Internet sites, such as the U.S. Geologic Survey's Earthquake Information page, to let the students "wander and wonder" through the Web's geological resources.

Group Dynamics. Collaborative learning was employed throughout the course, from group laboratory activities to group work on parts of the performance assessments in the course examinations. Groups were rearranged throughout the semester to give these future teachers exposure to a variety of learning styles and changing group dynamics.

Student Reactions. Expressions of bewilderment, frustration and confusion are fairly common in the beginning of this unit, and students are encouraged to share and to listen to these, as they only validate the enormity of the scale of the processes that the students are in the process of discovering.

Materials

The various maps used in this unit may be found in earth science supply catalogs (like Natural Science, Ward's annual catalog) and laboratory manuals in either physical or historical geology. Materials for the earthquake seismogram activity can also be from published case studies. The geologic dates of major events for the time scale construction can also be found in lab manuals. Other basic materials include rulers and calculators.

The most significant change I made when I taught this course for the second time, other than topic choices, was to incorporate a few CD-ROMs (such as The Theory of Plate Tectonics [Tarbuck, 1994]) for geophysical databases and interactive plate tectonic reconstructions. Several Internet sources were also used, such as sites for seafloor rock ages and current earthquake and volcano data.

Unit Chronology and Reflection

The first semester this course was taught, the unit on plate tectonic movements and reconstructions lasted for three class days (each class meeting time was 2½ hours). My team-instructor and I realized then that a fourth day would have provided more opportunity for students to practice their calculation skills and extend their comprehension. During the second semester, I added two days to the unit, and introduced earthquake data, determination of epicenter locations, and seismic wave behavior, which made the transition to the next unit on light waves and physical optics.

Day 1

As an introduction to the concept of plate tectonics, students examined continental shapes and their positions on a large physiographic map of earth's surface. Using the travelogue mentioned earlier, they took a "guided tour" with question prompts that followed mid-ocean ridges from Iceland around to Central America and up into the San Andreas fault of California. Observations of physiographic features such as volcanic islands were correlated with geologic activities that they knew about (earthquakes, volcanoes). During a class discussion, we connected a previously assigned reading (from Trefil & Hazen, 1995) with these discoveries, although prior readings are not necessary nor probably even desirable. A follow-up "homework" activity was to reassemble Pangaea as accurately as possible using cutout continents; problems encountered in the reconstructions were to be discussed in the next class.

Day 2

The class began with the film *Powers of Ten* (Demetrios, 1989). Students then constructed a geologic time scale using 15-meter lengths of register tape and a meterstick, with 1 meter being equal to 1 billion years. Students were to label the eras (Precambrian, etc.) and "discover" a conversion that would enable them to plot important dates onto the tape such as the extinction of dinosaurs 67 million years ago (lab manuals containing this information include Fletcher and Wiswall, 1990,p. 91–92). Students struggled a bit as they all discovered that they did not understand exponents as well as they thought they did. (This became a recurring mathematical theme in the course.) Student discussion and journal entries indicated that this was an eye-opening and thought-provoking experience.

Day 3

Students continued discussion of plate movements by manipulating a three-dimensional globe and examining "flip books" (Scotese, 1977) showing the plate positions for the last 700 million years. This led to the idea that plate movements can be quantified from age determinations in seafloor core samples as a function of distance from a mid-ocean ridge. Students' activities involved carefully measuring map distances of dated cores and calculating the spreading rate, being eventually guided into doubling the values because of the symmetry of the ridge. Expressing these rates in centimeters per year proved challenging, and we spent time manipulating exponents once again. Students were astonished to discover from their own calculations that the Atlantic is opening at the rate of several centimeters per year. They were then asked to convert this to something that they could visualize, such as rate of fingernail growth. This was undoubtedly much more meaningful than if they were told the plate movement rates as a given fact.

Day 4

Since the most dramatic evidence of plate movements is earthquakes, we discussed the basics of earthquakes, which diverted into an illustrated mini-lecture format to explain basic seismology terminology—epicenter, focus, magnitude, P-and S-waves. Longitudinal and transverse wave motions were illustrated with springs. Frequency, velocity, amplitude and energy were also explored and discussed.

Day 5

An earthquake epicenter location exercise involved measuring P-and S-waves arrival times from a seismogram, converting to distance, and plotting intersecting arcs on a map to pinpoint location. Various Web sites can be visited to examine some aspects of the occurrence of and parameters associated with earthquakes. Earthquakes provide a transition into the later study of waves.

Assessment

Several methods for assessment of student comprehension were utilized, including the weekly journals. The midterm exam contained two authentic assessment activities of student understanding of the features and measurement of plate tectonic movement. The first involved a physiographic map of the South Sandwich Islands; students interpreted this area's plate tectonic setting from the trench-island arc features, and then predicted what type of geological materials would be encountered there (the exam must follow igneous rock section). The second assessment problem included several maps of the Hawaiian Islands taken from a variety of sources. Each map displayed radiometric ages of basaltic rock from several islands, which have been moving over a stationary "hot spot" in the mantle for the last 100 million years. From the pattern of rock ages, which get progressively older to the northwest along the chain, students accurately concluded that plate movement over the hot spot produced this string of islands and submerged seamounts across the Pacific floor toward the Aleutian trench. They then measured the distances between rock localities and calculated the movement rate; expressing this in centimeters per year always proved to be a challenging test of their facility with exponents. Students then compared these with rates determined for the Atlantic, discussed the variations, and explained their significance (i.e., the Pacific rates are much faster). This process also required them to evaluate which of the published maps were most useful for this exercise, and to explain why.

Instructor's Reflections on the MCTP Experience

During the first semester, instructors as well as students kept journals of their thoughts and observations throughout the course and many of these were included in the previous description of the unit activities. I have since this time also followed a more constructivist approach in my "regular" physical geology course, and have noted similar student surprise and satisfaction when they "discover" for themselves evidence for plate movement and those processes that create mountains. However, I find it is generally difficult for many introductory students to realistically grasp and internalize either complex sequences of geologic events or time periods of more than a million years.

> *I have since this time also followed a more constructivist approach in my "regular" physical geology course, and have noted similar student surprise and satisfaction when they "discover" for themselves evidence for plate movement and those processes that create mountains.*

I have gradually become less devoted to "covering" a certain amount of content in my introductory geology courses, but rather to using a selection of thorough, student-centered investigations of key concepts and processes. It is still difficult for me, however, to whittle down the "core" of the physical geology course any further to include more constructivist units.

Students' Reflections

After my sense of initial frustration, I began to desire to understand. . . .

The students' experiences in this course were generally good, although frustration levels and grade anxiety were higher than usual throughout the course. Weekly journal entries were one way I tried to assuage their fears and provide them with encouragement through responses to their journal questions and suggestions for further explorations. I found that some students remained shy about asking questions in class, although their intellectual involvement in the course material and learning process was evident in their journal entries. I also came to prefer written journals to electronic ones because I felt I could gauge students' anxiety levels from their writing; they could also make sketches of geologic features they'd seen and wanted to ask about. I have continued these "learning journals" in all of my introductory courses because, despite the time involved, I get invaluable feedback and can keep some students focused on improving their performance rather than losing them in frustration during the semester.

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For this semester described in this report, the final journal entry was a reflection on the entire course and an assessment of their own efforts and participation. Students were to read through their entire journals prior to this exercise. I have excerpted below some of their most revealing comments, both positive and negative, and I think they tell us more about the success of the MCTP program than anything I could write.

Reflections on ways of learning:

I just finished reading all my journal entries from the past classes and I noticed a very strong trend: at the beginning of units I sounded baffled and unsure of myself and the material, by the mid-to-end of units it sounded like I was actually getting the hang of what we were doing during the class. . . .

∞∞∞

When it comes to testing, if you have learned the material rather than just memorized it, you can usually apply it to any situation.

∞∞∞

In the beginning, with the classification of minerals, I wanted to start the lab by measuring and calculating rather than just looking at what was there. But, by the end, I was able to just look at something and think about what it meant.

∞∞∞

After the first exam, I began to focus on understanding concepts instead of memorizing.

∞∞∞

These journals have been very helpful to me as well. I was able to write down questions, concerns, and new learning. After having read through my journal again, it is evident that I got better at figuring out the tough concepts within my group and on my own. I also got better at asking questions. Before this class I was embarrassed to ask questions. This has been tough yet rewarding.

∞∞∞

I learned much more from demonstrations than anything else. The hands-on approach makes me remember more for longer.

∞∞∞

It was a good idea having us figure out about plate movement instead of telling us. It really made me think about it and put different ideas together.

On group work:

Group work was very helpful for me. I have always learned best through discussion with my peers. However, I feel that we should have deserved more credit for our group assignments.

∞∞∞

I feel that group work really enhances one's sense of knowing. Working with peers allows you to actually discuss the concepts out loud and also allows you to help each other when one member of the group stumbles upon a problem they cannot solve by themselves.

On how tough the course was for some students:

[This course] was a challenge and frustrating and at times downright confusing. . . . I have learned quite a bit about physical science (although a different pedagogy would have made a less stressful learning experience). It's like the course was harder than it needed to be.

∞∞∞

I found myself taking great interest in the material for a couple of reasons: 1) the actual topics blew my mind, i.e., plate tectonics, and I wanted to know more about it for personal reasons; and 2) this was really the first time (in a science course) I had trouble grasping a concept upon initial introduction.

On the course's value for future teachers:

There are a lot of things that I have learned from this course that I can use in my own classroom. I learned that science can be fun! This is essential for children to realize, it sparks their interest. We did a lot of neat things with rocks, prisms, and rainbows, all of which kids in general like to learn about.

∞∞∞

This course not only taught me about physical science, but it taught me how I learn. . . . By understanding the process of learning, I feel I can be a much more effective teacher.

∞∞∞

I think the method of doing an experiment, without a lot of instruction, seeing what children gain from the experiment by discussing it, and then building and refining their experiment by discussing it, is a wonderful way to teach.

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This course successfully taught me physical science, but it also has impacted the way I learn and the style of teaching that I will use in my classroom.

∞∞∞

Another outstanding attribute I am taking from this course comes directly from your teaching: I will not give the students the answers. I will stick beside them and aid them in coming upon the answer for themselves.

∞∞∞

Before taking this course, the only way I could identify a rock or mineral was because I had seen it before and remembered what it looked like. Now I can look at a rock I've never seen before and find identifying characteristics in it. To me, it's so neat to be able to do that. And if I'm excited about it, and find it fun, when I get into a classroom, I can pass that excitement onto my students.

And my personal favorite:

It's like the old saying: You can catch someone a fish and they can eat for a day. But if you teach them how to fish you can feed them for a lifetime. Throughout this course I have learned how to fish.

Notes and References

The laboratory manuals listed below are widely used in introductory college geology courses; other texts would be appropriate as well. One of the best maps is the classic Heezen and Tharp 1977 Ocean Floor Map; large laminated versions of this map are available from Ward's, or smaller versions may be found in lab manuals like Fletcher and Wiswall (p. 256–257). Recently Web sites have become a good source of plate

tectonics information and other earth science subjects; addresses may be found in the newest geology texts like Press and Siever.

American Association for the Advancement of Science. (1993). *Project 2061, Benchmarks for Science Literacy.* New York: Oxford University Press.

Brice, J.C., Levin, H.L., & Smith, M.S. (1993). *Laboratory Studies in Earth History* (5th ed.). Dubuque, IA: Wm. C. Brown.

Demetrios, L.E. (Exec. Producer). (1989). The Films of Charles & Ray Eames—Volume 1—Powers of Ten [Film]. Santa Monica, CA: Pyramid Film & Video.

Dolgoff, A. (1996). *Physical Geology.* Washington, DC: D.C. Heath and Co.

Fletcher, C.H., & Wiswall, C.G. (1990) *Investigating the Earth: A Geology Laboratory Text.* Dubuque, IA: Wm. C. Brown.

Heezen, B.C., & Tharp, M. (1997) *World Ocean Floor [Scale 1:23,230,000].* Palisades, NY: Lamont Doherty Geologic Observatory.

National Research Council. (1996). *National Science Education Standards.* Washington, DC: National Academy Press.

Natural Science (Annual Catalog). (Available from Ward's Natural Science Est., Inc., 5100 W. Henrietta Rd., P.O. Box 92912, Rochester, NY 14692).

Press, F., & Siever, R. (1997). *Understanding Earth* (2nd ed.). New York: W.H. Freeman & Co.

Scotese, C.R (1977). *Phanerozoic Plate Tectonic Reconstructions: Paleoceanographic Mapping project* (Tech. Rep. No. 90). Austin: University of Texas, Institute for Physics. [Current availability unknown.]

Tarbuck, E.J. (1994). The Theory of Plate Tectonics [CD-ROM]. Albuquerque, NM: Tasa Graphic Arts, Inc.

Trefil, J. & Hazen, R.M. (1995). *The Sciences: An Integrated Approach.* New York: Wiley and Sons.

Appendix A

COURSE SYLLABUS
PHYSICAL SCIENCE II—PHSC103

Course Schedule

Date	Topic/Activity	Text
1/30	Introduction; Questionnaires; Observation of physical objects	
2/4	Description, measurement and classification of physical objects	2
2/6	Introduction to floating versus sinking	
2/11	Determining density: assessment activity	4, 5
2/13	Continued buoyancy, specific gravity measurements	
2/17	Physical properties of minerals: hardness, cleavage, etc.; Solid geometry of crystals, investigation of symmetry elements	28
2/19	Solids: dissolution; crystallization from solution (cont'd at home)	
2/25	Crystallization from a melt: inference of cooling rate from grain size	
2/27	Exam 1	
3/4	Igneous rocks: interpretation of textures, classification	
3/6	The Rock Cycle: weathering, transportation, deposition, lithification, etc.	
3/11	Soil: physical and chemical characteristics	
3/13	Earth's differentiated structure; Introduction to Plate Tectonics	27
3/18	Films: "Powers of Ten"; Geologic time scale; Tectonic plate movements	31
3/20	Measurement of plate movements	
4/1	Earthquake waves: epicenter location	
4/3	Waves and wave behavior; Interference	
4/8	The electromagnetic spectrum	16
4/10	Exam 2	
4/15	Color mixing: additive and subtractive	
4/17	Theatrical lighting: trip to Fine Arts	
4/22	Young's double slit demonstration: diffraction of blue versus red light	15
4/24	Atoms: emission spectra, identification of gases, solar spectroscopy	
4/29	Refractive index of solids and liquids	
5/1	Dispersion and the white light spectrum	
5/6	Rainbows, halos, and coronas	
5/8	Scattering; Why the sky is blue	
5/13	Mirages; Course evaluations	

General Course Information

Meeting Times and Teaching Methodology

Class meets in Smith Hall 473 on Tuesdays and Thursdays from 12:30 to 2:45 p.m. The sessions will generally be laboratory-type activities with little formal "lecture." The pedagogical approach in this course employs a series of student-centered collaborative exercises that hopefully lead to students' discovery of and construction of fundamental concepts. We will be integrating fundamental topics from the fields of earth science and physics, along with some chemistry and mathematics.

This course has been developed as part of a state-wide program called the Maryland Collaborative for Teacher Preparation (MCTP) that is funded by the National Science Foundation. Although the ultimate goal of the MCTP program is to prepare pre-service teaching specialists in science and math for middle grades, we strongly believe that other students will benefit from such a course that strives to integrate science topics in an innovative way. The essential prerequisite is Physical Science I, along with enough mathematics to handle the calculations and data manipulations we will be doing. This is a "content" course, rather than a "methods" course; the pedagogy will employ aspects of "constructivism" similar to what you might be using as in-service teachers. The content is appropriate to university students, although most of the topics are also designated for middle grades in both AAAS Benchmarks (AAAS, 1993) and the National Science Education Standards (NRC, 1996).

Text

The Sciences: An Integrated Approach: Laboratory Manual
by Robert M. Hazen & James Trefil (1995), Wiley and Sons.

This text will serve as a supplement to the laboratory handouts, and may prove a useful resource in your future profession. Additional readings will be assigned throughout the semester.

Grading

Exercises	approximately	250	points
Journal		100	
Exams		300	
Portfolio		50	
Participation		50	
		750	points

Exercises

The in-class activities and at-home assignments (homework, writing, Internet exercise, etc.) comprise the majority of your learning experiences in this course, and it is vital that you undertake these in a serious manner. Be prepared to turn in each day's exercise at the end of that class period. In-class writing will be done periodically as well. Keep all your course materials together in a portfolio that you will turn back in at the end of the semester, along with additional self-evaluations.

Journal

The journal is intended as a means for you to reflect on your learning experience: what your preconceptions were about a topic, a *very brief* synopsis of what you did in class, what worked for you in that activity, what didn't, what you discovered, what surprised you, what you still are confused or frustrated about. You should make at least one full-page entry for each class meeting. Unless otherwise instructed, the journals will be turned in each Thursday at the end of class. I prefer your entries be made on loose-leaf paper in a manila folder (so you can make an entry even when I have your journal). Please turn in your entire journal each time so that I may refer back to monitor your progress (this is one reason why I prefer written journals to electronic ones).

Examinations

The exams in this course will reflect its goals and methodology, requiring you to develop and display the higher-order thinking skills of application, analysis, synthesis, and evaluation, rather than just recall and comprehension. The exams consist of authentic and/or performance assessments and problem-solving exercises that you will work on alone and/or in a group.

Attendance and Participation

Because of the "hands on" nature of the activities, you (and your hands) must be here each class period. The instructor's schedule this semester rules out your making up a 2+ hour class without a legitimate, documented excuse involving some type of personal emergency. Your physical and mental participation are absolutely essential for this kind of pedagogy to work, as you and your colleagues learn from each other. Good participation includes asking and answering questions in class (reflecting your preparation), undertaking and completing the assigned activities in an engaged and thoughtful manner, cleaning up materials as instructed, and being in general a good classroom citizen.

Portfolio

At the end of the semester, you will assemble all of your course work (including your journals) neatly into a portfolio, which will include some new metacognitive reflections and self-evaluations. These portfolios may be displayed to other faculty participants in the MCTP program, and journal entries may be photocopied (all without your names). They will be returned to you after the semester ends.

Academic Integrity

Group work is of course collaborative by nature, but should not involve copying. You are expected to contribute your own ideas, and will be required to perform individually as well as a team member of your group. Groups will be reassigned periodically throughout the semester. Cheating on classroom activities will result in zero credit to all involved parties. Cheating on an exam will result in failure of the course and will be reported to the Physics Chair and the College Dean.

Appendix B

No name please

PHYSICAL GEOLOGY
PRELIMINARY QUESTIONNAIRE

What are the basic types of rocks and how do you tell them apart?

What exactly causes earthquakes? Why do they occur where they do?

How old is the earth and how do we know this?

What is the largest mountain chain on earth? Why are there mountains?

Appendix C

TRAVEL GUIDE TO THE TECTONIC FEATURES OF THE EARTH'S OCEAN FLOOR

Start at Iceland. What do you hear about geologic hazards in Iceland?

Draw a general sketch of the prominent feature you see running south from Iceland on the floor of the Atlantic Ocean:

Follow this mid-ocean ridge south. Compare the shapes of the coastlines of South America and Africa. How does the ridge relate to these coastlines? What process do you think could create this mid-ocean ridge? Now add arrows to your sketch.

Follow the mid-ocean ridge around the southern tip of Africa and into the Indian Ocean, noting that it branches. Explore the branch that goes under the seas that bound the Arabian Peninsula and northeastern Africa. From what you observe on the seafloors, how do you think these seas originated?

Now go back and follow the mid-ocean ridge across the Indian Ocean and all the way across the Pacific. Trace its end northward, where it becomes the San Andreas Fault. What are some of the geological events you hear about that occur here?

You have just traced an important plate tectonic boundary. Not all volcanoes happen along plate boundaries. Locate the Hawaiian Islands in the Pacific. Note that as you go northwest, the "islands" become submerged. Why do you think they do that?

The only active volcanism within this chain is at the southeastern edge of the "big island" of Hawaii, although all of these islands and seamounts are made of the volcanic rock basalt. What interpretations can you make about the origin of this chain?

This entire continuous chain is called the Hawaiian-Emperor seamount chain. What happens to the orientation of the seamount chain as you go northwest? What might cause this?

Draw the general map pattern of the chain, including arrows to illustrate your interpretations:

Now examine the islands of Japan. What geological activities do you hear about happening in Japan?

Mt. Fiji is a famous volcano in Japan that you've probably seen pictures of. How does its shape differ from the broad shield volcanoes of Hawaii? What does its steeper shape signify about its eruption style?

Note that the Japanese islands form an arcuate shape in contrast to the linear trend of the Hawaiian islands. What deep undersea feature lies adjacent to the islands?

How is it positioned relative to the archipelago of islands, that is, is the trench on the concave or convex side of the island arc?

Draw the general map pattern of Japan and the adjacent undersea trench:

Where else in the western Pacific do you see a similar pattern?

What can you predict about the geological hazards of these areas?

Now compare the eastern and western coasts of North America, particularly offshore. How are they different, and what might be some geological reasons for this?

A MATHEMATICAL MODELING COURSE FOR ELEMENTARY EDUCATION MAJORS: INSTRUCTORS' THOUGHTS

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Introduction to Mathematical Modeling is the first mathematics course in the sequence of MCTP courses taken at Salisbury State University by prospective elementary and middle school teachers of mathematics and science. It is taken concurrently with an interdisciplinary science course. The following case report is based on our experiences in designing and teaching the course and on material in our Instructor's Guide (Cathcart and Horseman, 1995), which is used to introduce other instructors to the MCTP philosophy and to provide a framework for the course. We first taught two sections of this course during the spring semester of 1996.

We designed the course to focus on problem-solving processes used in mathematics and science. It uses perspectives, knowledge, data-gathering skills, and technological tools relevant to those disciplines. Our underlying principle was to integrate mathematics and science using a constructivist, activity-based approach. Specific assignments are described herein, and one is covered in detail.

Students are required to use calculators, spreadsheets, and microcomputer-based laboratories (MBLs) for collecting their own data, generating graphs, and analyzing their results. Working together, students are encouraged to construct physical concepts from their observations and make connections between science and mathematics. At no time are the students permitted to use the technology for a "black box" solution. In other words, they are not permitted to use the curve-fitting capability of graphing calculators or spreadsheets.

Activities in the course focus on helping students to: (a) see connections between mathematics and other disciplines; (b) represent and analyze real-world phenomena using a variety of mathematical representations; (c) develop strategies and techniques for applying mathematics to solve real-world problems; and (d) explain and justify their reasoning, using appropriate mathematical and scientific terminology, in both oral and written expression.

The need to improve the mathematical preparation of pre-service elementary school teachers is well documented in recent reports such as *On the Mathematical Preparation of Elementary School Teachers* (Cipra and Flanders, 1992), and *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989) and *Professional Standards for Teaching Mathematics* (NCTM, 1991) by the National Council of Teachers of Mathematics. The NCTM Standards call for increased emphasis on thinking, reasoning, and problem solving. The NCTM Board of Directors, in a 1995 statement on interdisciplinary learning, stated, "... the curriculum must encourage the use of the perspectives, knowledge, and data-gathering skills of all disciplines. ..." (NCTM, 1995, p. 1).

Currently the mathematics requirement for elementary education majors varies widely from college to college (Cipra and Flanders, 1992). In many cases, prospective teachers take a single, one-year course covering a variety of topics such as number systems, a little number theory, a look at probability and descriptive statistics, and informal geometry. While some colleges require more than a single, two-course sequence, few prospective teachers are placed in situations where they are expected to discover and express relationships found in the world around them. Moreover, few are currently exposed to course content that integrates mathematics and science while placing special emphasis on the concept of a "function as a model" and on "model building" as a process.

In our experience teaching upper-level mathematical modeling courses for mathematics majors, we faced tension between our wish to cover specific mathematical content and our desire to develop the students' ability to solve real problems using mathematics. Our typical approach was to state a problem in some quasi-realistic context, introduce a technique or algorithm for solving the problem, and then require students to employ the technique or algorithm in isomorphic contexts.

. . . as students were involved with activities in this course, they actively engaged in confronting their misconceptions and creating their own knowledge. So, our role was that of facilitator or guide.

That is not the approach employed in this course. We decided to focus on processes used in applying mathematics to address questions in other disciplines. In our experience, we have found that students have difficulty focusing on problem solving as a process when simultaneously trying to understand mathematical techniques and concepts. So, the course described here was not intended to serve as a vehicle for teaching specific mathematics or scientific content. We assumed that pre-or co-requisite mathematical or scientific content had been, or would be, addressed in other courses.

Primary Expected Outcomes

In completing the exercises and activities we expected that students would:

- see and value connections between mathematics and other disciplines;
- represent and analyze real-world phenomena using a variety of representations;
- use their own observations, experimentation, computers or calculators, and references to find answers to questions;
- develop strategies and techniques for applying mathematics to solve real-world problems;
- work with others while solving problems and learning;
- become skillful in explaining and justifying their reasoning, using appropriate mathematical and scientific terminology, in both oral and written expression; and
- critically evaluate their own work and the work of others.

Pedagogical Approach and Course Content

We are convinced of the validity of a constructivist approach for teaching integrated mathematics and science. Therefore, as students were involved with activities in this course, they actively engaged in confronting their misconceptions and creating their own knowledge. So, our role was that of facilitator or guide. We determined the degree to which students met the expected outcomes and altered their preconceptions by examining their written work, listening to their oral explanations, and observing them during working sessions.

Our intent was to integrate mathematics and the sciences. We selected applications from both physical and life sciences. A few applications from sports and management science were included. Some microcomputer-based laboratory (MBL) activities were coordinated with a companion integrated science course taken concurrently with this course.

A sample course syllabus (Appendix A) and two sample exercises are provided (one within the body of this paper and another in Appendix B). The syllabus form is based on that of O'Haver (1994). The guidelines for exercises are adapted from those of Shannon and Curtin (1992), and the portfolio guidelines from Abruscato (1993).

Part I of this course focused on functions as models for phenomena and on the development of a repertoire of techniques to be used in modeling. Functions are used to represent relationships of some particular interest: A change in the value of one variable causes a change in the value of another variable. Students investigated the manner of that change in both qualitative and quantitative ways. Change and rate of change were illustrated and given meaning. Additional mathematical topics addressed in exercises included the following: difference equations, difference tables, difference quotients, recursive functions, secants, least-distances criterion, and least-squares criterion.

The focus of Part II was on the concept of a mathematical model and on mathematical modeling as the essential element in applying mathematics to real problems (e.g., studies of motion, heat loss, and light intensity). The phrase "applications of mathematics" usually means useful connections between mathematics and other fields. Although the application of mathematics in different fields requires a variety of different mathematical techniques, there is a common unifying element in applying mathematics to real-world problems. That unifying element is the concept of a mathematical model. The activity of constructing, analyzing, interpreting, and evaluating mathematical models is the central process in applying mathematics to real problems. Our view of the modeling process is based largely on that of Maki and Thompson (1973), Roberts (1976), and the *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989). This modeling process is illustrated in idealized form below (see Figure 1).

Step 1: Simplification/Idealization. The modeling process usually begins when one is faced with a situation and is concerned about some aspect of that situation. Often the situation is very "fuzzy" and the concern is vague. So, the initial step in modeling is to define the situation or

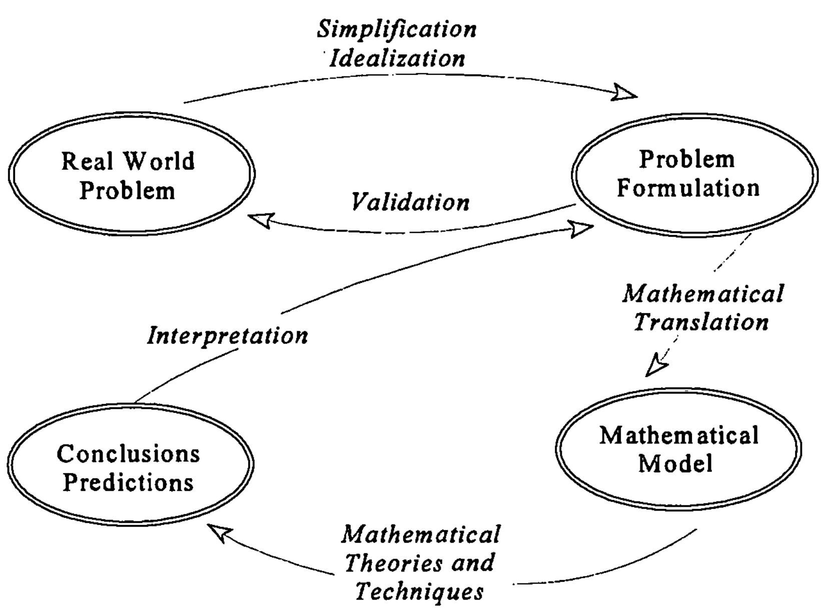

Figure 1. The Modeling Process

problem as carefully as possible. The formulation of a specific problem is important, but often difficult, and sometimes requires creative effort. Attempts at precision frequently involve making idealizations, simplifications, and approximations because most real problems are too complex or nebulous to be treated mathematically in a way that includes all real-world aspects of the problem (Maki, 1975). In this problem formulation step essential variables are isolated and the critical questions identified.

Step 2: Mathematical Translation. The real problem is translated into the language of mathematics. Symbols and mathematical operations are used to represent real quantities and processes. This process of mathematization produces a mathematical realization of the real problem called a mathematical model.

Step 3: Application of Mathematics. Once the problem has been expressed in mathematical form, we study the resulting mathematical system using concepts and techniques of mathematics. If we are skillful, persistent, or fortunate, we will produce mathematical conclusions or predictions.

Step 4: Interpretation. Our mathematical conclusions or predictions must next be "translated back from the language of our model to the language of the real world and interpreted as real-world conclusions or predictions." (Roberts, 1976, p. 8)

Step 5: Validation. The conclusions and predictions are compared with the real-world phenomenon being considered. Only rarely will our results from the mathematical theory agree completely with real-world outcomes. Usually a mathematical model will not reflect some important aspects of the situation being studied. Only when the results of our mathematical study compare favorably with real-world data will we have some confidence in our model. Otherwise, we must either make do with a model we suspect is inadequate, or we must refine the existing model by retracing the modeling process until an acceptable model is found. (Maki, 1975).

Prerequisite Knowledge

The emphasis in the exercises and activities was for the students to use mathematics and science they already knew in approaching a task. We would expect that students with two years of algebra, one year of life science, and one year of physical science would be able to perform and understand these activities and exercises. Of course, some review and study of forgotten material was at times required. The mathematical content required knowledge of the following terms and concepts: function; table of values for a function; graph of a function; inverse, linear, power, polynomial, rational, exponential, and logarithmic functions; ratio; proportionality relations; variation; slope; and average (mean).

Students' Preconceptions

Students enter mathematics courses with many preconceptions concerning mathematics, its usefulness, and their own abilities. Some student preconceptions that we needed to attend to are the following:

- Mathematics, beyond arithmetic, is of little value to me.
- There is only one correct answer to a math problem, and there is only one correct method for finding that answer (the teacher's).
- I can only solve easy math problems.
- The only important thing in solving a math problem is the answer.
- In functions, x and y are just numbers; not anything real.
- I cannot tell much about the graph of a function simply by looking at its rule.
- I cannot tell much about a function's rule simply by looking at its graph or table of values.
- We can easily tell who has the best answer to a math problem.
- In drawing a graph, I must use the same scale on each axis.

- Science is important, but lots of school math is not of much use in science.
- The math that is useful in science is beyond my capacity to learn.
- I don't know enough math to be able to solve real-world problems using math.

Activities and Equipment

Many of the course's activities required students to gather or develop their own data, display that data in tables and graphs, and then try to find a functional model fitting that data. Some of the activities required specialized equipment. In Part I for example, Cuisenaire rods were used for one activity, the Tower of Hanoi puzzle in another, and MBL or calculator-based laboratory (CBL) equipment (motion detector, photogate, and microphone) were used in several activities. In Part II also, some activities required equipment usually available in a chemistry or physics lab and MBL or CBL equipment (light sensor, temperature probe). We made graphing calculators and computers with spreadsheet software available to the students. Also, students were encouraged to use other resources that can be found in a library or on the Internet.

Case Report: Summary of Some Student Work

Midway through the semester, we presented a population prediction problem (see Student Handouts to follow). In one week, working in groups of two or three, the students completed the assignment. By this time in the semester, the students were expected to solve the problem without the assistance of the instructor. Since the students had progressed as anticipated, the following questions did not surface:

- What do we do?
- Where do we get the data we need?
- How much data do we need?
- Are we using the right procedures?
- How do we know when we have a right answer?

Students gathered and plotted their own data. We expected that linear, polynomial, and exponential functions would be suggested as models for the data. Consistent with an emphasis on intuitive understanding rather than just "plugging numbers into formulas," we decided not to cover techniques of curve fitting such as least-squares in this course. However, we expected that students had already developed heuristics and "best fit" criteria of their own in critiquing solutions discussed earlier in the course.

Student Handout

POPULATION PREDICTION (SESSION 1)

Introduction

We are interested in predicting what the US population will be by the years 2000, 2010, and 2020.

Personal Population Prediction

Take about one minute to record your best prediction for what the population of the US will be by the year 2000.

Individual Plan

Take about five minutes to record how you will attempt to solve this problem.

Group Prediction

Take about five minutes to record the group's best prediction. Compare the group prediction to your individual prediction.

Group Plan

Take about fifteen minutes to decide how the group will attempt to solve this problem. Compare the group plan to your individual plan.

Individual Assignment

Collect any data that will help to solve this problem and bring to the next class. Explain why the answer to this problem could be important. Send your explanation to your instructor by e-mail.

Results of Session 1

To follow are some student responses and instructors' comments on the first session of this activity:

Personal Population Prediction. This question was asked to encourage the students to draw on their preconceptions. Sample student responses:

> *I don't know what the population of the US is today but I would guess it to be 250 million–350 million. I would guess that the population will at least increase by 25% so my approximate guess for the population in the year 2000 would be 380 million.*

∞∞∞

> *The number of people living in most US cities is at least 2,000,000. I believe that the total US population would be in the billions and I'm going to guess 200 billion for the approximate number for the year 2000.*

∞∞∞

> *By the year 2000 the population of the United States will be around 290 million people. I am not sure what the population of the United States is now, but I think that it is around 250 million. I think that the population will increase, but not as rapidly as it has in the past because people are having fewer children than in the past.*

Comments on responses:

All of the students were willing to make an estimate even if they had no clear preconception concerning the current population. Misconceptions at the beginning of an activity are accepted without judgment so that students will take chances and not be embarrassed by their lack of knowledge.

How will you attempt to solve this problem? Each student was expected to formulate a plan for solving this problem. Sample student responses:

To solve this problem I will graph data points from about the year 1600, using increments of either 25, 50, or 75 years depending on how I space the graph. I will next extrapolate that data to get the points for the years 2000, 2010, and 2020.

∞∞∞

Go to the library and look at an almanac and find increases over last several years. Look up articles in database and see if there are any predictions.

∞∞∞

I plan on further investigating this problem in the library. By looking in almanacs and other reference materials, I can gather some statistics from about the turn of the century. I would gather a point for about every 10 years. These points would be graphed and I would try and come up with a formula. After I find a formula, I can find the values for the years in question.

Comments on responses:

The students have become independent enough not to be paralyzed by this problem. They expect to find the data they need in the library and they have a plan for analyzing the data.

How will your group attempt to solve the problem? This was an opportunity for the students to resolve their differences and arrive at a consensus. Sample student responses:

We agree that the population in the year 2000 will be around 300–400 million. We also agree that the best way to make our prediction more accurate is to look at previous year's population and find the rate of increase between each year. There are also materials which list predictions of the population—we think these would be helpful also. After we have collected our data, we can graph our data and attempt to construct a formula.

∞∞∞

Population for the year 2000 is predicted to be 260–300 million (range from group members).

1. *We plan to go to the library and get census data (as far back as accurate, 1900??).*
2. *Graph the data with years after 1900 on the* x-*axis and population on the* y-*axis.*
3. *Find a model (function) for the graph using standard functions as a guide.*
4. *Put in 100 for* x *and find* y. *This is the population prediction for the year 2000. (110 for* x *for 2010, etc.).*

Misconceptions at the beginning of an activity are accepted without judgment so that students will take chances and not be embarrassed by their lack of knowledge.

Comments on responses:

The group estimates narrowed the range of predictions. All three groups had definite plans for collecting data. The particular years that they plan to use will probably need to be changed but that should not be a problem because flexibility in planning is stressed throughout the course.

Explain why the answer to this problem could be important. This task required the students to reflect on the relevance of the problem. Sample student response:

The answer to the problem posed could be important for various reasons. First, it may *be important to have an estimate of the population of the United States for future years to plan for an increased use of energy. It is important to know how many people there will be so that we can estimate the amount of energy that will be needed in the future. One question that depends upon the population is 'When will our supply of fossil fuels run out?' Another estimate for the future that depends on population is living space. The more people, the more space is needed for living area and waste. Our country needs this information for planning purposes. In addition, the country needs to estimate future population for such issues as food supply, jobs, and government. Almost every issue in our world is dependent upon the future population, and if we were not able to estimate this number we may not be able to provide for the needs of everyone in our country. For these and many other reasons, predicting the future population of our country is extremely important!*

Comment on response:

This student recognized the relevance of the problem. The student's response shows a concern for preparedness in many aspects of society.

Student Handout

POPULATION PREDICTION (SESSION 2)

Group Revised Population Prediction

Based on your data, revise your estimate of the what the US population will be by the year 2000.

Group Plan for Analyzing the Data

Develop a plan for selecting the data you will use and how you will use this data to predict the population for the years 2000, 2010, and 2020.

Group Summary and Discussion of Accuracy

Explain the "best" way to solve this problem, and indicate your "best" estimates. Discuss your feelings about the accuracy of your estimates. Send your response to your instructor by e-mail.

Results of Session 2

Students collected data individually and used this session to compare data and form a plan for analyzing the data and for producing a group summary of their results.

Revise your previous population prediction. This activity required students to reflect on the predictions they had made before they had collected data, and gave them an opportunity to address their prior knowledge and misconceptions. Sample responses:

Our initial prediction for the year 2000 was 300 million to 400 million. We based this on the fact that there were 250 million people in the US in 1990. We felt that the population had been increasing at faster and faster rates. Our data does not support the idea of an increasing rate. We adjusted our prediction for the year 2000 to be between 270 million and 280 million.

∞∞∞

After seeing the data that we have collected, we have changed our prediction quite a bit. We do not think that the population increases by 5 to 10 million every year. Lately, the population has been changing by approximately 2.3 million every year. Our new prediction for the year 2000 is 270 million.

ooooo

After briefly examining the data that was collected, our predictions were revised. We had found census information from 1900 to 1990 and graphed it. The graphed data reveals the data to be almost a straight line. From this graph we realized that the US population increases by approximately 20 million people every ten years. We also learned that there are about 2 million more births than deaths in the US each year, making an increase in population over a ten year period about 20 million people. Our new prediction, therefore, became 270 million for the year 2000.

Comments on responses:

New predictions were based on new knowledge of the situation. Students analyzed the data intuitively. Either linear or exponential models might have emerged following quantitative analysis.

What data will your group use, and how will you use it? Since, at this point, data collected had been viewed only by individuals, it was important for the group members to agree on a strategy for analyzing the data. Sample student responses:

We noticed that the population data for the last thirty years seemed to be a straight line. We calculated the change in population for each of the ten year periods from 1960 to 1990. During this time the population has been increasing at approximately 2.3 million every year. A closer look at the data suggests a slightly decreasing rate for each decade. The trend seems to be that the change in population decreases by approximately one million each decade. We will use this approach to make our final predictions.

ooooo

With the gathered data, we decided to only use the known population for the years 1960 to 1990 because this information, when graphed, is almost a perfect straight line. From this data we will determine an equation that fits the points for 1960 and 1990. We can then use this line to predict the population for the years 2000, 2010, and 2020.

ooooo

We will calculate the average percent growth per decade, and then use that value to develop a formula to predict the future population.

Comments on responses:

Each group developed a plan. Linear models were likely to evolve from two of the plans. An exponential model was likely to evolve from the other.

Summarize your conclusions. Sample student responses:

Since the data from 1960 to 1990 suggested a straight line, we determined the equation of the straight line using the data for 1960 and 1990. The equation is $y = 2{,}300{,}000x + 41{,}000{,}000$ where x is the number of years from 1900 and y is the population for that year. Using this equation we calculated the population for the years 2000, 2010, and 2020 to be respectively 271,000,000, 294,000,000, and 317,000,000. Since our equation does not fit the data perfectly, our answers are only approximate. For a problem such as this one, the 'best' solution is to find the model that best fits the known data points and use that model to predict the unknown data points. We feel very strongly that our model will do this.

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We developed two models—one linear and one exponential. We found that the average population increase per decade from 1900 to 1990 was about 19.2 million, and the average percent growth per decade from 1900 to 1990 was about 14.1%. The 1900 population was approximately 76 million. We decided to let the population in millions *t decades after 1900 be represented by P(t). The equation for our first, linear, model is $P(t) = 76 + 19.2t$. The equation for our second, exponential, model is $P(t) = 76(1.141)t$. We compared the graphs of both equations to the actual data, and decided we liked the second (exponential) model better. Substituting 10, 11, and 12 successively for t in that equation we determined that the population of the US in 2000, 2010, and 2020 will be about 284 million, 324 million, and 370 million respectively. Since our equation's graph seems to follow the actual growth graph for 1900 to 1990, we think our predictions are fairly good.* (The graph these students produced using a spreadsheet is shown below in Figure 2.)

Comments on conclusions:

Although students were able to develop a pair of models, linear and exponential, little consideration was given to the superiority of one model over another. If the instructor had emphasized the importance of establishing both qualitative and quantitative criteria for goodness of fit before assigning this problem, students might have thought of a "compound interest" interpretation for the situation, and they might also have compared deviations of the competing models' estimates from the actual data. (For these students, apparent geometric closeness in the graphs was sufficient evidence to accept a model.) In the future, this problem will be assigned after the concept of best fit has been suggested and some criteria for determining best fit have been developed by the students.

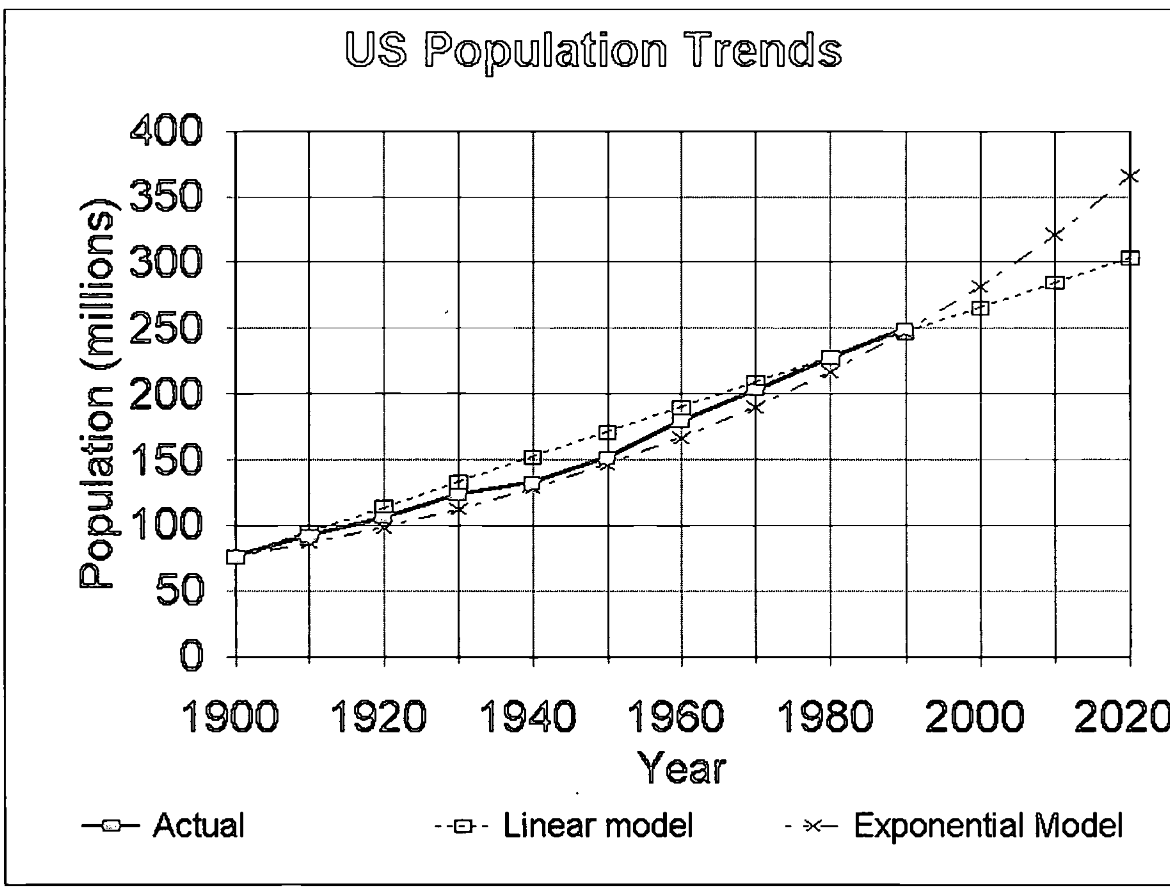

Figure 2. Student Graph of Population Prediction

Conclusions and Reflections

We attempted not only to address the expected outcomes discussed earlier but also to follow the guiding principles stated by Brooks and Brooks (1993) by (a) posing problems in such a way that kindle the students' interests and therefore are made relevant; (b) presenting broad primary concepts that the students must "break into parts that they can see and understand;" (c) seeking, addressing, and valuing students' points of view; and (d) adapting the learning environment to address the students' preconceptions. Our ultimate goal was to provide prospective teachers with an understanding of the problem-solving processes used in mathematics and science and a workable teaching/learning model for their own subsequent teaching careers. By de-emphasizing the teaching of specific algebraic and statistical content, special emphasis was placed on allowing students to construct personal knowledge and understanding of the concept of a "function as a model" and on "model building."

We found it very difficult at the beginning of the course to stay away from the lecture mode and to not answer questions that would have been answered in a traditional course. The students were also unsure of themselves at the beginning. Those who had previously completed other MCTP courses very quickly realized that they would have to accept the responsibility for their own learning. Once the other students also accepted that responsibility, the atmosphere of the course changed drastically. We were able to avoid lecturing and instead became facilitators while the students took a larger part in directing the class activities.

One consequence of this new atmosphere was that unanticipated topics had to be addressed and additional assignments prepared. The students were often too quick to generalize and consequently many of the classes ended with them possessing misconceptions. When this happened we needed to scramble before the next class to come up with another assignment that contradicted their erroneous generalizations. This approach worked; they quickly realized their misconceptions and modified their concepts. This process of making mistakes, realizing that something is wrong, and then adjusting thinking may be a major strength of this new approach to learning. It is very important to not penalize the students for their misconceptions.

It became apparent very early in the course that most of the students liked to work in groups. Even though the group composition changed for each activity, the group dynamic became a compelling force. The group activities allowed the students time to share ideas, preconceptions, and even their apprehensions about a particular assignment. Once they realized that most of the assignments would be discussed in groups, the students demonstrated very positive attitudes toward the assignments. The only detrimental aspect of the group work was that it became very difficult to get some of the students to do their individual activities before they started their group activities. It was necessary at times to collect individual efforts before initiating group activity.

> *This process of making mistakes, realizing that something is wrong, and then adjusting thinking may be a major strength of this new approach to learning.*

We are still struggling with the assessment aspect of the course. Students need to be given a variety of activities to assess their progress in problem solving. Utilization of an e-mail journal was an effective way to get immediate feedback from the students. Misconceptions and even attitude problems were quickly revealed in journal entries. The students were both serious and open with their journal entries. In grading group reports, it was difficult to determine the amount and quality of individual contributions. We still believe that a portion of the assessment should rely on traditional in-class examinations.

The students in this course recognized how the course differed from traditional mathematics courses. Class discussions and course evaluations suggest that they hope to implement similar instructional practices in their own classrooms. The intensity of their feelings and their confidence in their ability to teach in a different way was the most surprising aspect of this course. These prospective teachers have the potential to be instrumental in transforming the way mathematics and science are taught in elementary and middle school.

References

Abruscato, J. (1993). Early Results and Tentative Implications from the Vermont Portfolio Project. *Phi Delta Kappan, 74* (6), 474–477.

Brooks, J. and Brooks, M. (1993). *In Search of Understanding: the Case for Constructivist Classrooms.* Alexandria, VA: Association for Supervision and Curriculum Development.

Cathcart, D. and Horseman, T. (1995). Mathematical Models and Modeling for Middle School Teachers: Instructor's Guide. Available from Authors.

Cipra, B. and Flanders, J. (1992). On the Mathematical Preparation of Elementary School Teachers. *Report of a Conference Held at the University of Chicago.* Chicago: The University of Chicago.

Maki, D. and Thompson, M. (1973). *Mathematical Models and Applications.* Englewood Cliffs, NJ: Prentice-Hall.

Meir, S. (1992). Evaluating Problem-Solving Processes. *The Mathematics Teacher, 85* (8), 664–666.

National Council of Teachers of Mathematics. (1989). *Curriculum and Evaluation Standards for School Mathematics.* Reston, VA: NCTM.

National Council of Teachers of Mathematics. (1991). *Professional Standards for Teaching Mathematics.* Reston, VA: NCTM.

National Council of Teachers of Mathematics. (1995, January). *NCTM News Bulletin.* Reston, VA: NCTM.

O'Haver, T. (1994). CHEM 121/122—Chemistry in the Modern World (MCTP Physical Science), Course Syllabus. [On-line]. Available: http://www.wam.umd.edu/~toh/MCTP.html [1997, Dec 18].

Roberts, F. (1976). *Discrete Mathematical Models.* Englewood Cliffs, NJ: Prentice-Hall.

Schaufele, C. and Zumoff, N. (1993). *Earth Algebra: College Algebra with Applications to Environmental Issues* (Preliminary Version). New York: Harper Collins.

Shannon, K. and Curtin, E. (1992). Special Problems: An Alternative to Student Journals in Mathematics Courses. *PRIMUS, II* (3), 247–256.

Appendix A

COURSE SYLLABUS: INTRODUCTION TO MATHEMATICAL MODELING

Objectives

To help prospective middle school teachers of mathematics or science (a) see connections between mathematics and other disciplines; (b) present and analyze real-world phenomena using a variety of mathematical representations; (c) develop strategies and techniques for applying mathematics to solve problems; and (d) explain and justify their reasoning, using appropriate terminology, in both oral and written expression.

Prerequisites

Three or four years of college preparatory mathematics (including at least two years of algebra) and two or three years of college preparatory science (including a life science and a physical science).

Course Outline

Part I. Functions as Models—Curve Fitting

Development of a Repertoire of Techniques to Be Used in Modeling:

- Recognizing Some Standard Functions
- Qualitative Aspects of Graphs
- Change, Rate of Change
- Scales Used in Graphs
- Finding Perfect Fits
- Looking for Good Fits

Part II. Mathematical Modeling

Focus on Modeling as the Process of Applying Mathematics to Solve Real Problems:

- Modeling Examples
- Modeling Activities

Activities

The course is built on a variety of activities, including classroom activities, laboratory experiments, group discussions and reports, and modeling projects. Usually students will be working in groups.

Notes

Students are expected to take and organize class notes. Since there is no conventional textbook for this course, students will need to take good notes when terms, techniques, and concepts are introduced during class discussions.

Journal

Each student will write a weekly e-mail message to the instructor based on the student's reflections on the week's activities in the course. The instructor will reply to each student's message by e-mail. All messages and replies will be kept in an electronic journal.

Portfolio

Each student will develop a modeling portfolio providing (a) samples of the student's best work in problem solving and mathematical communication, and (b) an indication of the range and quality of mathematical and scientific skills and concepts acquired.

Assessment

Exercises, Group Activities, Reports	40%
Electronic Journal Entries	10%
Portfolio	10%
Examinations (2 @ 20% each)	40%

Calculators

Students are expected to bring calculators to class, the laboratory, and exams.

Appendix B

SAMPLE MODELING PROBLEM: DESCRIBING THE MOTION OF A BOUNCING BALL

Develop a mathematical model to describe the motion of a bouncing ball. Create a model appropriate for considering questions such as the following:

- How high will the ball bounce on the *n*th bounce?
- What will be the ball's velocity at time *t* seconds?
- When will the ball stop bouncing?
- Do basketballs and volleyballs exhibit the same behavior?
- Of what significance is the type of surface upon which the ball is bouncing?

Before starting on this task, take a moment right now to sketch a position-versus-time graph predicting the ball's distance above the floor from the moment it is dropped until four or five seconds have elapsed. Also, sketch a velocity-versus-time graph predicting the ball's velocity at any time from the moment it is dropped until four or five seconds have elapsed.

In writing up your solution, be sure your paper conforms to our guidelines by communicating your efforts in:

- Problem Formulation
- Mathematization of the Problem
- Solving Within the Model
- Interpreting Your Solution
- Validation of Your Model

ADAPTATION OF A TRADITIONAL STUDY OF ENZYME STRUCTURE AND PROPERTIES FOR THE CONSTRUCTIVIST CLASSROOM

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At Towson University the MCTP Program in Elementary Education includes a two-semester sequence of introductory biology classes. The unit described in this paper was used in the second semester course we taught together in the spring of 1995. We chose to teach as a team and to integrate concepts from our two disciplines—biology and chemistry—as we wanted our students to appreciate the interdisciplinary nature of science. This was a natural strategy for us since we had previously collaborated in writing a series of chemistry texts that integrate inorganic, organic, and biological chemistry, as well as biological applications based on fundamental chemical principles. The course first focused on the concepts of chemical bonding and the links between a molecule's structure and its chemical and physical properties. These concepts were then applied to the study of enzymes, photosynthesis, and aerobic respiration.

Context and Goals

The topics addressed in this course are a selection of those one would find in introductory biology and chemistry courses. We began with the structure of the atom, helping students to construct the periodic table. This led naturally to an investigation of the principles of chemical bonding and how they apply to biologically important molecules. Students designed a series of experiments to investigate the relationship between bonding, structure, and properties. These relationships were then applied to the study of enzymes and biochemical pathways.

In the past, we both had used a conventional lecture style to convey basic information. Laboratories were largely of the "cookbook" variety. In these laboratory exercises (notice that we do not call them experiments) students served primarily in the role of technician. They benefited mainly by learning technique and manipulation. They were not challenged to make predictions, design experiments, or evaluate the experimental design or conclusions.

There are several reasons why we chose a different path. We were dissatisfied with the conventional teaching methods just described, as well as with the lack of student involvement in that type of classroom. We were also disturbed by our students' inability to appreciate the interrelationships of the concepts taught in various courses in their undergraduate curriculum, including writing, mathematics, physics, chemistry, and biology.

All of the activities designed for this course were planned with a central goal: to give the students primary responsibility for their own learning and to allow them every opportunity to explore new relationships through observations and experimentation.

Enzyme Unit Objectives

There were a number of major themes and objectives addressed by this unit. The first was for students to apply their knowledge of molecular structure and property relationships to construct a model of a protein structure, which they would use to understand the role of enzymes in chemical reactions. A second objective was to integrate the scientific method into the students' daily activities by having them design and critically analyze their experiments. We also wished to provide the students with an appreciation of the way in which scientific knowledge is acquired and how it changes as new technologies become available. Finally, we endeavored to prepare pre-service teachers to use a constructivist approach in their science teaching, an approach modeled after their own learning experiences in our course.

Pedagogical Considerations

Before we began the unit, the students were assigned an article entitled *Life Beyond Boiling* (Hively, 1993) to engage their interest in protein structure and enzymes. The article describes microorganisms that live at temperatures above the boiling point of water and discusses aspects of protein and enzyme structure that allow life to exist at such extreme temperatures. The article was accompanied by a set of questions designed to assess the students' prior knowledge and possible misconceptions, to determine what factual information they had derived from the article, and to challenge them to use the information learned in problem-solving and critical thinking.

We ensured that the students' ideas and hypotheses were respected both by the other students and by the instructors, by continually reinforcing the idea that any model has strengths and weaknesses regardless of whether the model was constructed by a Nobel laureate or a beginning student.

Through classroom discussion of the engagement article, we provided the students with the opportunity to examine their prior knowledge. We were able to learn that the students had a functional understanding of enzymes. They knew that enzymes speed up chemical reactions and that they are proteins. We continued to monitor student ideas and beliefs throughout the unit through their electronic-mail journal entries, classroom discussion, and cooperative model-building.

The students were provided opportunities to invent and consider alternate beliefs about the way enzymes function through a series of experiments that encouraged them to investigate the nature of enzymes and enzyme-catalyzed reactions. Discussion of the way in which scientists have modified the concept of enzyme-substrate interaction over the years allowed the students to appreciate the fact that our understanding of science changes as new information is gathered.

Students were encouraged to make connections between their classroom experience and the world around them. Throughout the course students were expected to communicate these associations both in class and in their electronic-mail journal entries. During this unit the students posed questions about the nature of enzymatic contact lens cleaning solutions and digestive enzymes. These questions gave rise to very lively classroom discussions.

We ensured that the students' ideas and hypotheses were respected both by the other students and by the instructors, by continually reinforcing the idea that any model has strengths and weaknesses regardless of whether the model was constructed by a Nobel laureate or a beginning student. All student ideas were subject to discussion, and were frequently modified as a result of class discussion. This was not treated as a means of criticizing students, but rather as an effective sharing of ideas to establish and extend their level of understanding. All students participated in this model-building and each seemed to feel satisfied that he or she had made a valuable contribution.

Unit Chronology

The unit on enzymes required eight class days. Because constructivist courses are primarily student-driven, the time required to cover these concepts and the precise content covered will vary for each class. Included in the following chronology are brief anecdotes that describe the responses of our class to this unit.

The exercises described below involved simple, safe experiments requiring only inexpensive equipment and supplies available in an undergraduate chemistry or biology laboratory. The complete laboratory exercise is appended to the end of this paper. Technological support included commercial videotapes of experiments and computers for transmitting journals and preparing reports.

Day 1

To give the students a practical introduction to reaction kinetics, we showed a videotape of an experiment called "Elephant Toothpaste" (Brown, Wm. C. [Publisher], 1993). The reaction studied is the breakdown of hydrogen peroxide into water and oxygen:

$$2H_2O_2\ (aq) \rightarrow 2H_2O\ (l) + O_2\ (g)$$

The evidence of the progress of the reaction is readily seen by the oxygen bubbles produced. The investigators in the video examined the effects of temperature, concentration, and catalysis on the rate of the reaction. Following the video, group discussion of the experimental results allowed the students to construct an elementary understanding of rates of reaction and the factors affecting reaction rates.

We then gave the class some further information about this reaction to make it biologically relevant. We explained that hydrogen peroxide is a toxic by-product of aerobic respiration, which must be broken down in the cells of the body so that it does not damage our biological molecules. We poured some hydrogen peroxide into a graduated cylinder. The students perceived that, left to itself, the reaction occurs very slowly. In fact, their observations led them to conclude that no reaction was occurring and that spontaneous breakdown of H_2O_2 would not be sufficient to protect cells from the harmful effects. We discussed how we could speed up this reaction without harming the biological system. All agreed that if we used heat it would harm the cells, and that we could not control the reactant concentration. The class concluded that adding a catalyst would be the best solution.

We discussed the fact that the catalyst used in the videotape, potassium iodide, was inappropriate for biological systems. This allowed us to introduce the concept of enzymes as biological catalysts. Students then watched a second videotape in which dried yeast cells (bakers' yeast) were used to "catalyze" the breakdown of hydrogen peroxide (*Catalysis*. Brown, Wm. C. [Publisher], 1993). They then carried out a modified version of the yeast experiment by pipetting drops of hydrogen peroxide onto a sterile agar medium and onto similar plates that had been inoculated with a variety of bacteria. No reaction was apparent on the agar; however, the bacterial colonies caused furious bubbling. This reinforced the idea that cells contain an enzyme that dramatically speeds up this biologically important reaction.

Day 2

Since the first day of class we had stressed model building as a means of understanding complex systems. Today the class constructed molecular models of amino acids as a first step toward understanding protein structure. Each student constructed a different amino acid. This was easy for them because of their previous experience constructing different kinds of organic molecules. They then modeled peptide bond formation and constructed a tetrapeptide. We drew the reactions on the board, using a color-coding scheme for the reacting functional groups to help the students focus on the bonds being broken and the bonds being formed in the reaction. Again the students were able to "perform" the reactions and summarize them on the board with ease because of the chemical reactions they had modeled earlier in the course.

Using drawings, we then worked through the secondary and tertiary folding of a peptide chain. We used the models and diagrams of the amino acids to predict the types of interactions that would maintain these folded shapes (Caret, Denniston, & Topping, 1993). Because of the solubility experiments that the students had previously carried out, they were able to categorize the amino acids as polar, nonpolar, or charged. They were then able to predict which amino acids would be involved in the weak interactions that are responsible for protein folding: hydrogen bonding, hydrophobic and hydrophilic interactions, ionic bridges, and so on.

Day 3

The students' electronic-mail messages and in-class agitation made it obvious that they were overwhelmed by the quantity of information generated in the preceding class period. As a result, we reviewed the key concepts from the previous lesson. Having been through the information once before, the students had lots of questions along the way. This interactive discussion allowed us to clear up misunderstandings immediately and provide the "missing links" in their model of protein structure.

Day 4

We introduced the quaternary level of protein structure using hemoglobin as the example because it is a protein familiar to most students (Caret et al., 1993). We then discussed the older (lock-and-key) and more recent (induced fit) models of enzyme-substrate interaction. The students were very impressed that Dr. Topping had learned the older model as short a time ago as when he was in school. This seemed to give them a real "feel" for the fact that scientific information is constantly changing as new information becomes available. The incident also impressed upon us that the experiences of people the students can relate to are valuable tools in the engagement process.

Day 5

The goal for this class period was to have the students perform a set of experiments on enzymes, collect the data, and discuss the results. These experiments are similar in content and objective to those used in many introductory biology courses for non-majors (Hull, 1995). To adapt them for use in a constructivist classroom, these laboratories were redesigned. Students were required to predict the experimental results. These predictions would be based on the experiences of the students in the classroom during the first part of this unit and on the information they gained from reading the engagement article. In addition, the students were required to construct their own data tables and, when applicable, to prepare a graphic representation of the results. Finally, students were required to interpret their data, develop a model of enzyme-catalyzed reactions, and share their models with the class.

We studied the properties of the enzyme *polyphenoloxidase* (PPO). This enzyme catalyzes the oxidation of catechol to produce benzoquinone and water. For a number of reasons this is an ideal enzyme to study. First, students have observed this reaction many times. When you bite into an apple or cut open a potato, the injured surface darkens. The dark areas are caused by the PPO catalyzed oxidation of catechol to produce benzoquinone, which has been shown to exhibit anti-fungal properties and hence is beneficial to the injured plant tissues. Benzoquinone is a rust-brown colored compound; thus students can easily observe the reaction by the development of this color. Finally, the students can easily prepare the enzyme from a potato or apple (see Appendix for details).

In the first experiment, positive and negative controls were carried out. The positive control, a mixture of enzyme and substrate, allowed the students to recognize a meaningful color change and understand the chemical and biological significance of the color change. The negative controls, substrate alone or enzyme alone, demonstrated that both the enzyme and the substrate were required for the reaction to occur. All reactions were carried out at 37°C and were observed at 5 minute intervals. These tubes were saved to compare with the results of other experiments.

In the second experiment the students investigated the biochemical composition of this enzyme. We proposed that an enzyme is composed of one of three types of biological molecules: starch, protein or lipid. All of these are polymers that can be destroyed by hydrolysis. Samples of the potato enzyme were treated with either bacterial protease, which hydrolyzes protein, amylase which hydrolyzes starch, or lipase, which hydrolyzes fat. If the enzyme is broken down, it can no longer convert substrate to end-product and no rust-brown color occurs. Alternatively, if the enzyme is not broken down, it will produce the end-product and the rust-brown color will appear.

In the third experiment, the students investigated whether PPO requires a metal ion cofactor in order to catalyze the reaction. Phenylthiourea (PTU), which binds very strongly to divalent cations, was added to the PPO extract to remove any such cations that might be acting as cofactors for the enzyme. By observing whether the enzyme was still able to catalyze the formation of benzoquinone, students were able to determine whether a metal ion is required by the enzyme.

In the fourth experiment, the students investigated the specificity of PPO. Enzymes may accept only a single substrate into the active site, in which case they are described as exhibiting absolute specificity. However, some enzymes are able to form complexes with several substrates bearing the same functional group and having similar structures. An enzyme having this property is said to have group specificity. The students compared the ability of PPO to catalyze the oxidation of three different but structurally related substrates: catechol, phenol, and hydroquinone. Based on product accumulation, students were to determine whether PPO demonstrates group or absolute specificity.

In the fifth experiment, the students investigated the effects of pH on enzyme activity. Extremes of pH can affect the structure of an enzyme by disrupting the hydrogen bonds that link the amino acids between different portions of the protein strand. This results in a change in the structure and hence the shape of the active site and influences the ability of the enzyme to function. Students estimated the level of enzyme activity at three pH levels—2, 7, and 14.

In the sixth experiment, the students investigated the effects of temperature on enzyme function. Increasing the temperature may increase the rate of a reaction by increasing the kinetic energy of the molecules. However, if the temperature becomes too high, the shape of the enzyme active site may be changed, thereby destroying enzyme activity. Students estimated the level of enzyme activity at 0, 20, 37, and 100°C.

After the students had completed the experimental work, we began a discussion of the purpose of the control experiments. Following a lively discussion involving both students and instructors, the students concluded that both enzyme and substrate are required for the reaction to occur. From their data, students further concluded that this enzyme is a protein and that it requires a cofactor. We talked about the differences between a cofactor (a metal ion that remains bound to the enzyme) and a coenzyme (an organic molecule that participates in the enzyme-catalyzed reaction but is not permanently associated with the enzyme structure). In response to one of the questions accompanying the lab exercise, the class designed an experiment to show whether the metal ion was acting as a cofactor or a coenzyme. The students decided that they needed to find a way to separate molecules from one another. Because these students have no molecular tools in their tool kits, we described ways to separate proteins and other cellular components by column chromatography. We told the students to continue working on their experimental design and to consider the laboratory questions for the next class period.

Day 6

Because the students had shown great interest in separation of cellular macromolecules by column chromatography, we brought some high performance liquid chromatography

(HPLC) columns and packings for them to examine. They were fascinated with the idea that this fine powder really consisted of tiny glass beads with even tinier pores and channels through them. Because they wanted to examine the beads in greater detail, we brought out the microscopes and the class examined them thoroughly and discussed the way in which they were manufactured. This allowed us to introduce the history of an ancient technology, production of lead shot and miniballs, to explain the methods used to manufacture some types of chromatography beads. We then completed our discussion of the experiment the students had designed to distinguish between a coenzyme and a cofactor. They "argued" back and forth and, in the end, put together a well-designed, properly controlled experiment.

We then continued our discussion of the experimental results from the previous class period, beginning with the enzyme specificity experiment. We immediately ran into a problem. The students had recorded different "colors" for their results. Of course, the tubes had been discarded the period before, so there was no way to observe the result again. As we discussed this experiment further, it was also clear that one of the experimental substrates, phenol, generated a completely atypical color reaction. From their description, it sounded as though the phenol had denatured the enzymes. The students decided that phenol was a poor choice as an experimental substrate. Thanks to our prior class work on isomers, they recognized that another structural isomer of catechol was possible, and proposed that it might work better than phenol. They drew the structure of the proposed compound on the board; we determined that it was resorcinol and decided to order some for further experiments. The students also recognized flaws in their observational skills, ability to accurately describe results, and record-keeping procedures. After a rather intense group discussion, the students decided on a more accurate, efficient, and reliable method.

We then looked at the experiments designed to test the effect of pH and temperature on enzyme activity. The students prepared graphs of their experimental results and concluded that the enzyme has a very broad range of pH and temperature over which it is active. We discussed why this might be the case. The class then initiated a discussion of digestive enzymes that must function at extremes of pH.

We concluded the day by deciding to repeat the control and specificity experiments using the substrate and experimental design modifications suggested by the class. These included the use of resorcinol instead of phenol, preparation of enzyme from apples as well as potatoes, carrying out all reactions in duplicate, and trying to improve upon the observation and data recording skills.

Day 7

The students prepared enzyme from potato and apple and carried out the experiments as they had planned during the previous class period. The atmosphere in the lab was very interesting to observe. The students were very familiar with the procedures. As a result, setting up the reactions required less concentration than it had the previous class period. They chatted with one another in a very relaxed fashion. When attention to detail was required, the chatter stopped and the experiment was attended to. Then the chit-chat started again. This is very reminiscent of the atmosphere in a research laboratory. When concentration is required, all is quiet; but at other times there is relaxed conversation.

At the end of the period we examined the results. Catechol gave the most complete reaction; resorcinol resulted in no reaction; hydroquinone showed some darkening. The class decided that the reaction was occurring, but at a slower rate because the substrate does not fit as well into the active site. We decided to test this by leaving the reactions in the refrigerator over the weekend.

Day 8

We carried out a discussion of the entire enzyme lab. I told the students that I had discussed their experimental modification with Dr. J. Hull, editor of the introductory biology lab book (Hull, 1995). The students were delighted to learn that the experimental substrate they had selected would be used in the next edition of the lab manual. This was very important reinforcement of their sense that they have the ability to contribute significantly to the sciences.

Since this was the last day of the enzyme unit, we had the students compare their understanding of protein structure and enzyme activity at that point with their understanding at the time we began the unit. After each student had prepared his or her own written summary, the students shared the summaries with one another. They then came up with a series of global statements to summarize their understanding of proteins and enzymes. This proved to be a very useful assessment tool.

Assessment

Throughout the course we relied on a variety of types of assessment. In some cases, the assessment was used to assign a grade; more frequently the assessment was simply a tool to allow us to monitor the level of understanding or to determine the direction the course should take.

Student electronic-mail journals proved to be a very effective means of assessing student progress in constructing their models of the concepts being studied. Because our class was small, we frequently began with an informal discussion. This allowed us to delve into some of the ideas and questions the students expressed in their journals and to discover developing misconceptions or faulty preconceptions that students had not yet addressed. Periodically the students were required to summarize their current understanding of a topic and compare this to the ideas they had at the beginning of the unit. They then shared their summary with the class, and worked cooperatively to arrive at a class consensus, which was discussed by all.

Assessment for grading purposes was generally in the form of a problem-solving exam. To make the exams authentic, they reflected the experience of the students in the class. Many exam questions focused on critical analysis of experiments done in class, requiring the student to discuss the limitations of the experiment and design an improved experiment. Others required the students to use the approaches and concepts studied in class to solve related problems. As the course proceeded, greater numbers of questions focused on the application of the basic principles of chemistry, studied in the first half of the course, to problem-solving in biological systems.

Reflection

One of our concerns was that we would be unable to cover enough content in this course because of the large amount of time required by the students to construct their own understanding of each of the principles investigated. To our surprise, the limited number of topics and the freedom of the students to investigate them allowed the students to adopt a "need to know" attitude. As a result, they came to recognize what information they needed to bring to bear on the solution of a particular problem and to independently seek out that information. In addition, they developed an appreciation of the need to apply information from different disciplines to the solution of a problem. Thus, the students not only learned a reasonable cross-section of material, but were able to apply their knowledge to the solution of problems and design of experiments.

> *To our surprise, the limited number of topics and the freedom of the students to investigate them allowed the students to adopt a "need to know" attitude.*

Although we tried to model learning science by doing science, and thereby hoped to engender an attitude of scientific curiosity, we were disappointed with two aspects of the students' behavior. The first was that they remained extremely grade conscious. The second was the difficulty with which the students adapted to cooperative group work. These two concerns may be, in reality, a single concern. From early days these students have been taught to be competitive and that sharing work is an act of cheating. As we all know, preconceptions are very difficult to overcome.

Summary

A commonly used set of laboratory exercises investigating the properties of enzymes was adapted for use in a constructivist classroom. These studies involved student preparation of an enzyme extract from a potato and use of the extract to investigate the properties of the enzyme. Before each experiment, students were required to predict the outcome based on previous classroom investigation of the role of enzymes in biochemical reactions. Students were further required to carefully analyze the results of each experiment and present the results in a meaningful way. Throughout each experiment the students were given the opportunity to suggest and conduct experiment design modifications based on their analysis of the results. Authentic assessment was an ongoing component of the course.

References

Brown, Wm. C. (Publisher). (1993). *Elephant Toothpaste* [Videotape]. Dubuque, IA: Exploring Chemistry Videotapes.

Brown, Wm. C. (Publisher). (1993). *Catalysis* [Videotape]. Dubuque, IA: Exploring Chemistry Videotapes.

Caret, R.L., Denniston, K.J., & Topping, J.J. (1993). *Principles and Applications of Inorganic, Organic, and Biological Chemistry.* Dubuque, IA: Wm. C. Brown.

Hively, W. (1993, May). Life Beyond Boiling. *Discover,* 87–91.

Hull, J.C. (Ed.). (1995). Properties of enzymes. In *Contemporary General Biology Lab Book* (5th ed.). Dubuque, IA: Kendall/Hunt.

Appendix

PROPERTIES OF ENZYMES

Introduction

Objectives

The purpose of this exercise is to examine biological reactions with respect to the characteristics of the enzymes which control them. You will examine how enzymes are affected by various factors including substrate availability and type, inhibitors, temperature, cofactors, and pH. In addition, you will draw conclusions from a series of observations. Upon completion of this exercise, you should be able to:

- describe the effects of pH, temperature, substrate availability, and cofactors on enzymatic reactions;
- draw conclusions from observed experimental results; and
- develop hypotheses to propose the cause of observed results.

Materials and Equipment

- Each of the following solutions should be placed in wash bottles and kept in an ice bath: potato extract containing polyphenoloxidase (PPO), 1% catechol, 1% resorcinol, 1% hydroquinone, 1% bacterial protease, 1% amylase, 1% lipase, pH 2.0 buffer, pH 7.0 buffer, pH 14.0 buffer.
- The following should be available at each table: test tube rack with 18 test tubes, glass marking pencils, wash bottle containing distilled water, 15 cm ruler, phenylthiourea crystals (PTU).
- The following should be available for the entire class use: test tube brushes, carboy filled with distilled water, electric blender, 1000-ml plastic pitcher, cheese cloth, white potato or apple, waterbath with capacity for 120 test tubes, potato peeler, paring knife, 600-ml beaker ice bath, hot plate with 600-ml beaker.

Preparations

Immediately prior to class, you should prepare the potato extract as follows: Peel and slice a white potato and place into a blender with 700 ml distilled water. Homogenize for two minutes. Strain homogenate through cheese cloth. The liquid portion contains the enzyme, polyphenoloxidase (PPO). This extract should be divided into several wash bottles and placed into an ice bath. This potato extract contains polyphenoloxidase as well as numerous other enzymes and materials which we will not be measuring. In addition there is some catechol which occurs in the potato which will serve as a naturally occurring substrate for the reaction we will be studying.

You should work in cooperative groups. Before beginning, all test tubes should be rinsed with distilled water. Using a glass marking pencil, divide each tube into three 1 cm units beginning at the inside bottom of the tube. To save time, substances will be "squirted" into the tubes in 1 cm units. All of the following experiments may be set up and run at the same time.

Key Concepts

Develop an understanding of each of the following concepts: catalyst, coenzyme, cofactor, enzyme, hydrolysis, and substrate.

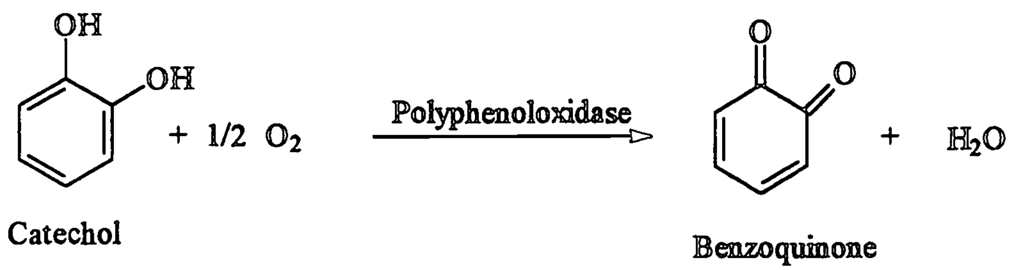
General Introductory Questions

- What happens to the white flesh of an apple, banana, or potato when you cut it open and expose it to the air?
- Why do you suppose that this change occurs?
- Do you think this is a physical or a chemical change?
- Have you ever prepared a fruit salad and added an ingredient that stopped this reaction from occurring?

Background

Most chemical reactions which occur in living cells are catalyzed by enzymes. Without these naturally occurring biocatalysts, the rate of physiological reactions at physiological temperatures would be so slow that life as we know it could not exist.

We shall study the properties of one particular enzyme, *polyphenoloxidase* (PPO). This enzyme catalyzes the oxidation of catechol to produce benzoquinone and water.



This reaction is one which you have observed many times. Many plants contain catechol and PPO in their tissues. When these tissues are damaged (e.g., when you bite into an apple), the injured surface darkens. The dark areas contain polymers of benzoquinone. Benzoquinone has been shown to exhibit anti-fungal properties and hence is beneficial to the injured plant tissues.

This reaction has practical application for the food processing industry. Fruits and vegetables are processed in reduced oxygen conditions, such as in a SO_2 atmosphere, until the enzyme is broken down by heat processing. Therefore, processed foods do not show the unappetizing appearance caused by the polyphenoloxidase reaction.

Benzoquinone is a rust-brown colored compound, so its presence can be easily detected qualitatively. This property allows us to detect that the reaction has occurred by the development of a rust-brown color.

Experiment 1: Reference Reaction

Obtain three tubes and mark off three 1 cm increments on each. Each tube must be labeled with an appropriate symbol. Place 1 cm of potato extract (w/PPO) + 1 cm of catechol + 1 cm of distilled water in the first tube, 1 cm of potato extract (w/PPO) + 2 cm of distilled H_2O into the second tube, and 1 cm of catechol (1% solution) + 2 cm of distilled H_2O into the third tube.

Shake all tubes and place in a waterbath at 37°C for 10 minutes. Save the tubes to use for comparison with the results in the other experiments.

Prediction:

Which of the tubes in Experiment 1 do you think will show the color change that indicates that the reaction has occurred? Why?

Observations and Interpretation of Results:

- Construct a data table. At 0, 5 and 10 minute intervals note and record the color of the solution in each tube.
- What is the brown-colored substance in Tube A-1?
- From this experiment, what materials are necessary for the reaction to occur?
- Why were the tubes placed in a 37°C waterbath?

Experiment 2: The Chemical Composition of Polyphenoloxidase

In this experiment you will test the kind of chemical substance which makes up an enzyme such as polyphenoloxidase. To perform this test we will propose that an enzyme is composed of one of three types of chemicals: starch, protein or lipid (fat). All of these are polymers which can be hydrolyzed into their component parts. A hydrolysis reaction is one in which the larger molecule is broken down enzymatically by inserting water into the molecule, breaking it down into smaller molecules. The basis of this experiment is that if we treat the extract with a material known to break down a specific type of substance, we can deduce the chemical nature of polyphenoloxidase from the results. If the enzyme is broken down, it can no longer convert substrate to end product and no rust-brown color occurs. Alternatively, if the enzyme is not broken down, it will produce the end product and the rust-brown color will appear. We will use the following hydrolyzing enzymes: Bacterial protease hydrolyzes protein; Amylase hydrolyzes starch; Lipase hydrolyzes fat.

Mark four tubes into 3 intervals of 1 cm and label them. To each of the four tubes add 1 cm of potato extract (w/PPO). Then add the following: 1 cm of distilled water to the first tube; 1 cm bacterial protease solution to the second tube; 1 cm of amylase solution to the third tube; and 1 cm of lipase solution to the fourth tube.

Shake all tubes thoroughly and place them in a waterbath at 37°C. After 45 minutes, add 1 cm of catechol to each tube. Shake. Return the tubes to the waterbath for 10 additional minutes.

In the tubes in which polyphenoloxidase was not digested by the hydrolytic enzyme, benzoquinone and a rust-brown color will be formed when catechol is added. This would be a negative result. In the tube in which PPO was hydrolyzed, no benzoquinone will be formed and hence no color change will occur when catechol is added.

Predictions:

- If the enzyme polyphenoloxidase is a lipid, which hydrolytic enzyme will destroy it?
- If the enzyme PPO is a starch, which hydrolytic enzyme will destroy it?
- If PPO is a protein, which hydrolytic enzyme will destroy it?
- How will you tell if the PPO has been destroyed?

Observations and Interpretation of Results:

- Construct a data table and record your results.
- In which tube(s) was benzoquinone formed?

- In which tube(s) was benzoquinone not formed?
- What is the purpose of Tube B-1?
- From the observations in Experiment 2, what can you conclude about the chemical structure of polyphenoloxidase?

Experiment 3: Cofactors

Some enzymes require the presence of other molecules or ions to perform their function. These non-enzyme substances are called cofactors. In this experiment we will use phenylthiourea (PTU), which binds very strongly to divalent cations (ions with a plus-two charge such as copper, manganese, magnesium, ferrous iron, etc.), to remove any cation from the enzyme and, therefore, determine if a cofactor is needed for the catechol-PPO reaction.

Label two tubes and mark two intervals of 1 cm on each. To each tube (C-1 and C-2) add 1 cm of potato extract. Add a few crystals of PTU to the second tube. Shake both tubes thoroughly and frequently for 5 minutes. Add 1 cm of catechol solution to each tube and place them in a waterbath at 37°C for 10 minutes.

Predictions:

- If PPO requires a divalent cation (a positively charged ion with a +2 charge) to remain active, what effect do you think the PTU will have?
- What do you think is the function of a metal ion in the function of an enzyme?

Observations and Interpretation of Results:

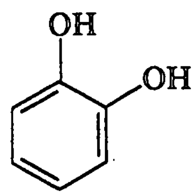
- Construct a data table and record your observations.
- What is the importance of tube C-1?
- What conclusion can you make concerning the necessity of a cofactor for polyphenoloxidase to function?
- Some cofactors are prosthetic, which means they form an integral part of the enzyme, while other cofactors are free and must simply be present in the medium. If the cofactor for PPO was copper, suggest a treatment you might perform to test if the PPO cofactor is prosthetic or free.

Experiment 4: Enzyme Specificity

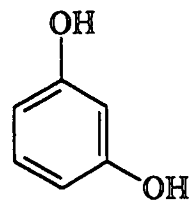
The current theory of enzyme activity states that an enzyme catalyzes a reaction by forming an enzyme-substrate complex. Formation of this complex is dependent upon the substrate fitting into the enzyme at a location called the "active site." Some enzymes are able to form complexes with several substrates which are of similar structure. An enzyme having this property is said to have "group specificity." Other enzymes are known to react with only one substrate and are said to exhibit "absolute specificity." The following experiment compares the ability of polyphenoloxidase to combine with three different but structurally related substrates: catechol, resorcinol, and hydroquinone.

Label three test tubes and add 1 cm of potato extract (w/PPO) to each. Add 1 cm of catechol to the first tube; add 1 cm of resorcinol to the second tube; and add 1 cm of hydroquinone to the third tube.

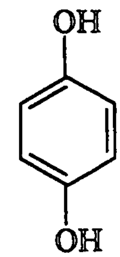
Shake the tubes gently. Place in waterbath at 37°C for 10 minutes.



Catechol



Resorcinol



Hydroquinone

Predictions:

- If PPO were group specific, which substrates do you predict would be most likely to serve as an alternate substrate?
- Explain your reasoning.

Observations and Interpretation of Results:

- Construct a data table and record any color change.
- With which substrate does polyphenoloxidase react best? Least?
- Does polyphenoloxidase exhibit absolute specificity, group specificity or something in between? Explain your reasoning.

Experiment 5: Effects of pH

Because the shape of the active site has important influences on the ability of an enzyme to form an enzyme-substrate complex, the pH of a solution often influences the ability of an enzyme to function. The hydrogen ion concentration in a solution is measured by the pH. Hydrogen ions (H^+), or alternatively hydroxyl ions (OH^-), affect the secondary (and to a much less extent the tertiary and quaternary) structure of enzymes by disrupting the hydrogen bonds which link the amino acids between different portions of the protein strand. This results in a change in the secondary structure and hence the shape of the active site.

Mark three tubes with three intervals of 1 cm. Label these tubes. Into each of the tubes add the following: 1 cm pH 2.0 buffer + 1 cm potato extract (w/PPO) to the first tube; 1 cm pH 7.0 buffer + 1 cm potato extract (w/PPO) to the second tube; and 1 cm pH 14.0 buffer + 1 cm potato extract (w/PPO) to the third tube.

Shake. Add 1 cm of catechol to each tube and shake again. Place in the 37°C waterbath for 10 minutes.

Prediction:

- The pH in the interior of a cell is near 7 (neutral). Knowing this, at which pH do you think the enzyme will function optimally?
- Explain your reasoning.

Observations and Interpretation of Results:

- Construct a data table and record your results. Rank the tubes from lightest to darkest as 1 to 3.
- Prepare a graph representing your results.
- Does pH affect polyphenoloxidase?
- Does pH slow the reaction or stop it altogether?

Experiment 6: Effect of Temperature

Temperature affects enzymatic reactions in several ways. During the reaction, temperature affects the kinetic energy of the molecules, which in turn affects the frequency of collisions between substrate and enzyme as well as the energy of activation for the reaction. In addition, enzymes are directly affected by temperature. If temperatures are not appropriate, the shape of the enzyme's active site may be changed. In some cases this change is permanent, and the enzyme is referred to as denatured. Denatured proteins usually appear as a white precipitate.

Mark four tubes with two intervals of 1 cm and label. Into each tube add 1 cm of potato extract. Place one tube into the following conditions for 5 minutes: ice bath (0°C); room temperature (20°C); 37°C water bath; boiling water (100°C).

After the 5 minutes add 1 cm of catechol to each tube and place back into the conditions above. Observe after an additional 5 and 10 minutes.

Predictions:

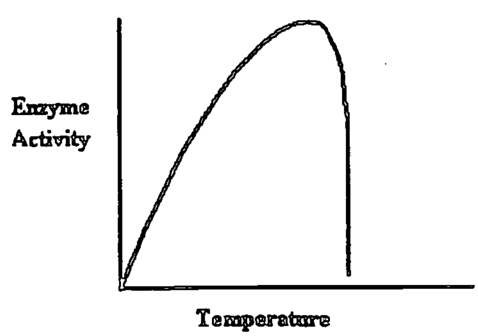
- Most living systems that we know about function best in the temperature range of 20–40°C. Knowing this, at what temperature do you think the enzyme will function optimally?
- From reading the paper on life above the boiling point of water, why do you think that the potato enzyme is most active at the temperature you have predicted?

Observations and Interpretation of Results:

- Construct a data table and record your observations.
- At which temperature did the most benzoquinone form? At which temperature did the least benzoquinone form?
- Did any temperature treatment denature the enzyme?

Concluding Questions

- Why do cooks sprinkle lemon juice on cut bananas which are used for decorations on top of cream pies? What is the mechanism of action of the lemon juice?
- Explain the effects of increasing temperature, shown in the graph below, on enzyme activity.



- Propose a mechanism for the effects of pH on enzyme activity.
- What determines with which substrate an enzyme will react?

THE AIR WE BREATHE: IS DILUTION THE SOLUTION TO POLLUTION?

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After participating in the Maryland Collaborative for Teacher Preparation for a year, I redesigned Chemistry 121, an introductory chemistry course for non-science majors, and taught it in the fall of 1994. Prior to joining MCTP, I had been a fairly traditional faculty member in a large, research-oriented chemistry department. I taught a wide range of courses, mostly for chemistry majors, and did research in analytical chemistry with my graduate students. I had always been interested in teaching—over the years I had developed several new courses and had engaged in some educational software development projects. However, I had never taught a non-science major course before my involvement in MCTP. Only the lecture portion of the course (CHEM 121) had been taught before; the laboratory portion (CHEM 122) had never had sufficient enrollment to be offered.

What's Different About This Course?

My redesigned CHEM 121/122 differed from previous courses in the following ways:

Course content. I "covered" less material than I probably would have, but I spent more time thinking about which concepts and topics were really important. We did use a textbook—"Chemistry in Context", which had just been published by the American Chemical Society specifically for non-science major courses (Schwartz et al., 1994). I liked this textbook's case-study approach, in which chemical principles are imbedded within, and arise naturally from, a consideration of major societal issues such as global warming, destruction of the ozone layer, energy, human nutrition, and health. I based some of the course activities on that text, but I also developed a number of hands-on activities of my own. It should be no surprise that we were not able to cover the entire book.

Course structure. I scheduled three two-hour class meetings per week rather than the usual three one-hour lectures and three-hour lab schedule. This structure allowed for greater flexibility—depending on the topic and the students' progress, sometimes we would meet for several consecutive class periods in the laboratory, the computer lab or the regular classroom.

Teaching methods. I did not lecture; rather, most class time was devoted to small-group cooperative activities. Students worked with information sources, data, observations, hands-on manipulatives, computer-based activities, or laboratory experiments, interspersed with small-group and whole-class discussion.

Use of technology. I had previously used computers in my upper-division and graduate-level teaching, but not in the first-year courses. In the redesigned CHEM 121, I introduced spreadsheets early on as an approach to complex, multi-step, quantitative problem solving and graphical data display. I also introduced software for organic chemistry nomenclature and molecular modeling to help develop the students' ability to visualize and work with bonding and three-dimensional structures. When I taught the course again in 1996, I integrated the use of the World Wide Web into two of the experiments.

Assessment. Grades were based primarily on written assignments, experiments, and exams. The exams used an essay and word problem format rather than multiple-choice. In the last formal activity of the course, I asked student groups to list the most important concepts and skills they developed in the course, and to compose several test questions—including one "performance assessment"—to assess mastery of those skills and concepts. I promised them that I'd use the best questions on the final examination.

Instructor's Course Journal. For the first time, I kept a course journal that recorded my daily class activities, difficulties, student reactions, and things that did and did not work. I composed my journal on a word processor and distributed it via e-mail to the MCTP listserv for scrutiny and comment by the whole Collaborative. The feedback from my colleagues in the Collaborative made me feel less alone in this enterprise and provided many helpful tips.

Themes and Big Ideas

Most of the instructional units and activities in this course were centered around two main themes or "big ideas":

1. The observable *macroscopic* behavior of substances is determined by their unseen *microscopic* structure and behavior.

Activities that supported this theme were entitled:

- Temperature and Molecular Motion
- Explaining Cold Boiling and Other Puzzling Observations
- Counting Bonds and Calories: A Molecular View of Reaction Energy
- Chemical Reactions and Energy
- Does a Gas Have Mass?
- pH Balanced: The Meaning of pH

2. Atoms and molecules are far too small to be seen, handled, weighed, and counted individually, so scientists have devised a number of models and methodologies that overcome this "inconvenient fact."

Activities that supported this theme were entitled:

- Counting by Weighing: Bead Jewelry Construction as a Metaphor for Chemical Stoichiometry
- Visualizing Molecules with Computers
- The Structure of Simple Carbon Compounds
- Drugs and Molecular Symmetry
- Molecular Modeling with "Ball-and-Stick" Model Kits
- The Air We Breathe: Is Dilution the Solution to Pollution? (described in this paper)

Additional units were not related specifically to either of these themes; these include: "Problem Solving with Spreadsheets"(also described in this paper), "Chemical Information Scavenger Hunt on the Internet," and "A Penny for Your Thoughts."

The student handouts for all of these activities are available on the World Wide Web; go to http://www.wam.umd.edu/~toh and click on *Chem 121: Introductory Chemistry Course for Non-Science Majors.* The exams, quizzes, and instructor's daily course log are also included on this Web site.

Caesar's Last Breath: Modeling the Unimaginable

In developing the unit, "The Air We Breathe: Is Dilution the Solution to Pollution?," I was guided by the *AAAS Benchmarks for Science Literacy* (AAAS, 1993). In particular, I found guidance in the benchmarks for "Physical Setting" ("The Earth," p. 66; "The Structure of Matter," p. 75), "Habits of Mind" ("Computation and Estimation," p. 288; "Manipulation and Observation," p. 292), and others related to ratio and proportion, scale, solid geometry, and multi-step problem solving. The benchmarks aligned well with the text's first chapter on air pollution, which was the springboard for this unit. (See Appendix A for student handout.)

In this unit, the students interpret published air pollution data, compare local vehicle emission standards to national air pollution standards (using actual Maryland Vehicle Test Reports that I provided), and attempt to draw a scale model of the Earth and its atmosphere. In trying to draw the scale models, students find, to their surprise, that the task is virtually impossible, because most of the atmosphere lies in a layer that is only $1/100$th of the radius of the Earth. After attempting this, they have a better grasp of why the drawings of the Earth and its atmosphere in their textbook are not to scale.

This paper describes the last activity in this unit. It relates to a question raised in the text about whether the atmosphere is large enough that toxic pollutant emissions would simply be "diluted away to virtually nothing" by mixing with the atmosphere. The textbook asks this rhetorical question: "Is it possible that we are breathing air that was once breathed by famous historical people: Julius Caesar's last breath, for example?" The textbook did not actually answer this question, but it greatly interested the students and generated a good deal of discussion in class.

I decided to challenge the class to consider a related but simpler question: "If I took one liter (about one deep breath) of an inert gas and released it into the outside air, then waited until it completely mixed with the entire atmosphere of the Earth, what would be the average number of molecules of that substance that I would breathe in each breath?" All of the students felt intuitively that the volume of the atmosphere must certainly be so large that a single liter of air would be "negligible" in comparison, so that we are not likely to be breathing air once breathed by Julius Caesar—much less the air in his last breath.

I myself had no idea initially how this might play out numerically, but I was confident that, if nothing else, the *process* of answering this question would draw together aspects of science, math, and technology in a rewarding manner. In essence we were all *curious* about this question—and curiosity is one of the important driving forces in science and mathematics that is often neglected.

Because an actual physical experiment is clearly out of the question, we sought to develop a mathematical model that would give us at least an approximate answer to this question. This computation has three challenging aspects: First, it is a multi-step computation; second, it involves some rough order-of-magnitude estimations of several quantities; and third, it involves very large numbers.

I asked the students to map out a strategy for estimation. During one class period, the following questions arose for discussion: What information would we need? What is the volume of one breath? How many molecules of gas are in a given volume of air (e.g., one liter)? How could we estimate the total volume of the atmosphere in liters? What assumptions are reasonable? Can we model the Earth as a sphere and the atmosphere as a spherical shell? What is the volume of a spherical shell (the difference between volumes of two spheres)? What is the formula for the volume of a sphere? How can we estimate the thickness of the atmosphere? How can we take into account the fact that the atmosphere gradually "thins out" with increasing altitude rather than ending abruptly?

In essence we were all curious about this question—and curiosity is one of the important driving forces in science and mathematics that is often neglected.

Some of this information could be looked up, such as the radius of the Earth, the number of molecules in a liter under normal atmospheric conditions, and plots of air pressure versus altitude. But it soon became clear that the computations themselves would be challenging and the students would need more guidance. Nevertheless, they were very interested in an actual numerical answer.

A Spreadsheet Solution

Accordingly, we tackled the actual numerical computation during the unit we started in the next class period, which happened to be, "Problem Solving with Spreadsheets" (see Appendix B for student handout). The use of spreadsheets is specifically recommended in the AAAS benchmarks (AAAS, 1993, p. 291). As luck would have it, I had scheduled the computer lab for this exact time in the semester, which enabled the students to pursue the "pollution dilution" question while it was fresh in their minds.

It turned out that most of the students had *used* spreadsheets before, but none had *constructed* their own spreadsheets. During this two-day spreadsheet unit, the students developed this skill by constructing and testing a series of small spreadsheets to solve practical numerical problems, starting with very simple unit conversion problems and progressing gradually to more complex constructions involving volume and concentration. We decided that the culminating activity would be to develop a spreadsheet to solve the "pollution dilution" problem stated above.

> *. . . we were all amazed at the result, which seemed counter-intuitive to everyone, including myself.*

This calculation really came down to a comparison of two unimaginably large numbers: the volume of the Earth's atmosphere (in liters) versus the number of molecules of gas in one liter. From our earlier discussions, students realized that the latter is a "standard" chemistry textbook number and could be looked up or calculated; it happens to be 2×10^{22} at normal atmospheric pressure and temperature. They also knew that the volume of the atmosphere could be estimated by subtracting the volume of the Earth from the volume of the Earth plus its atmosphere.

Estimating the volume of the Earth from its radius (6300 km) was not difficult for most of the students. But to derive the combined volume of the Earth and its atmosphere, they needed to have a value for the thickness of the atmosphere. That was the hard part, because the atmosphere thins out gradually with increasing altitude. I suggested that treating the atmosphere as a homogeneous layer with a discrete cut-off height would be an acceptable approximation for our purposes. I encouraged them to choose their own value for the thickness, based on an inspection of a graph of air pressure versus altitude found in their textbook (Schwartz et al., 1994, p. 6). Most students chose values around 4 to 8 km, where the air pressure is about half of its ground-level value. Different final answers would be expected, therefore, depending on the choice of this value.

As the students worked their computations using the spreadsheets, a few got bogged down in the early stages and some were unable to complete the final solution. Several of them, however, not only finished, but arrived at answers that substantially agreed. Four students determined that, on the average, there would be about 8 molecules of the original gas per liter of atmosphere, so the probability of breathing at least one molecule of the gas per breath is excellent. (They estimated the volume of the atmosphere to be 2.5×10^{21} liters, and found that the ratio of 2×10^{22} molecules to 2.5×10^{21} liters is 8 molecules/liter.) Thus, we could literally be breathing some of the molecules in Caesar's last breath! During a discussion of the results on the next day of class, we were all amazed at the result, which seemed counter-intuitive to everyone, including myself.

These spreadsheet activities were challenging assignments for these students, many of whom struggled with logic, basic math, ratio and proportion, and unit conversions. It was too much for one student, who objected to the use of mathematics in a chemistry course. Another student confided that she never thought she would ever be able to "program" a computer to solve such "hard" problems. I pointed out that it was really *she* who had solved those problems, using the computer as a tool.

Later, in class, I asked the students if they felt that the use of a spreadsheet was helpful, harmful, or made no difference in working out complex multi-step "statement problems" such as the atmospheric dilution problem. Students unanimously agreed that the use of a spreadsheet was helpful. They volunteered with the following three advantages: Use of a spreadsheet reduces arithmetic errors; allows the variables to be changed to see what effect they have; and makes the problems clearer by virtue of the *spatial layout* of the numbers on the page, with cells and columns clearly labeled. I felt that this last aspect was particularly interesting and was not one that I had recognized explicitly.

Course Changes and Student Performance

This course differed substantially from the usual freshman chemistry course (taken mainly by science majors) that I had taught in the past, in that:

- This class was much smaller, with only 10 students as opposed to perhaps 200 in a typical general chemistry lecture.
- Less material was "covered," and the topics that were covered were different—typically more practical and less theoretical.
- There was less emphasis on solving the standard chemistry word problems that are considered by most chemistry faculty to be the "meat" of general chemistry. More emphasis was placed on conceptual understanding rather than numerical computation of correct answers.
- The instructional approaches were much more varied, and there was much more class participation and discussion than in the standard lecture-discussion-laboratory model.

As to the effect of those changes on the content knowledge of the students, I found, based on an analysis of student answers on the final examination, that the students did very well on questions that were essentially conceptual and spacial/visualization oriented. For example, all students answered correctly a performance assessment question on the final exam that asked them to use kits to construct molecular models that met certain structural and symmetry requirements.

Students also did very well on complex, non-quantitative, cause-and-effect relationships; they scored an aggregate 98% in explaining how the unabated large-scale use of chlorofluorocarbons in refrigeration units and aerosol can propellants would be expected to result in an increase in the incidence of skin cancer. They performed adequately on questions that involved visualizing quantitative relationships; they scored an aggregate 84% on a question that required them to explain why equal weights of two different compounds might have different numbers of molecules.

In contrast, they did less well on complex, multi-step word problems. This is to be expected, as even science majors typically have difficulty with those types of problems, even when they get lots of practice learning algorithmic solution methods. However, the kinds of knowledge and skills that the MCTP students have demonstrated are much more aligned with the AAAS benchmarks and therefore more likely to serve them well in their future teaching jobs.

Student Reflections

At various points throughout the course, I asked the students to reflect on their learning by having them write responses to questions such as: "Describe something that you have learned in this course that was somewhat of a surprise to you, that is, something that you didn't expect," and "Describe one scientific concept or idea that you have learned in this course that changed one of your previously-held concepts or ideas about science or chemistry." Several students mentioned the environmental chemistry topics that we had covered, including the "pollution dilution" problem and the spreadsheet tool that allowed us to obtain an estimated answer:

> *[It] surprised me to know that there are so many liters in our atmosphere yet we exhale so many molecules that our breath can fill every liter of air with 8 molecules!*
>
> ∞∞∞
>
> *I . . . didn't know that if only one liter of a toxic substance was released into the whole*

atmosphere, it was likely that I would be breathing it. . . . I always thought that 1 liter was nothing compared to the atmosphere.

[I was surprised by] the use of computers in relationship to chemistry, specifically, the spreadsheets. I always thought those were for . . . business and statistics.

. . . it has been rewarding to watch students working together, actually talking about science and chemistry rather than about grades, points, right and wrong answers, requirements, course policy, and the like.

In some of their comments, evidence of *conceptual change* is clear:

I had previously had the idea that an electron was similar to a moon orbiting a planet. This image restricted me from understanding, in a visual way (which is necessary for me to understand most things), the way atoms are said to share electrons. The fact that electrons can be thought of as clouds or shells helps me tremendously in visualizing chemical bonds.

I always thought that environmentalists were people who loved nature and had a lot of time on their hands. Now I see why they made such a big deal about the destruction of the ozone. I also found it fascinating how the layer of ozone is created.

Some of the students' comments were more general, reflecting the overall approach and the choice of topics:

I was kind of surprised when this course started off with environmental chemistry issues. (But I was happily surprised.)

. . . this class relates chemistry to real life, which makes it far more interesting to the layperson.

I [learned that] chemistry is useful or even fits in with everyday life such as about the chemical spills, gasoline, pollution, and how it affects us, the ozone layer and how it is being destroyed.

Some of the students' comments admitted their surprise that doing science activities might actually be fun:

What I DID expect was to learn about bonding, atoms, elements, and typical chemistry stuff, but what I DIDN'T expect was to learn about them in fun ways.

I didn't think the course would be so much fun! Chemistry is generally not my forte.

Instructor's Reflections

While the easiest aspect of teaching this new course was its interesting content, the most challenging aspect was the time and effort it took to develop new instructional materials for that content, and to set up a laboratory program from "scratch." In the "regular" general chemistry course, the laboratory program is designed by a separate faculty laboratory director and implemented by a staff of several stockroom employees who order equipment and chemicals, stock the laboratories, and so on. None of these services was available to me.

In a standard chemistry class, however, I would never have had the luxury of following the students' curiosity, and my own, into unknown territory. The new format gave me that opportunity, and it was a very satisfying experience. In addition, it has been rewarding to watch students working together, actually talking about science and chemistry rather than about grades, points, right and wrong answers, requirements, course policy, and the like.

In my regular chemistry classes, I have always made extensive use of hands-on laboratory experiments, which are generally done in small groups because of equipment limitations. Having seen the benefits of cooperative learning in this new course, however, I now have another justification for small-group work in the labs of my standard courses. Also, I now attempt to make my laboratory activities a little more "discovery" oriented wherever possible and to de-emphasize the "verification" aspects of experiments.

My MCTP experience has prompted me to undertake a little educational "research" of my own. For my lecture-only classes, I created a set of theory-based interactive computer simulations that I use for homework assignments. These simulations give students hands-on, "experiment-like" activities, complete with goal-driven questions and open-ended explorations. I have evaluated the student responses to those simulations and have now compiled a considerable amount of evidence over the last several years that these kinds of simulations drive students to think more deeply, and to uncover and confront misunderstandings.

Another area of personal change is that I am now more willing to allow students to work things out for themselves, especially when they are working in groups, even if they seem to be struggling. In the past, I would have stepped in sooner to "help." Now I will keep my distance and let them thrash it out. I am even beginning to answer questions with other questions rather than with answers.

References

American Association for the Advancement of Science. (1993). *Benchmarks for Science Literacy.* New York: Oxford University Press.

Schwartz, A.T., Bunce, D.M., Silberman, R.G., Stanitski, C.L., Stratton, W.J., and Zipp, A.P. (1994). *Chemistry in Context: Applying Chemistry to Society.* Dubuque, IA: Wm. C. Brown.

Appendix A

CHAPTER 1: THE AIR WE BREATHE

This is not a quiz, but rather a class exercise. The papers will be collected and graded. You may talk to your classmates, but you must *write your own individual answers* to each question.

1. List the air pollutants that are discussed in Chapter 1 (give the names or chemical formulas).
2. Of the air pollutants listed on page 8 of the textbook, which do you think is the most hazardous?
3. On the basis of the data on page 15:
   a. Would you say that air pollution has been getting better or worse since 1975?
   b. Which air pollutant has had the largest change since 1975?
   c. What do you think is the largest source of this pollutant?
   d. Why do you think this pollutant has decreased so much since 1975?
   e. Why were lead compounds (e.g. tetraethyl lead) added to most gasoline that was sold before 1975?
   f. Why do you think that the gasoline companies were able to "get away" with adding lead—a substance that has been known to be toxic for many years? In other words, why was there not a public outcry from the very beginning?
4. Some copies of recent Maryland Vehicle Emission Test Reports are being circulated around the class.
   a. Look at these and list the pollutants that are measured here (HC = hydrocarbons).
   b. Convert the test reading for carbon monoxide (CO) on the test ticket from percent (PCT = percent) to PPM (parts per million).
   c. How does the test reading for CO compare to the permissible limit for CO listed on page 8 of the textbook?
   d. How can the car pass the test when the CO emission is so much greater than the permissible limit?
5. Look at the textbook drawings of the Earth and its atmosphere on pages 54 and 64 of the textbook. Using the data in the textbook, draw a scale model of the Earth and the atmosphere on the back of this paper, representing the Earth as a large circle and the atmosphere as an enclosing concentric circle. Rulers and compasses are available for your use. Based only on your experience, what can you say about the accuracy of the scale of the drawings on pages 54 and 64?
6. Consider the following hypothetical experiment. Suppose you were to take one liter of a toxic but otherwise stable gas and release it into the outside air and wait until it is completely mixed with the entire atmosphere of the Earth. What would be the concentration of the substance expressed in ppm by volume?
   a. Without actually performing this calculation, what other piece of information would you have to know to obtain the solution of this problem?

b. What is the probability that one molecule of that substance would be found in one breath of air? How many molecules of that substance would I breathe in each breath of air for the rest of my life? How can the concentration expressed in ppm seem so low but the number of molecules in a breath seem so large? Do they not express the same concentration? On the basis of this result, comment on the reasonableness of achieving truly zero levels of toxic molecules such as carbon monoxide.

Appendix B–Part 1

OVERVIEW OF BASIC SPREADSHEET OPERATIONS

ClarisWorks is an integrated, multi-purpose program that contains an easy-to-use spreadsheet.

A. To launch the ClarisWorks spreadsheet program, click on the **ClarisWorks** button on the main menu screen, then click on the **Spreadsheet** button.

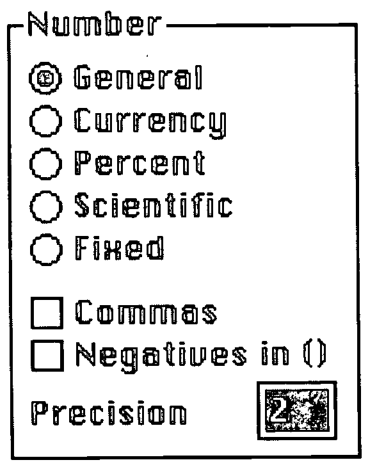
B. To enter a label or a number into a cell, click on the cell, type, and press the enter key.

C. To move to another cell, either click on the new cell or use the cursor (arrow) keys to move.

D. To edit a cell, click on it, make the changes in the "entry box" at the top of the window, then press the enter key.

E. To enter an equation into a cell, click on the cell, type an = sign followed by the desired equation, and press the enter key. When typing equations, use * for multiplication, / for division, + and – for addition and subtraction, ^ for exponents (e.g. ^3 means to raise to the third power). The values of other cells are referred to by location (A1, B12, etc.). Use pi( ) for the value of π. Example: if the radius of a sphere is contained in cell B7, then the equation for the volume of that sphere is "=(4/3)*pi( )*B7^3." Don't forget to press enter when you are finished entering or editing an equation.

F. You may optionally change the way a number is displayed in a cell by double-clicking on it. This brings up the dialog box shown in part here. Click on desired buttons and then click on the **OK** button to return to the spreadsheet.



You may also use the **Format** pull-down menu to change the **Font, Size, Style, Text Color,** and **Alignment** of the contents of a cell, just like in a word processor.

G. To save a spreadsheet on your floppy disk, select **Save** from the **File** pull-down menu, insert your floppy disk into the disk drive, type a file name, and press return.

H. To print a spreadsheet, select **Print . . .** from the **File** pull-down menu and press return.

I. To get more help, select **ClarisWorks Help** from the menu.

Appendix B–Part 2

SPREADSHEET CONSTRUCTION EXERCISE

In each of the following spreadsheet layouts, <INPUT> marks the cells into which you are to type the numeric inputs (variables) and the blank cells are calculated cells that contain the equations referring to the input cells. *Write your cell equations in the blank cells on this paper.*

A. Construct a simple spreadsheet that converts distances entered in kilometers into meters and centimeters. 1 kilometer = 1000 meters; 1 meter = 100 centimeters. Suggested layout:

<INPUT>	kilometers (km)
	meters (m)
	centimeters (cm)

Use your spreadsheet to compute the radius of the Earth (6300 km) in meters: ____________ and in centimeters: ____________________

B. Construct a spreadsheet that performs the calculations needed to draw a scale drawing of the Earth and its atmosphere, given the actual radius of the Earth (6300 km), the thickness of the atmosphere (6 km estimate), and the radius in inches of the Earth in the scale drawing. Suggested layout:

Radius	Thickness	
<INPUT>	<INPUT>	kilometers
<INPUT>		inches

Use your spreadsheet to compute the thickness, in inches, of the atmosphere in a scale drawing that has a radius of 5 inches: ____________

C. Construct a spreadsheet that performs calculations related to car travel, taking the first four items in the table below as givens and computing the last three.

Distance, miles	<INPUT>
Speed, miles/hour	<INPUT>
Mileage, miles/gallon	<INPUT>
Price of gas, $/gallon	<INPUT>
Time required, hours	
Fuel used, gallons	
Cost of trip, dollars	

If you drove 1000 miles at a steady 55 miles/hour, in a car that gets 20 miles/gallon, when gas costs $1.20/gallon, how long would it take?__________How many gallons of gas would you use?________ And how much would you spend on gas?__________

D. Construct a spreadsheet equation that computes the number of molecules of an air pollutant per liter, given the concentration of the pollutant in parts per million (ppm). Any gas contains a total of 2×10^{22} molecules per liter at atmospheric pressure. Given that the permissible concentration of sulfur dioxide according to the 1991 EPA standards is 0.03 ppm, how many molecules of sulfur dioxide would there be in one liter of air at this concentration? __________
(Hint: 1,000,000 ppm = 100% = 2×10^{22} molecules per liter.)

E. Construct a spreadsheet that computes the number of liters (1 liter = 1000 cm^3) of air in a rectangular room of a given height, width, and length in feet (1 inch = 2.54 cm). Compute the volume of a 12' × 10' × 8' room: __________ Suggested layout:

	Length	Width	Height	Volume	
Feet	<INPUT>	<INPUT>	<INPUT>		
Inches					
Centimeters					Cubic cm
					Liters

F. Construct a spreadsheet that computes the volume in liters of the atmosphere of the Earth, assuming that the Earth is a sphere with a radius of 6300 km and that the atmosphere is 5 km thick. Suggested layout:

	Radius of the Earth	Thickness of atmosphere	Radius of Earth + atmosphere	Volume of atmosphere
kilometers	<INPUT>	<INPUT>		
meters				
centimeters				
volume, cm^3				
volume, liters				

Suppose that you used a value of 10 km for the thickness of the atmosphere. How would this affect the calculated volume of the atmosphere?

G. Expand the above spreadsheet to solve the following problem: Suppose that one liter of a stable gas X is released into the outside air and completely mixed with the entire atmosphere of the Earth. What would be the concentration in molecules per liter of X in the atmosphere after mixing? (Any gas contains a total of 2×10^{22} molecules per liter at atmospheric pressure.)

CONSTRUCTING THE STREAM COMMUNITY: THE ECOLOGY OF FLOWING WATERS

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"An individual can and cannot step into the same river twice"
—(Heraclitus)

In restructuring our introductory biology course, we wanted to set a stage for our students that was not based upon dogma, sterile content, or rigid process, but rather on the changing nature of systems so well exemplified by the "stream." As implied by the quotation by Heraclitus above, nothing stays the same; the passage of time brings change. The stream community, a prime setting for observing the effects of time on a system, became a symbol of change for our course as well as its central theme. During the course we changed both processes and pedagogy to meet the needs of students at various points in time. We were not fixed to a set schedule and felt the need to be free to adapt to any learning situation.

Context and Goals

We first taught the MCTP course "Principles of Biology" in the fall semester of 1995. Our course was an "Honors Section" with 24 students who were screened to be a part of the honors program; three of them were preparing to become teachers.

Prior to our MCTP section, this foundation course had been taught in a traditional lecture/laboratory format. Most of the labs in the traditional section were hands-on, but not constructivist-based. Students were given background information and explicit instructions on how to perform procedures; this was followed by discussions of results. Students were asked to do very little connecting and integrating of knowledge they had gained. Content was more important than process.

Our major goal for the course was to restructure the way in which students (and instructors) assemble, learn and evaluate biological principles. Based on our study of constructivist principles, we drastically changed the course design. We agreed that instead of just learning biological principles in an isolated format, students might better master the concepts if they could tag biological principles onto real life experiences. We also decided to vary from traditional lecture/lab courses by ensuring that students observed phenomena and engaged in activities *before* formally studying biological principles. By reversing the order of exposure for students, we hoped that the laboratory would become more than just a "look—see—I told you so" experience. (In fact it did; it actually became a place for discovery.) Here is an overview of the changes we made:

- The course followed a central theme or strand, "The Stream Community."
- The course was team-taught, with both professors present in the classroom most of the time.
- The biological principles examined in the course were integrated with underlying mathematics and physics concepts.
- The course was inquiry-based: Introduction of concepts often began with observing

phenomena, experimenting, and collecting data, rather than through lectures.

- Technology was integrated into course activities, with students using computer spreadsheets, graphing software, and computer statistical evaluation.
- Preconceptions and misconceptions of students were identified and sometimes became the starting point for classroom activities.
- Questioning and question development was central to student-teacher interactions. Great care was taken to develop questioning techniques.
- Cooperative learning was supported from the beginning of the course and was recognized by both students and instructors as a powerful learning tool.
- Literature and writing reinforced the learning of biological concepts. Relevant research articles were assigned for reading, and both professors and students kept journals.
- Words like *predicting, hypothesizing, analyzing,* and *classifying* became a part of our daily routine. Students sometimes wondered if the instructors were ever going to answer one of their questions directly.
- The instructors had to "buy in" to the idea that "less is more" from a learning/instructional standpoint. Nevertheless, many of the principles that would be found in an introductory biology text were included.

In adopting the less is more principle, we devised three main themes for the course: Energy in Biological Systems, Evolution, and the Stream Community. Concepts related to the first theme, energy in biological systems, were constructed and reinforced through a variety of activities on surface area-to-volume ratios, photosynthesis, metabolism, and organism adaptations to thermal loss. For our evolution theme, we engaged students in plant genetics and population dynamics activities, and added a zoo field trip, after which students were able to construct models for vertebrate limb evolution. This case report focuses on our third and central theme, that of "The Stream Community."

Exploring the Stream: New Depths of Understanding

In keeping with our goal to help students tag principles of biology onto real life experiences, we began the course with a field trip to a stream in southern Pennsylvania. There, our group of inner-city students got what was, for most of them, their first chance to observe numerous parameters of a stream ecosystem. They collected data on both living and non-living stream features, which became the focus for later units on the following topics:

- water and its properties;
- pH and the effects of acid rain and mine waste on ecosystems;
- classification and the use of simple dichotomous keys;
- photosynthesis and primary production in the stream; and
- construction of food webs and pyramids of biomass.

The student handout to follow outlines our expectations for this activity.

CONSTRUCTING THE STREAM COMMUNITY: THE ECOLOGY OF FLOWING WATERS

Introduction

The ever-changing nature of streams makes them interesting communities to study. Because the water is flowing, the condition of a stream one minute is not exactly the same as in another minute.

Streams are divided into two major sections—riffles and pools—which usually alternate down a stream. The nature of each is determined by flow rate. Water flow also plays a major role in the kinds of adaptations made by the aquatic life found in the stream.

The stream is also a unique community due to the nature of its energy flow. Where does all the energy come from to support such an abundance of life? In most ecosystems the driving energy comes from within the system, from photosynthesis by plants. By contrast, the stream community gains much of its energy from external plant material that falls into the stream.

A stream's measurable physical parameters—such as pH, flow rate, and dissolved oxygen—are of great importance in determining its health, that is, its ability to support plant and animal life. For most organisms in the stream to thrive, these parameters must stay within very narrow ranges. In addition, the adverse effects of pollution often work against the health of a stream.

In this unit you will measure physical factors and observe stream organisms prior to your formal investigation of this community. You will be asked to arrange the organisms in the community by assembling a food web and a pyramid of energy. You will be further asked to predict the effect of acid rain, one changing parameter, on the community. This activity will be accomplished early in the semester and references will be made to it throughout the remainder of the course. Math and chemistry concepts, along with classification skills, will be integrated into this unit.

In today's study we will measure and observe a stream, looking in particular at the organisms there. We will also try to determine if the stream is healthy or polluted. So let's get started observing our stream. Remember to wear some real old shoes or sneakers because to do our work we will have to wade in some very rocky, shallow water.

The Riffles

The riffles of a stream are waters that move very rapidly (50 cm/second or faster), have a high oxygen concentration (at least 10mg/L) and a good pH value (above 7), and contain organisms like caddisflies, mayflies and stone flies. Trout and other stream fishes are also found in riffles.

With your instructors' help you should:

1. Measure the speed of the stream using the meter stick, watch and cork. Record your data.
2. Using a kick seine or by picking up rocks, collect as many aquatic insects as possible and identify them using the attached keys. Record your data.
3. Using the pH kit, measure the pH of your riffles. Record your data.
4. Using the thermometer, measure the temperature of your riffles. Record your data.
5. Using the dissolved oxygen kit, measure the dissolved oxygen level of the riffles. Record your data.

The Pool

The pool is much quieter than the riffles. Water in pools moves more slowly, is cloudier, has lower oxygen levels, and contains a much different group of organisms. Some of the organisms you will find in pools will be trout, bass, crayfish, leeches and plankton.

With your instructors' help you should:

1. Measure the speed of the stream using the meter stick, watch and cork. Record your data.
2. Help your leader use the drag seine to collect and identify as many organisms as possible. Record your data.
3. Use the pH kit to measure the pH of your pool. Record your data.
4. Use the thermometer to measure the temperature of your pool. Record your data.
5. Use the dissolved oxygen kit to measure the dissolved oxygen level of the riffles. Record your data.

We believed that the stream experience would be an interesting one for our students, but both of us were surprised by the amount of excitement and energy generated by this field trip. Even before we got to the site, the students were showing signs of both expectation and trepidation. Many of the students had not ventured far from Baltimore City previously and were at first hesitant to wade into the stream. After some bold students proceeded, all eventually got caught up in the excitement and were soon collecting data and organisms. The site itself was a quiet, wooded area reached through winding dirt roads, and students remarked later of the beauty of the countryside.

Comments excerpted from student and faculty journals illustrate how the stream environment was initially a little intimidating for an urban student, and how it also served to facilitate the "bonding" of classmates.

> *The thing that I am beginning to enjoy about our class is that we are learning while at the same time being occupied with fun and interesting activities. . . . We went to a stream near Professor Hooe's house in Pennsylvania today. I never could have thought I would have enjoyed myself so much. We split into groups and collected data on velocity, temperature, oxygen and pH and we sampled specimens from the riffles and pools. I think that our class bonded on this trip. . . . Although at times during the course I have felt discouraged because what's expected of us was a little ambiguous, I am very happy that I am in the program.*
>
> (David, 9/21/95)

∞∞∞

> *Well, we are back from the stream field activity and we had no casualties. We assembled at 8:00 a.m. and were back by 12:20 p.m. Quite a task since we drove all the way to Pennsylvania, did the stream in about an hour and a half and were back for other classes and the honors reception in the afternoon. The field experience went well and they made a great number of observations of biotic and physical components of the stream. The students were hesitant at first to immerse themselves into the stream but after a few minutes they were busy exploring the community.*
>
> (Professor Hooe, 9/21/95)

∞∞∞

> *Most of the students were quick to wade right into the stream and several exclaimed with delight as they experienced a stream for the first time. Several students were very tentative and held back until fellow students*

chided them to join in. As the students began to feel more comfortable in the stream they began to venture further, collecting organisms from the different riffles and pools and taking pride in the number and variety of organisms found.

When we left the stream for the drive back to school, the students were still talking about the experience. They were actively generating ideas about how to determine if the stream was healthy. We were delighted by the experience and plan to use examples from the stream throughout the rest of the course.

(Professor Settel, 9/21/95)

Reflection on the Course as a Whole

We have spent many hours assessing the course and specific units. Below we share some of our feelings both of success and of possible failure.

We tried a new class format—a three-hour period, twice a week. At the onset we were afraid that the period would be too long, but we have found it to be just the opposite. It allowed us to vary the activities and to complete some activities that demanded the time. Students surprised us by spending more than the three-hour period engaged in class activities. Having the time, then planning and using it wisely, was essential.

We realized early on that we were not going to be able to cover all of the content that we had originally planned. Modifying our course outline, mid-stream, allowed us to select what we could reasonably do and still give the students experiences that we felt would be valuable in their construction of the concepts. We came to the realization that simply "covering" more material does not improve student learning. Instead, we adopted the "less is more" concept, which is hard for many professors to accept. But we believe that when assessments show that students really aren't learning effectively when you just "cover" the information, then you must search for new ways to facilitate student understanding.

One part of the teaching-learning process that still poses the greatest problem for us is the students' ability to apply constructed concepts to new problems or situations. For example, in our units on "Percent Composition of Living Cells" and "Surface-Area-to-Volume Ratios and Energetics," students were able to manipulate the math to solve the biological problems. But when we asked them to apply these skills and knowledge to a new situation, only about one-third of the class could reasonably do so. We plan in the next semester to do some initial assessment of developmental level, math proficiency and biological conception of students. We especially want to monitor concept accuracy, concept development and misconception of students through more extensive writing exercises in the course.

We came to the realization that simply "covering" more material does not improve student learning. Instead, we adopted the "less is more" concept, which is hard for many professors to accept.

An area of student concern that surfaced early on was their frustration with the fact that we did not answer all of their questions, and when we did, it was usually with another question. They eventually caught on to this inquiry-based approach, and they saw that we were trying to lead them to an answer instead of giving them the answer. They also began to use one another as resources, which really supported collaborative learning in the course.

We plan to change several other aspects of the course for the second offering, based upon observations that we made from the first course:

- We are changing how we use the journal as a device to give us student feedback about the course. We will probably be a little more structured in what we ask students to document in their journals.
- We are adding more structure and organization to the course to allow us to better manage it. This does not mean that we

are going away from the constructivist approach.

- We are going to devise new techniques to engage students with their preconceptions, misconceptions, and final conception of the topics covered. For example, we plan to have the students write their preconceptions and revisit them periodically, so that they confront the old concepts with the new.
- Team instructors are going to meet prior to every class to review strategy and pedagogy.
- We are going to respond to student requests for some closure at the end of units and some sort of a "big picture" review.
- We are changing the grading policy to include quizzes spaced at shorter intervals in the course.

Some final thoughts: We are committed to making student learning and assessment the driving forces for what we do as professors. Indeed, we will not spew information at students; we will continue to search for new and different ways to facilitate student learning. This will mean continuing to change pedagogy mid-stream to find alternative ways to assist students in their learning.

References

Eddy, S. & Hodson, A.C. (1970). *Taxonomic Keys To the Common Animals of the North Central States.* Minneapolis, MN: Burgess Publishing.

Maryland Save Our Streams. (1975). Key to stream dwelling macro-invertebrates. (exerpted from Aquatic and Stream Sampling Kit). Severn, MD: Author.

Odum, E.P. (1971). *Fundamentals of Ecology.* Philadelphia: W. B. Saunders.

Pennsylvania Game Commission. (1969). *Pennsylvania Fishes.* [Brochure]. Harrisburg, PA: Author.

Smith, R. L. (1990). *Ecology and Field Biology* (4th. ed.). New York: Harper and Row.

Appendix

COURSE OBJECTIVES AND ASSESSMENT METHODS

Objectives

The student will be able to:

- construct concepts and biological ideas using knowledge gained from experimentation, observations, readings and classroom discussions;
- define selected biological nomenclature at the comprehension level of understanding in each of the topic areas of the course;
- construct and perform experiments in biology using standard laboratory apparatus and employing skills of hypothesizing, data collection, evaluation and drawing conclusions;
- construct an ecological community and its interactions using data from the stream study and information presented throughout the course; and
- maintain and organize data in a laboratory notebook, evaluate data by computer, and keep a course journal.

Assessment Methods

- *Laboratory Notebook and Journal* (20%). This book and journal will be reviewed every two weeks and at the end of the course for form, completeness, and accuracy.
- *Three Major Exams* (20% each). These exams will evaluate the student in the areas of knowledge (recall of facts), terminology comprehension (putting definitions in the students' own words), analysis and synthesis (analyzing data and putting together elements of a biological concept), and application of knowledge to new situations.
- *Project and Presentation* (20%). This aspect of evaluation will attempt to involve the student with library research on a topic of ethical or technological significance to biology and will measure the ability of the student to research, analyze and critically evaluate a topic.
- *Quizzes* were added to the course about half-way through at the request of students who felt that they needed to assess their progress at shorter intervals of time.

ADDITIONAL INFORMATION FOR INSTRUCTORS

Student Preconceptions

- A stream community might not have many living things in it (since they are not easily seen).
- All the energy that drives the stream community comes from within the stream.
- Stream life might be the same along its length.

Student Prerequisite Knowledge

- The student will have an understanding of water chemistry.
- The student will have an understanding of pH.
- The student will be able to measure using the metric system.

Student Learning Outcomes

The student will be able to:

- measure flow rate, pH, dissolved oxygen and temperature of two selected regions of a stream;
- observe and classify stream organisms using appropriate biological keys;
- predict the effect of flow rate on living and physical factors of the stream;
- construct a non-quantitative pyramid of energy and food web for the stream community; and
- predict and conduct research on the effects of acid rain on the stream community.

Related Activities

- Both before and after the field trip, we held laboratory activities in which we guided students through the process of identification of stream organisms using taxonomic keys. At the stream, we did not indicate any detail of any parameter of organism found, but instead asked questions that led the students to further research and investigation.
- After the stream study, students were asked to make a list based on class discussion of observable features of the stream, and to predict the effects of flow rate on living and non-living aspects of the stream.
- Students were asked to predict the effect of acid rain as one changing parameter on the community. This activity was accomplished early in the semester, and references were made to it throughout the course.

THE CHALLENGE OF TEACHING BIOLOGY 100: CAN I *REALLY* PROMOTE ACTIVE LEARNING IN A LARGE LECTURE?

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When I returned to full-time teaching after nine years in academic administration, I spent a number of months reexamining my teaching practice. I realized that the students in my classes read a lot, and memorized a lot, but didn't always understand a lot. Often what I said in lecture was simply not sufficient to connect similar concepts across seemingly different topics. Many students expected lectures to follow the text closely, and did not easily absorb explanations and examples drawn from different chapters or from non-text sources. A typical student response at the end of the semester was that my lectures had often been disorganized and difficult to follow.

In the fall semester of 1995, I decided to see if any of the theory and practice associated with constructivist teaching could be used to advantage in a large lecture environment. I saw examples and read descriptions of how MCTP students were learning actively in laboratory settings and smaller classes, but I wondered whether active learning could be encouraged in a large lecture. I decided to experiment with my teaching practice in a large, introductory biology course (Biology 100). I asked to be given half of the class (approximately 240 students) as a single section for which I would be solely responsible. I felt strongly that the emphasis on a large body of factual knowledge did not provide students with the sense of wonder and excitement that scientists normally experience. I resolved to place a greater emphasis on questions, particularly those posed by students, and to use whatever means possible to challenge students to take greater responsibility for their own learning.

The summer before I started my experiment, I was lucky enough to meet Dr. Susan Blunck, who was being recruited as a science education specialist at UMBC. Her area of expertise is constructivist education. When I asked if she would collaborate with me in the MCTP program, she enthusiastically agreed. Moreover, she agreed to participate actively as a colleague and on-site observer in the classroom in the fall. At MCTP meetings that summer, Dr. Blunck and I gathered ideas and information from other MCTP faculty, and worked together to develop a set of somewhat radical changes in the way Biology 100 was finally taught that fall. Our goal was to employ a multiplicity of approaches to see if we could promote active (or participatory) learning in a large lecture environment.

The Course and Grading

Biology 100 ("Concepts of Biology") is a 4-credit, one-semester course designed primarily for beginning biology and biochemistry majors. It is traditionally offered by two, or occasionally three, tenure-track faculty members who take turns lecturing three times a week in 50-minute sessions to classes ranging from 240 to over 400 students. Students also meet in weekly, small-class discussion sections of 25 to 50 students led by graduate teaching assistants. The corresponding laboratory (Biology 100L) is taken as a separate course either simultaneously or in a subsequent semester. Students other than those majoring in biology or biochemistry (or allied health students for whom Biology 100 and 100L are also required), can enroll in the lecture course to meet a general education requirement in science without taking the associated laboratory course.

Traditionally, students in Biology 100 received a grade based entirely on their performance on four multiple choice exams consisting of 35–50 questions: the top scores earned on three out of four hourly exams, plus their score on the comprehensive final exam. In our new, active learning course, multiple choice exams were also administered, but these counted for less than a third of the course grade. Students were given three hourly midterm exams of ten questions each and a comprehensive final of twenty-five questions. All exams were open book. The top two midterm scores plus the score earned on the final exam determined 30 percent of a student's grade. Students were told that the remaining 70 percent of their final grade would be determined by their performance on written, take-home assignments (30 percent); by their participation both in the large class and in smaller, weekly discussion sections led by graduate teaching assistants (35%); and by their scores on oral and written quizzes administered during the discussion sections (5%).

Approaches Used to Promote Active Learning

We employed five specific approaches that we anticipated would make the large-lecture environment more personal, student centered and interactive. These were: (1) name badges; (2) cooperative learning groups; (3) large-group discussion; (4) in-class written responses; and (5) written, take-home assignments. An expanded description of each is given below:

1. Name badges. Large lecture halls and classes of more than 100 students seem impersonal—especially to freshmen. To help personalize Biology 100, we prepared individual, pin-on, name badges for each student at the beginning of the semester from the official enrollment list. I explained that each student should view him/herself as a member of a professional community and that, like scientists attending a professional symposium, they should wear their name badges whenever they were in class. It was noted that wearing name badges was a non-verbal means of participating.

One of the most immediate effects of the badges was that both the students and I could identify people in the class by name. When students raised their hand, they could be recognized by name without the need for a seating chart and assigned seating. This helped greatly to personalize the large lecture environment and encouraged more student questions and responses from a wider array of students than is typical in a large lecture course. Badges also helped me to learn students' names so that by the end of the semester I could recognize more than half of the students on sight even outside of the classroom.

Many students initially resisted wearing their name badges in class, but by the end of the semester most had become accustomed to the practice. Surprisingly few comments about name badges were made on student evaluations, and almost all were positive. One student wrote, "Name tags were a good idea. It is good to know that at least one instructor is interested in learning the names of his/her students!"

2. Cooperative learning groups. Research suggests that students learn higher order thinking skills when they can discuss their ideas and actively engage in dialog (Johnson, Johnson & Smith, 1991). Therefore, randomly selected cooperative learning groups, or teams, of up to four students were used to foster dialogue in Biology 100. In a class session at the start of the semester, four sets of cards numbered 1 through 70 were randomly distributed. One of the numbered sets was colored, and the 70 students who received these colored cards were asked to hold them up. Then all students whose numbers matched were asked to move together so they could easily converse. Groups were instructed to turn in the colored cards listing the members' names and one sentence describing something unusual or uncommon that they all had in common. Finally, they were invited (but not required) to agree upon a team name.

Once formed, learning groups remained remarkably stable throughout the semester. Few students asked to switch teams. When given the opportunity at mid-semester to form new teams, the class overwhelmingly chose not to change partners. Team members were asked to sit near each other whenever they came to class, but sometimes individuals waited until I gave directions to start a small group activity before moving to sit with their other team members.

Team activities were varied throughout the semester as was the format of the response. All team activities took place during class and required either an oral or written response. In some cases I posed a short-answer question related to the topic at hand, and teams were asked to come to a consensus which would be reported to the class by a team spokesperson. At other times students were shown results of an experiment related to the day's topic, and then were asked to work together to develop a written team response that described and interpreted the results displayed. On still other occasions the class was presented with a concept question, and students were asked to provide individual written responses after a short period of team discussion.

For example, after a unit on cell respiration, the class might be asked to answer the following: "Do plant cells have mitochondria? Explain why or why not." Or, following a discussion of photosynthesis, I might ask: "How do plants that lose their leaves stay alive during the winter?" Or, as part of a unit on natural selection, students might be asked to respond to this question: "If an allele is recessive and is harmful, can selection eliminate it entirely from the population? Explain your reasoning."

Consistent with others who have used cooperative learning methods, we found that students enjoyed working together in small groups and reported that group work improved their understanding of the material. One student wrote on an end-of-semester evaluation, "I love being able to do group work because I am able to discuss my answers with other people." Another noted that as a non-native speaker of English she sometimes had difficulty with concepts such as osmosis, but could always turn to her group for help. When asked to assess their own contribution to group discussions, almost all students rated their participation as moderate to high. In contrast, when asked to evaluate the contribution of the other team members, students were typically quite candid and tended to be more discriminating in their assessments.

3. Large group discussion. Students were encouraged to ask questions in class, to reply to questions posed by me or by other students, and to respond to others' replies. In order to assure that students could hear each other speak, my wireless microphone was passed to any student who had a question or who wanted to respond to a question or statement. In previous classes, when I called on students for recitation, they were often reluctant to speak into the microphone I was holding. However, in the experimental section, such reluctance was much less evident, in part, because I only called on students who asked to be recognized. Perhaps more important was the fact that in this class I gave the students the microphone to hold during their responses. Thus, students easily and naturally obtained control of the means of communication with the entire class, and I could assume the role of listener rather than lecturer.

> *Consistent with others who have used cooperative learning methods, we found that students enjoyed working together in small groups and reported that group work improved their understanding of the material.*

Students were initially reluctant to speak out in a large lecture hall. Many who felt this way also resented the heavy weighting of participation in the final course grade, since they assumed that speaking out in the large class was the only (or major) method of participation. I tried to correct this impression by reminding students they could also participate in the smaller, weekly discussion sections and by emphasizing that there were other, non-verbal means of participation. At about mid-semester, students who had become concerned about their participation grade complained that although they raised their hands in class, they were being recognized rarely or not at all.

I responded by providing a sign-up sheet at the end of class for all students who had raised their hand during class—whether or not they had been recognized. Not only did the number of complaints decline, but students did not abuse this unmonitored means of assessing their participation. About the same number of students signed the participation sheet as raised their hands in class—typically 20 to 30—and, aside from those who were already known to us as "high-frequency responders," names on the list differed from one class period to the next. I plan to continue this practice when the course is repeated.

On the course evaluation, students were asked, "What was the best part of the course and why?" Many responded that they appreciated the open atmosphere of the class and liked being able to hear different points of view. One student wrote, "The course involved lots of give and take between Dr. Sokolove and the pupils during the lecture. This made the class more dynamic. Also it provided an atmosphere where questions and a variety of perspectives were encouraged." Another appreciated " . . . the open discussions during which everyone had an opportunity to participate and share their ideas." A third commented, "I liked the fact that the students were able to give so much input. It made the class much more interesting. It was better than listening to lectures every day."

On the other hand, a few felt that the discussions in the large lecture were too disorganized and that there were too many people in class for participation. One student wrote, "The interaction takes away from the class. Straight lecture would be better. And [the instructor] should go over more chapters [in the textbook]." Another commented thoughtfully, "Although the discussions during lecture were great, we need to perhaps set aside [time for] a structured lecture in order to cover more information . . . "

4. In-class written responses. Some education specialists have emphasized the need to get written feedback from students no matter the size of the class. In Biology 100 students were required to bring to every class session a laboratory research notebook (published by Jones & Bartlett; Sudbury, MA) in which they could write their responses and comments. The notebook had numbered, duplicate pages of carbonless paper that allowed students to retain a permanent copy of everything they wrote. A notebook page might be turned in to ask questions about the day's material, or to reply to a short-answer question. Other examples of how the notebook was used include responding to informal survey questions (such as "What would you suggest to improve this course?"), and writing one-minute papers relating one main point that they learned in class that day along with a question that they had about that day's topic.

The advantage of the notebook was that it offered a vehicle for shy students to communicate with the instructor without having to raise their hands and speak out, or to remain after class to ask questions, or to make an appointment to meet with the instructor. As the semester progressed, the notebook was used more and more frequently to facilitate non-verbal, in-class student input. When students wrote down their questions, responses, and comments, they were generally thoughtful and explicit in expressing themselves.

Reading and responding to one or more excellent questions from students at the beginning of class was sometimes used to provide positive feedback on student questions and to exemplify what I considered to be a good question. Students' written responses were also helpful in identifying misconceptions, misunderstandings, or confusion about the material so that these could be addressed in the subsequent class period.

5. Written, take-home assignments. There were three take-home assignments during the semester, each of which focused on an application-oriented question. For example: "You are a track star scheduled to compete in a 1,500 meter race next week. Your coach tells you to 'load up' on carbohydrates the day before the track meet so that your body will have plenty of energy in reserve for the race. *Is the coach correct in her advice? Why or why not?* Cite evidence to support your position."

For each assignment, students were asked to provide a three-part response of up to five typed pages: Part I asked students to describe what research sources they had consulted and explain why these had been chosen, and also to list any resources that were not consulted and to explain why these had not been used. Part II asked for a response to the question that had been posed with appropriate citations. Part III asked students to pose two questions of their own that resulted from the research they had done.

All papers were read and graded either by me or by graduate teaching assistants using a rubric based upon the following grading approach. For each section of the paper that met a minimum level of acceptability, the student was guaranteed a "good" grade of B-(e.g., 8 out of 10 possible points). There were no correct or incorrect responses. To be minimally acceptable, a paper had to demonstrate an honest effort by the student, and each part of the response had to be complete (all directions followed) and readable (clearly organized with few spelling or syntax errors). Additional points could be earned if a student displayed extra effort and thoughtfulness in his/her response; points could be lost if a student failed to follow fully the directions provided—for example, noting which research sources were consulted (books in the library, my high school track coach, etc.), but failing to explain why these were used and others (the World Wide Web, sports or nutrition journals, articles in the popular press, etc.) were not.

Take-home assignments served to initiate discussion about the types of information sources that are available and about the reliability of the information they provide. Students typically reached different conclusions about the answer to the question posed in the assignment. These were aired in class discussion to illustrate the importance of scientific discourse and to allow students to gain experience in defending the interpretation of their research findings. Take-home questions were assigned that could be readily related to one or more biologically important concepts or topics. In the case of "carbo-loading," such topics might include digestion, cellular respiration and muscle energetics. Students could thereby learn key facts and concepts in an applied context with guidance from the instructor, rather than feel they needed to memorize them from lecture notes or the textbook only because "they might be on the next exam."

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The response of students to take-home assignments was generally positive, although one student advised us to " . . . do away with those silly research papers." Most felt that the assignments provided a chance to engage in self-directed learning and to demonstrate what they *could do* as opposed to what they *could not do*. One student commented that, "The take home assignments were a help in the understanding of certain topics." Another wrote, "The take home questions were a good opportunity for students to demonstrate knowledge without being in an exam situation." A third noted, "I learned the most from the take-home assignments, researching and discovering information on my own. I feel there should be twice as many take-home assignments as there was [sic]! They are great practice [for writing] and they are very helpful in learning on our own! I feel it is important to learn on your own—it really sinks in that way."

What Have We Learned?

"He makes us think." This is how one student in fall 1995 introductory biology responded to the following question on the course evaluation questionnaire: "What personal qualities did this instructor have which hindered his/her teaching?" Another student answered, "He doesn't answer questions directly and lets students find it for themselves." A third replied, "He openly stated he didn't know. Made opinions about him skeptical about his abilities [as an instructor]."

Dr. Blunck and I have learned a number of lessons that we hope will allow us to improve our efforts to promote active learning in introductory biology. First, we recognize that students do, indeed, have different ways of learning, and we will continue to provide choices both within class and between classes for those with different learning styles. Within the class, we have used multiple teaching/learning approaches and will continue to do so. But we will emphasize at the outset that there are many ways for students to succeed besides simply doing well on exams or speaking up in lecture.

Based on our findings, we will refine some approaches, modify others, and eliminate still others (see examples of planned changes under "Work in Progress" below). We may also add new approaches such as "concept tests" that show much promise (Mazur, 1995). We will also respect those students who feel they learn best in a more familiar lecture course. When the course is repeated, such students will be advised that they can enroll in a different section of Biology 100 that is offered by the department using a more traditional approach.

Second, we have confirmed that cooperative learning is as fruitful in professional development as it is in the classroom. The collaboration between Dr. Blunck and me was, I think, essential for effective modification of my teaching. It has often been said that student evaluations are of limited use in assessing the quality of teaching. Nevertheless, there are few instances at the college level where other methods of assessment, such as peer review, are regularly and conscientiously employed. Even fewer are cases in which teaching practice is assessed by an experienced field evaluator on an ongoing basis. The model of continuous improvement in teaching requires continual feedback. In reforming Biology 100, we have found that sharing the experience of a professional science education specialist (Dr. Blunck) and a scientist instructor (me) has allowed us to meet common educational goals that could not be achieved by relying on student assessments alone. In the case of Biology 100, regular, constructive input from Dr. Blunck was instrumental in promoting rapid and effective changes in my teaching practice.

Third, we have found it possible to implement a variety of active learning approaches in a large-lecture environment, but we cannot yet stipulate which of these has been more (or less) effective in promoting understanding of basic concepts. From the perspective of students, it appears that cooperative learning groups were the most helpful of the methods employed. Virtually all students who commented on small group discussion claimed that it significantly aided their understanding, and no student commented negatively about team learning. However, an approach such as large group discussion that elicited positive responses from many students, was viewed by others as a distraction. While a large number indicated that the best part of the course was class interaction and having input from the students in the class during lectures, one student commented, "Sometimes class seemed like a talk show." A significant fraction of the class felt that there should have been more structure, less class participation, and more text book related material on exams]. Clearly not all agreed with the student who wrote, "I loved this new teaching technique. I learned more in this class than I have in any science course. Everybody could benefit from this change if they don't resist it."

Work in Progress

Dr. Blunck and I regard our efforts as a "work in progress" and not as a finished product. Students who completed the semester did not necessarily appreciate being asked to participate in their own learning and a number continued to prefer traditional ways of learning biology. Some of the changes we plan to make when the course is repeated will be in response to student input, while others will be new. Among the changes we plan are the following:

- Students will be given more explicit information about what they can do to participate during class so that speaking out in front of the whole class is not viewed as the sole means of participating.
- Additional wireless microphones will be purchased so that the instructor does not have to race around the lecture hall in order to hand the microphone to a student.
- More effort will be made to provide structure by providing a short list of the major concept or concepts we hope to cover each week together with a list of the relevant text chapters.
- Cooperative learning groups will be employed more frequently during class using a wider range of activities.
- Peer evaluation of written take-home assignments will be used in conjunction with a grading rubric that will be discussed (and possibly modified) before assignments are made.
- Students will be given the option of purchasing a higher level textbook in lieu of the "required" text, but those who choose this option will need to assume responsibility for determining what sections of that text relate to the concept list.

What About Content?

Virtually all of the teachers who have tried to promote active learning in their classrooms, whether in grades K–12 or at the post-secondary level, have had to struggle with the fact that active learning approaches take more time and consequently reduce the time available in class for "coverage" of material. I, too, have had to struggle with the coverage issue in Biology 100. However, I recognized at the outset that even in a traditional lecture course, it is impossible to cover within a single semester all the material contained in even the least challenging introductory textbook. Thus, it is always the case that regardless of who teaches the course (or, perhaps, *depending* on who teaches), some topics will be covered and some not. In our case, I tried to reduce the number of topics to a core of essential concepts. However, it will take many iterations of teaching Biology 100 before I am comfortable with the choices. No doubt even these choices will change with time and experience—and after many discussions with other faculty members in my department.

National groups such as the American Association for the Advancement of Science and the National Research Council have been engaged in developing new guidelines for science education. A consistent finding expressed in these efforts is that students learn best when exposed to environments that encourage reflection, self-directed and inquiry-based learning, and higher order skills that go beyond memorizing items of information (AAAS, 1993; NRC, 1996; see also, Yager, 1993). Content issues are not ignored. Indeed, almost half of the NRC's *National Science Education Standards* is devoted to content standards. However, the emphasis in these content standards is shifted in important ways. One shift is from expecting students to know scientific facts and information to expecting them to understand scientific concepts and develop abilities of inquiry. Another major shift is from covering many science topics to studying a few fundamental science concepts (*Standards*, p. 113).

I recognized at the outset that even in a traditional lecture course, it is impossible to cover within a single semester all the material contained in even the least challenging introductory textbook.

Still, there are many who continue to wonder, are there any "objective" data regarding student learning when these standards are applied in the college classroom? Can students really learn "enough" even though one covers less material? One way Dr. Blunck and I attempted to determine whether students in our student-centered, active-learning version of Biology 100 had been "short changed" was to examine their performance on the same final exam questions given to students in the traditional lecture section taught that semester. Whether we examined average performance on the entire set of questions or looked at the percentage of the class that answered each question correctly, we found that students in the active learning section performed *as well as or better than* the students in the traditional lecture section. The following student comment captures our subjective impression of how well students learned: "I liked the new format. I tried to take this class a year ago and was confussed [sic] and bored senseless. I picked up a lot this time and I enjoyed it!"

References:

American Association for the Advancement of Science. (1993). *Project 2061, Benchmarks for Science Literacy.* New York: Oxford University Press.

Johnson, D.W., Johnson, R.T. & Smith, K.A. (1991). *Active Learning: Cooperation in the College Classroom.* Edina, Minnesota: Interaction Book Company.

Mazur, E. (1995). *Concept Tests in Physics.* Englewood Cliffs, New Jersey: Prentice-Hall.

National Research Council. (1996). *National Science Education Standards.* Washington, DC: National Academy Press.

Yager, R. (ed.) (1993) *What Research Says to the Science Teacher, Volume 7: The Science, Technology, Society Movement.* Washington, DC: National Science Teachers Association.

A SHIFT IN MATHEMATICS TEACHING: GUIDING STUDENTS TO BECOME INDEPENDENT LEARNERS

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In the fall semester of 1994, we began testing a new approach to teaching special sections of Math 207, "Fundamental Concepts of Mathematics II." This is the second mathematics course required for our early childhood/elementary education majors. Two of us—Drs. Weimer and Parks—taught sections of Math 207 that fall, and Dr. Jones added his section a year later.

In the past we all had used a standard textbook for Math 207. We spent the major portion of time teaching geometric concepts (usually about five chapters) and a much smaller portion of time (about one chapter each) on probability, statistics, and computers (using BASIC and LOGO). Each of us felt that the students in the traditional classes had not been fully involved in the learning of mathematics. We believed that the students had been passive learners at best and non-learners at worst. Therefore, our major goal for the "new" course was to get the students actively involved in constructing their own understanding of mathematics.

Facilitators of Learning

The two of us who pioneered the course decided to take a constructivist approach to teaching our sections. We decided to do very little lecturing; instead, we would serve primarily as facilitators of learning. During the summer of 1994, in conjunction with the MCTP program, we developed new course materials to support this approach. (Later, when Dr. Jones observed our classes in action, he decided to join forces with us.)

When our first two Math 207 sections got under way, we took a new approach to responding to student questions. We answered questions directly when appropriate, but more often we "answered a question with a question." We tried to aim the students' inquiry in ways that would enable them to find their own answers. Sometimes we would do a mini-lecture at the beginning of a project to set the stage, review, or provide background information. At other times we would be prompted to give a mini-lecture during the project for clarification when several groups seemed to be struggling with the same concept.

Cooperative learning became our standard mode of operation. Throughout the semester, students worked together to complete twelve class projects designed to actively engage them in learning the course content. Working in groups of four, they constructed their own knowledge using a hands-on, laboratory approach to learning. To demonstrate that they had learned the material involved in an activity, they were required to write a report explaining the major mathematical ideas developed within the context of the activity.

The students worked in pairs to produce the reports, and we required them to switch partners after completing two projects. This allowed the students to experience different learning styles. (One student commented that her partner approached problems by drawing pictures or diagrams while she approached problems algebraically. She said she liked the visual approach and decided to try to use it more often.)

The "new" course materials we developed included much of the original mathematics content but in a radically different format. Each of the twelve projects included questions that asked students to investigate concepts by collecting and analyzing data. Students were then required to justify and explain their answers. All class time was devoted to the projects, each of which took approximately one week to complete. In addition, in order to complete the projects, groups needed to meet outside of class to answer questions as well as write and type the final reports (one per group). There were no tests; instead, the group project reports formed the basis for assessment. Students were also involved in analyzing their thought processes by submitting e-mail journals at least once each week.

In short, the majority of my students were not being reached by the traditional methods from which I had learned so well as a student in a different era. For me, the time was ripe for a change!

Time for a Change

While our first two sections were in full swing, Dr. Jones often stopped by the classes and couldn't help but notice a major difference in the level of student interest and involvement. Ultimately, he decided to join our efforts, adding a new section a year later. Below, in his words, is a description of his evolution.

> *I have been teaching mathematics content courses for prospective elementary school teachers for over 25 years using somewhat traditional methods of instruction. Although I have experienced a moderate degree of success in teaching Math 207 in the past, in recent years I had been haunted with some nagging reservations about how these future educators are being prepared to teach mathematics.*
>
> *My typical format consisted of lecture for three weeks, interspersed with encouraged discussion (often unsuccessful), which was followed by the students' cramming for the traditional timed examination. This conventional approach seemed to be counterproductive with respect to motivating students to truly learn mathematics.*
>
> *Furthermore, while a small minority of my students did respond with genuine interest in learning mathematics, the overall atmosphere in my classroom bordered on "siesta time." In short, the majority of my students were not being reached by the traditional methods from which I had learned so well as a student in a different era. For me, the time was ripe for a change!*
>
> *I became interested in the MCTP project after my colleagues shared some of their new experiences with me. The constructivist approach to teaching sounded promising, especially on those occasions when I would walk by their classrooms and watch interested students working actively in groups. I noted that these students were actually communicating with one another about mathematics and they appeared to enjoy the process (a far cry from my own typically apathetic spectator-type students).*
>
> *When my colleagues first approached me about joining this constructivist experiment, I was a bit apprehensive. I was concerned about the considerable content that might not be covered, about this new role of the teacher as a facilitator, about turning over more of the responsibility of learning to the students themselves, about forfeiting periodic timed examinations, and so on. Yet, I knew all too well from the past the consequences of maintaining the status quo. So, in spite of these lingering reservations, I decided to "jump in and get my feet wet."*
>
> *This move proved to be "a shot in the arm" for my teaching. My entire focus in the classroom became dramatically changed with a stronger emphasis on student*

learning. In the past, I would focus my thinking on the issue, "How can I (as a teacher) best explain a particular topic?" Using the constructivist approach, I found myself asking, "How can I best provide an opportunity for significant student learning where discovery is encouraged and understanding is promoted?" I began to acquire a new appreciation of what is sometimes referred to as the art of teaching. My energies were redirected toward questions such as, "How much of a hint should be shared so that the student is not robbed of the discovery experience, and yet is not so completely discouraged with the feeling of batting his or her head against the wall?"

Although our individual circumstances differ somewhat, much of Dr. Jones' story can be considered "our" story, in that all three of us went through similar shifts in our thinking and in our approaches to teaching.

Circumference vs. Diameter: A Sample Activity

To follow is a description of the first activity that each of us used in our own sections of Math 207. In "Circumference vs. Diameter," the students were asked at the outset to make a conjecture as to how the height of an ordinary tennis ball can compares with its circumference (see the Appendix for the activity). This counterintuitive experience seemed to hook the students from the beginning. Most students guess that the height is greater than the circumference, or those students who think that this is a trick question will say that the height and the circumference of the can are the same. Rarely do students guess correctly.

This question, of course, is a good attention-getter for the first activity. When students measured the can and found that their answer was incorrect, they discussed this finding within their groups. They then proceeded to the next phases of the activity to see what further challenges lay ahead. While it is true that our students had been informed about "pi" in their past studies, in this first activity they developed a first-hand understanding of how any circle's diameter and circumference relate to each other. Indeed, as in future activities, the students were able to come up with the formulas themselves. Admittedly, this process took longer than our previous traditional approaches, but once our students were equipped with a stronger understanding of circles, they were able to effectively handle, on their own, deeper thought processes and applications of the topic.

Change is not easy. Although the students found the projects interesting, they disliked writing out explanations. They would much prefer to give a one-word or simple numerical answer to a problem than to explain how and why they came up with an answer. More than one student has lamented, "I hate the word EXPLAIN." But since they are pre-service teachers, they know that explaining is an important skill for them to develop. Many admit to having had poor experiences with mathematics in elementary school themselves and therefore know the value of a teacher's understanding and answering questions clearly and precisely.

> *The difficult part for all of us was not giving students the answers directly or showing them the easy way to solve a problem. We had to learn to be patient with their learning and to ask leading, yet judicious questions.*

The difficult part for all of us was not giving students the answers directly or showing them the easy way to solve a problem. We had to learn to be patient with their learning and to ask leading, yet judicious questions. This was an adjustment both for us and for the students. Students often look to their instructors for validation, approval, and an indication that they are on the right track when solving a problem. We wanted our pre-service teachers to become independent learners and to be able to critically evaluate their conclusions.

The following student comments, compiled from each of our classes, were written immediately following completion of the first activity:

I never realized exactly how circumference and diameter related, in all past classes, I had always just been told, diameter times pi equals circumference. Without thinking about why this formula was true I never really understood it. After seeing it, hearing it, touching it, and actively using it, I now understand it.

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I think what challenges me most is taking the math from the equation type form and applying it to a problem in real life. I have no problem computing things once I'm shown how to do that type of problem, but I really don't know how to use it any other way. I guess what I'm trying to say is that there is more to using math than what I recall being taught.

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I like working hands-on. Sometimes numbers and formulas seem so abstract, but when you have something like the tennis ball can that you can actually touch and feel it makes things easier to understand.

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I am realizing that I learn a lot more when I work problems out for myself than having you [the instructor] tell me the answer even though it would be ten times faster.

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I like the way you format the project in the form that questions lead to one another. The questions were written in a manner that you had to think because the answer was not there in the question. The project also is helping me become more comfortable with word problems. The questions were challenging but not overwhelming.

Learning Together

Having the students work in cooperative groups appealed to all three of us. We believed that the students would bring various skills and knowledge about mathematics to the groups and that by working together on a project they would be more inclined to participate. We also hoped that by discussing mathematics with each other they would learn to rely upon themselves to decide if an answer made sense. For most of the students, working in cooperative groups was a new experience. The following are some student thoughts about their first experiences with partners:

I'm finding that I really like working with a partner. When you are unsure of a question you always have someone there to help out. I also have found that having a partner, it also helped my thinking process. At one point during our discussion on the project I asked my partner a question. She was unsure of the answer also. But, to my surprise simply by verbalizing the question out loud I was able to find the answer myself.

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Working with a partner helps me to remain focused because you know that another person is depending on you to help get the work done. This is great practice in the area of responsibility.

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In terms of working with a partner, I found it to be very challenging. My partner and I go about things in very different ways. For example, when we got stuck on a problem I wanted to skip it and move on, where she wanted to search through the book until she found an answer.

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After doing this project I have discovered that I am capable of resolving a problem. However, I find it difficult some of the time to explain why and how I did what I did to solve the problem. I found this out when I worked with my partner. I had to read the problem several times then answer it the way I thought might be right, then try to help her also understand the problem after I did. This was good practice for me so I can become the best teacher possible. I think that we should have the chance to work with *everybody in the class so that we have the chance to learn and help each other better.*

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Using cooperative learning is a very good instructional tool for a mathematics class. It helps me to be reassured and it builds my confidence by having someone to work with. The first activity was very thought provoking, and required my partner and I to cooperate and share the work, while allowing each of us to learn from the other's experience.

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I have come to like working with different partners. It is more challenging to learn about each person's learning style, as well as various patterns of thinking.

Activity-Driven Ingenuity

Throughout the course we were sometimes discouraged with students' lack of standard knowledge (i.e. the Pythagorean Theorem, how to solve simple equations, or the fact that 1 mile is equivalent to 5,280 feet), but in this kind of course the students' thought processes are revealed and there is no place for them to hide. On the other hand, we were often delightfully surprised at many students' ingenuity in attacking problems.

For instance, we asked students to determine the maximum volume of a box that can be constructed from an ordinary sheet of paper by cutting squares of the same size from each corner. Students were to construct various sizes of open boxes and look for patterns among the data. One student quietly folded her paper twice and cut out one square from a corner, which magically multiplied in front of her partner's eyes to four squares when the paper was unfolded and a box was formed.

In retrospect, we have no doubt that better learning did occur within this "activity-centered" classroom than within our past "teacher-centered" courses. Although there may have been some sacrifice in the amount of content covered, the entire process involving student discoveries, peer interactions, individual journaling, oral communication, and written reporting provided a valuable multidimensional learning experience for our students.

The Value of Journals

As the semester progressed, we learned along with the students. During each period, we had the opportunity to interact with students as they interacted with their partners and sometimes within larger groups. It was especially gratifying to witness the thought processes utilized by students as they communicated with one another. We were also impressed with the weekly student journal entries describing their learning experiences, after which we attempted to offer appropriate written feedback. Throughout the semester these journal writings displayed a variety of feelings about mathematics, but overall they reflected that significant learning was occurring. A sample of these student ponderings includes the following quotes:

> *. . . we were often delightfully surprised at many students' ingenuity in attacking problems.*

This lesson is put together well and forces us to THINK about why things happen. What we find in the activities are often counterintuitive, and this forces us to think through our answers a little more carefully.

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I am beginning to lose some of the anxiety I first had about venturing into the unknown. The labor involved in our pursuit is where the real learning occurs and this seems far more valuable to me as a future educator than merely obtaining the actual "answers" to this assignment.

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Class is more fun, but it's a lot more work.

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I find that when I am forced to write about the mathematics we are doing that I gain a better understanding of the concepts we are learning.

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I am beginning to think of my future as an elementary school teacher. Already I have decided one goal of my career will be to teach math as a fun, interesting, and valuable subject that anyone can learn. I really want to "breed" a generation of youngsters who like math and do not fear it.

On occasion, students did have legitimate concerns, which they were able to share with us through their journaling. One problem in particular that surfaced in all of our classes is that of partner-shared responsibility. One student writes:

I was a little disappointed with my partner during the second project we did together. I felt she really didn't do her share of the work. The last part of the project was the most challenging and I was left to do it alone. In certain cases like this one, when your partner doesn't pull his/her share of the weight in helping with the project, it doesn't seem quite fair that they receive an equal grade.

Although we have not completely resolved this issue, we feel that it is important for students to be able to privately describe their learning frustrations by way of their journals, and for us to be able to give suggestions on how they might go about trying to solve their problems. We also point out that these problems exist not just in our current classroom, but that they will face problems of motivation, responsibility, and fairness in grading in their future teaching assignments as well. The journaling process also provides a way of showing the students that we really are listening to them and that we care about them as learners.

At the end of the semester, one student summarized her experience as follows:

I think that I really have learned a lot this semester. I think that going into this class, I felt as if I really wouldn't LEARN anything at all but I found that I did. . . . I learned new ways of approaching [the concepts] and how to work together with people to get to understanding those concepts.

I also discovered how much more I learned from the report writing rather than the standard tests and quizzes that the student I tutor has. She still doesn't truly understand the concepts that she has learned because her way of explaining them is to take a test, whereas ours involves an understanding in order to complete an explanation. These reports have also taught me to think before I write and to EXPLAIN myself more clearly. I may understand what I am trying to write but the reader (or my future student) may not.

Working with a partner was also helpful. Although in the beginning, I was apprehensive about working with someone new every other week, I have found that working with a partner helps a lot because we both may be thinking of two different ways of doing something. We can combine our ideas to make something better, or maybe just to solve a problem.

And most of all I liked the journal writing. I think that it gave us another way of communication and it helped a lot with the solving of the problems in our reports. Sometimes when I would write and ask a question, I would end up solving it in the way that I asked you. I think it made us feel closer to you as a teacher, giving us a link that most students and teachers don't have in their classroom.

Basically, what I am trying to say is that this is probably the most worthwhile class I have had here. I was beginning to hate math in general until now. I am now looking forward to taking other math classes for my concentration.

Looking Back

In reflecting on our experiences, we all admit they were most rewarding. The most difficult part during the semester was learning not "to spill the beans" too quickly. In the traditional classroom a "good" teacher will always answer questions clearly and succinctly for his/her students. We had to learn how not to answer questions directly, but to gently guide our students to find their own answers without causing them so much frustration that they would have given up on the problem.

There was a major adjustment period for our students at the beginning of each semester. Most of the students, even the good students, were dependent upon us to tell them if they were doing the problem correctly. So even though the students worked in groups, they still wanted us to tell them if they were doing the activities correctly. So we had to make sure we visited with all groups and that one or two groups could not be allowed to dominate our time.

We found that if we did our jobs correctly, our students would ask us different kinds of questions, and fewer questions towards the end of the semester. They also learned to know when they were doing the problems correctly.

As mentioned earlier, we still have not solved the problem of all students contributing equally to each and every part of the projects. When we were able to identify students who were not contributing, we paired them together for the next project. That at least forced one of them (if not both) to become more involved. However, we do believe that by using the activity-centered materials and requiring written reports, many more students were truly involved in learning mathematics—and in learning more mathematics—than in our traditional classes. In a traditional teacher-centered class it is much easier for a student to hide because the teacher often does the majority of the work.

> *Clearly, when the students began to find their own answers they were pleased with themselves, which increased their confidence and encouraged them to continue to find more answers on their own.*

Finally, it was a wonderful experience to stand back and observe students making sense of mathematics for themselves. There were many occasions when we could see "the light bulb turning on." In the "Circumference vs. Diameter" activity, many students were surprised to learn for themselves how pi was related to the circumference and diameter of a circle and how pi was then related to the slope of a line on the graph. It was great to hear a student say, "Hey, that's cool!" in a mathematics class.

CIRCUMFERENCE vs. DIAMETER ACTIVITY

1. How does the height of the can compare to the circumference of the can? What is your conjecture? Explain your reasoning.
2. Test your conjecture by measuring, and describe your process and result. How does this result compare with your original conjecture? Explain.
3. Choose five cans of different sizes and complete Table 1. For each can, measure the diameter and circumference three times.

TABLE 1

Can	Diameter				Circumference			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
1								
2								
3								
4								
5								

4. Why is it a good idea to measure the diameter and circumference three times and then take an average?
5. Plot the diameter, D, on the horizontal axis and the circumference, C, on the vertical axis. Does it look like the best fit curve should be a straight line?
6. Should the best fit curve go through the origin? Explain.

7. Draw in the best fitting curve.
8. What does the best-fitting curve represent, and how can it be used?

Comprehension Questions:

Use your graph to answer the next three questions. For each, show your work using dotted lines on your graph.

9. a. If a circle has a diameter of 3 cm, what is its circumference?
   b. Did you use interpolation or extrapolation?
10. a. If a circle has a diameter of 7 cm, what is its circumference?
   b. Did you use interpolation or extrapolation?
11. a. If a circle has a circumference of 75 cm, what is its diameter?
   b. Did you use interpolation or extrapolation?
12. From your curve find a formula relating variables C and D. Explain your reasoning, including any constants used. What do you think the exact value of the constant should be?
13. For the three circles on the attached page, measure the circumference and diameter and add this information to Table 1. Plot a new graph with all eight points. Does the best-fitting curve change? Explain.

For the next five problems, use your formula relating C and D with the exact constant to answer the questions.

14. What is the diameter of a circle if the circumference is 117 cm?
15. A tire on a bicycle has an inside diameter of 45 cm and an outside diameter of 52 cm.
   a. What is the inner circumference?
   b. What is the outer circumference?
   c. How far will the tire roll in two complete turns?
   d. If the distance from your home to school is 4000 meters, how many revolutions will the wheel make?
16. It takes 25 adults, arms outstretched, to surround a Redwood tree. Approximate the tree's radius. Explain how you arrived at this approximation.
17. Which would have the larger circumference, a heavy copper cylinder that is 5 cm in diameter or a light plastic cylinder that is 5 cm in diameter? Explain.
18. The diameter of a large soup can is 4.5 inches. Its height is 6 inches.
   a. What shape did the label have before it was put on the can?
   b. What are the dimensions of the label if it covers the can?
19. Return to the tennis ball problem. Without using measurements, provide some mathematical justification for your conjecture.
20. a. Construct a circle.
   b. Inscribe a square in your circle.
   c. Circumscribe a square about the circle.
   d. How do the perimeters of the two squares compare? Explain your reasoning.

21. Refer to the large circle below. Determine the length of the arc between any two successive small marks. Explain what you did.

Critical Thought Questions:

22. Is the circumference part of the circle?

23. Is the diameter part of the circle?

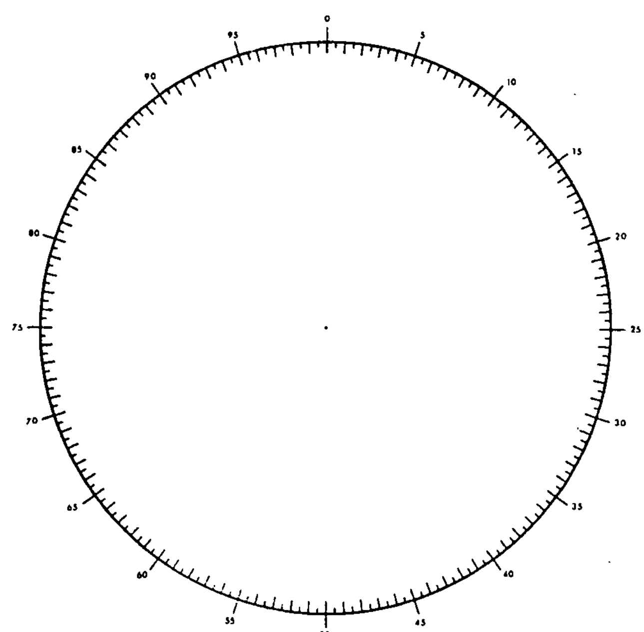
24. Is the center of a circle part of the circle?

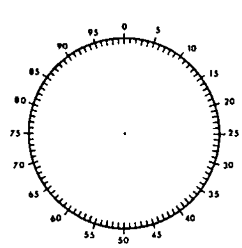
25. Define a circle, its circumference, diameter, radius, and center.

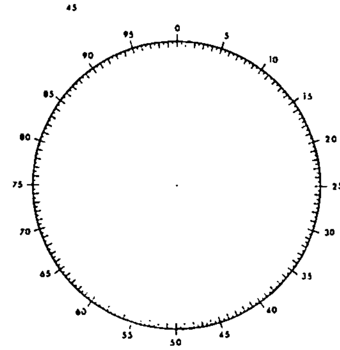
26. a. Define pi.

    b. Is pi equal to $^{22}/_{7}$? Explain.

27. Can a straight line intersect a circle in one point, that point being the center of the circle? Explain.







A TALE OF TWO PROFESSORS: FACULTY PROFILES

The mathematics and science professors who joined the MCTP program came aboard through different routes. Some had been actively seeking new teaching methods to boost their students' level of interest and class participation. When they heard about the MCTP program, they signed up readily. Others had resigned themselves to student disinterest as "part of the package" of teaching college mathematics or science. They wound up joining the program, however, after a colleague convinced them to try something new.

The following interviews convey the journeys of two professors who came to MCTP from opposite ends of the spectrum. First is the story of chemistry professor Pallassana Krishnan of Coppin State College, who had not considered altering his methods of instruction until a colleague persuaded him to give this new program a try. Second is a profile of physical sciences professor Rich Cerkovnik of Anne Arundel Community College, who knew he wanted to change his teaching strategies before MCTP came into being.

Regardless of their paths of entry, each of these professors took from the program many new ideas for creating active learning environments for their students. They also gained support from a statewide network of colleagues as they ventured into new ways of teaching. And both agree that what they're doing in the classroom now is definitely better than what they were doing before.

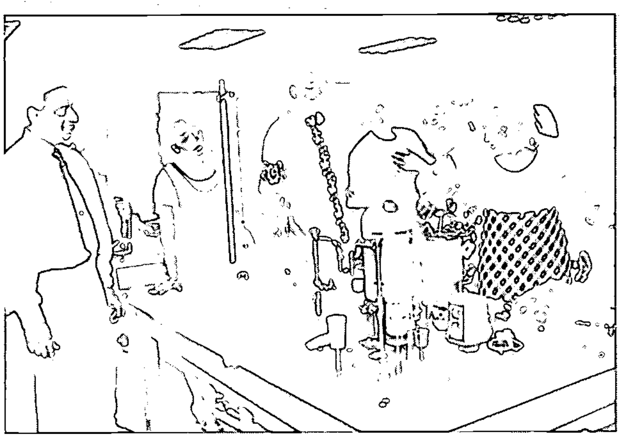
These stories, written by Maureen Gardner, MCTP Faculty Research Assistant, were originally published in the *MCTP Quarterly*, the project newsletter.

CHEMISTRY PROFESSOR TRANSFORMS ENERGY—HIS OWN

Profile of Professor Pallassana Krishnan, *Coppin State College*

He was not looking for a new way to teach. After more than two decades as a chemistry professor at Coppin State College, Dr. Pallassana Krishnan was resigned to the lack of student participation in his traditional lectures and labs. Although it bothered him, he said, "you get adapted; you say 'this is life . . . it's a job you have to do.'"

It's all different now. Since two summers ago, when a colleague at Coppin persuaded him to give MCTP a try, Dr. Krishnan and his students have been energized by major changes in his course. Gone is the lecture room, the classroom format, the table behind which he used to sit, separate from the students. Now professor and students interact, side-by-side in the lab, throughout each class.



Dr. Krishnan, now in the role of the "guide on the side" as opposed to the "sage on the stage," as his students experiment with liquid nitrogen in his physical science class.

Instead of listening passively, Dr. Krishnan's students now learn chemistry by *doing* things, like flash-freezing items in liquid nitrogen or heating them in a solar oven. The activities drive students to ask question after question, which Dr. Krishnan tosses back to them to figure out. "You know he's not going to tell us the answer," said one student to another during a recent class. Textbooks are used for reference purposes only.

The transformation wasn't quick, and it certainly wasn't easy. The way Dr. Krishnan sees it, however, it's now a part of him, and there is no turning back. Here are some of his thoughts on how this all happened:

On the first attempt. The first time I taught an MCTP class it was a disaster. I was trying to change from one mode of teaching to another, and after lecturing for 24 years, I wasn't able to do that properly. If the professor is confused, the students sense that so easily, and that causes a lot of disturbance in the students. It took a whole semester for me to adjust.

On why he didn't "bag it" when times got tough. "Bagging it" flew through my mind several times, but bag it and do what? If you go back to the old way, that isn't any better; it's equally bad.

On trying again. The next semester I tried again. Fortunately that was a smaller class—only 12 students—and that helped a lot. Then I saw that maybe this is the way to go after all. It takes awhile. That time was good and the third time, this semester, is good. . . . If you want it to work it will work.

On resisting the urge to answer student questions. This is the hardest part for me, because students expect an answer immediately. Not answering comes naturally now. . . . There is a question, and you just open it up and let the students kick it around. Eventually the answer evolves from the discussion; if it doesn't then

Now We're Really Cookin'

We hear a lot of talk about motivating students, said Dr. Krishnan, but MCTP teaching offers motivation for professors, too. He offers a prime example: It began during a class discussion about papers the students were writing on energy topics, when a couple of his students from Kenya brought up the use of solar energy in developing countries. Dr. Krishnan said, "Wait, I might be able to help you with that." He had read the work of Dr. Dan Kammen at Princeton, who is developing solar ovens for people in Kenya and other African nations. "I sent him an e-mail and he responded immediately and suggested that we meet," Dr. Krishnan said.

Dr. Krishnan (foreground, left) talks with students about the solar-powered oven on which they will be doing research this summer.

During their meeting at Princeton, Dr. Kammen said that some undergrads there would be doing research on the oven, such as measuring temperature differentials. Noting that both good students and good sunshine were available at Coppin, Dr. Krishnan asked whether his class could help collect the data. "Professor Kammen thought it was fantastic," said Dr. Krishnan. "He jumped on it very quickly, and carried this solar oven all the way out to my car."

Back at Coppin, "the students were really thrilled," said Dr. Krishnan. "Six of them have volunteered to come in this summer to take the measurements." He adds, "These things I would not have done five years ago. That's the difference MCTP has made."

you give them a small hint and then it keeps on. It takes a little bit of time, but then this *learning* takes place, which is exciting.

On content coverage and meaning. Others may think that in teaching this way we don't cover enough material as we do otherwise. I don't think so; I think we cover a whole lot. Once the students' interest is sparked, they are going to read, and they are going to find out. Then how you spark that interest becomes the question. And if you do not spark that interest, no matter what you do, it has no meaning at all.

On how you know you've got 'em hooked. During the second semester, one class was scheduled for Friday afternoons, from 4–5 p.m. Typically one does not get too many students for a physical science class held at that time, but I had almost full attendance in every class. That means they were understanding it. Once you understand it, you like it.

On an innovative way to introduce other professors to MCTP-style teaching. I invited a newly hired chemistry professor, who teaches another section of the same course, to just come sit in my class. I didn't tell him anything about

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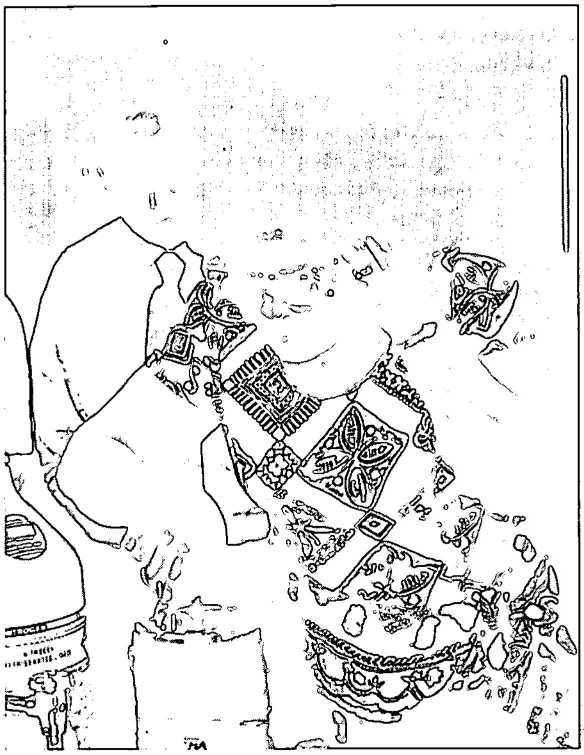


MCTP student Amanda Rice of Coppin State College dips an object into liquid nitrogen as Dr. Krishnan looks on.

constructivism or about MCTP; I just asked him to observe and make some comments. He came in and watched. Right after the class he jumped up and said "I am amazed at the way the students participate in your class—it is totally different! They all do the work and you do the least amount of work." I said that's interesting to know, that's good to know. He had some very positive thoughts about that class and I felt good about it. Now we can probably talk to him about MCTP.

On the importance of institutional backing. If it were not for MCTP, I don't think that this kind of change could have taken place. If the MCTP program was not here when I started teaching this way, I would not have survived. People would have jumped on me very quickly, saying "Oh the professor has gone senile after all these years." The education system is a big machine—you just don't change things easily or quickly. So MCTP was the backing; I knew at least that somebody was behind me to help me out.

On resolve. Now that we have started this new way of teaching, I think it can go on. Even if someone were to question it, I still would not go back to the lecture again. I guarantee you that I would not do it—that's all there is to it. The students are learning and they're excited; that's all I need. Having made this change, it's something you feel that's inside. You will not change back once you really are convinced. It may not be perfect yet, but it's certainly better than what I was doing before.

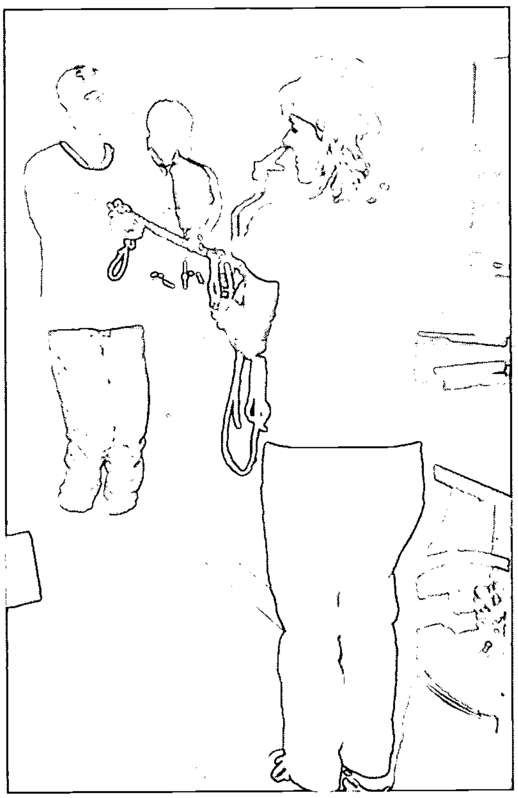
STUDENT QUESTIONS HOLD THE ANSWER

Profile of Professor Rich Cerkovnik, *Anne Arundel Community College*

Wondering how to reform a college physical science course? When Assistant Professor Rich Cerkovnik at Anne Arundel Community College was not satisfied with his students' level of interest in his physical science course, he began searching for new ways to teach. The search led him to MCTP, and to a realization that valuing student questions—to the point of building a course around them—would provide him with an answer to his own inquiry. The following interview gives a little insight into how this came about.

How would you describe your teaching style or philosophy before you entered the MCTP program?

I'd have to say it wasn't straight lecture, because within the first month of teaching I decided the lecture wasn't doing it. So I just tried different methods for the next few years—group work, different assessments and so on. I was adjusting a little bit at a time because I was reluctant to change dramatically. I was really searching for some new methods but I didn't have the big picture.



As Prof. Cerkovnik looks on, AACC students John Hardy and Jama Carey rollerblade their way through a demonstration of Newton's third law of motion, that is, "to every action there is an equal but opposite reaction." Inspired by class discussions, the students themselves suggested using rollerblades to help them understand this concept as well as Newton's other laws of motion.

What led you to the conclusion that straight lecture wasn't working?

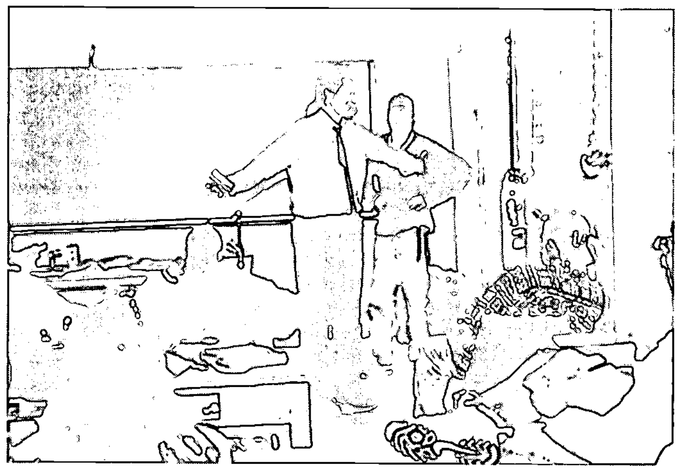
Students just weren't getting it. They didn't care. Exams and quizzes and tests weren't coming through; and in addition to that, the students just weren't excited and there's so much in science to be excited about. The reason I got into physics teaching is because I had so many uneventful physics classes, and I always thought I could do it better. But then of course I was teaching the way I was taught, and it just wasn't working.

How did joining MCTP help you?

By interacting with all the MCTP participants I could gather ideas and make judgments as to what would work for me. I gained a focus for my lab, which I needed. Then last semester I just changed my entire course and did everything—group work, questions, demonstrations, microcomputer-based labs, and was in general much more student-centered.

How is your course student-centered?

Although I provide an overall direction for the course, generally the class works off questions posed by students. In the lecture, for example, we do a lot of demonstrations that are driven by the students' questions about what they think will happen and why. I then set up activities that lead them where *they* want to go in terms of scientific understanding, that build to the point that the students make connections among concepts based on *their own* observations and analyses. Before we do demonstrations I have them write their ideas down, then they discuss them and offer their opinions. We then do the demonstration, observe it, and go back into the "why's" and whether or not we need to change our models. I also incorporated student questions into their journals so that I get at what they want to learn.



Prof. Cerkovnik goes for a spin to help students understand rotational inertia and its effect on rotational motion. Before the demonstration, he asked students to predict how and why different arm positions would affect rotational inertia and in turn how that would affect the motion.

Do you require students to pose questions?

At the beginning of the semester I required each student to generate a list of 15–20 questions. I had them read some material in the later chapters of the text that deal with astronomy—planetary motion, star formation, galaxies—things they're interested in. They were to pull out ideas, concepts that they did not understand, that they felt they needed to know in order to understand what was going on in those chapters. The students typed their questions into the lab computers, then I compiled them and organized demonstrations and activities to address them throughout the semester. I even used some of them as the basis for their final exams.

What tells you that the changes you made in your class are working?

One is that I get a larger variety of students asking questions and answering questions. Also, when I give them time to talk with a neighbor about a question, they appear to be talking about what's going on. Some of the best times are when I walk into the classroom, and I know it's working when I ask if there are any questions, and that's all I have to do. Before I know it the period's over, and we've set up demonstrations, possibly ones I've anticipated or perhaps ones we put together on the spur of the moment. Our science division has a new combined lab and lecture room, with easy access to demonstration equipment and student materials, which has been a great help.

You mean you walk in and ask "Are there any questions?" and that drives the day?

Yes. Generally I'll ask "Are there any questions?" and I'll wait as long as 2–5 minutes, because they need a certain amount of adjustment to this active learning. Sometimes students will come up with questions from the student-generated list. If I get no questions, then I ask a student to tell me what we did in the last class. This usually brings up some questions that give direction for the day's class.

How do you manage to keep the course on track while giving the students so much input into the day-to-day activities?

There is a healthy tension between my wanting to use every demonstration and activity my technician and I have planned and wanting the students to have a significant impact upon the direction of the course. It's important to me that each student feel that he or she has ownership of this course, but of course I have ownership of the course, too. Sometimes this means that we start with a student question and while we are investigating it, through a series of gentle nudges, I extend it and connect it to other concepts that I feel are important. Other times, I bypass a planned demonstration or activity because it no longer fits the direction the class is currently taking.

With this student-centered approach, do you know week-by-week where you're going?

Not week by week, but within a 3-week period we'll get to where I think we want to be, and we'll generally do it in association with the student questions. For my two sections of the course, the demonstrations I use in each class may be different because of what gets asked. I feel it's much more meaningful when they see their professor responding to their questions.

In teaching this new way, what's been the most surprising aspect? The most difficult?

The most surprising aspect has been the students' being able to drive a class. The hardest has been getting the students to do that. I did this by making very sure that within the first two weeks, any time that a student mentioned a question in a journal I addressed it within the next class period and indicated that it came from a journal. Or if a student asked a question and I didn't have the demonstration materials available at that time, we did it the next class period. This reinforced their questions and helped them realize that what they were saying was feeding back into the course and coming back out. I then saw an increase in the questioning and an increase in the journal writing in terms of things they were confused about. They would ask if we could do something about their questions, so they were taking more responsibility for the course. It was hard for me in that it took a lot of writing back to the students in their journals and spending time putting together stuff that I hadn't anticipated, to meet what they needed at that time.

What's been the easiest aspect of teaching this way? The most rewarding?

It's been coming in and saying "Are there any questions?" and having students ask wonderful questions that give the class direction. That makes things easy and fun. This is a rewarding structure—once you've got the students moving in this direction, it's such a wonderful experience to come in and ask what they want to talk about today. It's really rewarding to not have to force people to follow you on the board.

Appendix I

REFERENCES FOR READING

The references provided below were compiled by Genevieve Knight and John Layman, MCTP Co-Principal Investigators, as part of a Collaborative-wide effort to define a framework of guiding principles for MCTP courses.

Mathematics References (Genevieve Knight)

Artzt, A.F. & Newman, C.M. (1990). *How to Use Cooperative Learning in the Mathematics Classroom*. Reston, VA: National Council of Teachers of Mathematics.

Case, R. & Bereiter, C. (1984). From behaviorism to cognitive development. *Instructional Science, 13*, 141–158.

Cobb, P. & Steffe, L.P. (1983). The constructivist researcher as teacher and model builder. *Journal for Research in Mathematics Education, 14*, 83–94.

Confrey, J. (1990). *What constructivism implies for teaching.* (Journal For Research in Mathematics Education, Monograph No. 4). Reston, Va.: National Council of Teachers of Mathematics.

Davidson, N. (1990). *Cooperative Learning in Mathematics: A Handbook for Teachers.* Reading, MA: Addison-Wesley.

Davis, R.B. (1984). *Learning Mathematics: The Cognitive Science Approach to Mathematics Education*. Norwood, NJ: Ablex.

Davis, R.B., Maher, C.A. & Noddings, N. (1990). Constructivist views on the teaching and learning of mathematics. *Journal for Research in Mathematics Education, Monograph No. 4.*

Feldt, C. C. (1993, May). Becoming a teacher of mathematics: A constructive, interactive process. *The Mathematics Teacher, 86* (5), 400–403.

Gadanidis, G. (1994, February). Deconstructing constructivism. *The Mathematics Teacher, 87* (2), 91–96.

Goldin, G. A. (1990). *Epistemology, constructivism, and discovery.* (Journal For Research in Mathematics Education, Monograph No. 4). Reston, VA: National Council of Teachers of Mathematics.

Graves, N. & Graves, T. (Eds.). (1993). Cooperative learning and mathematics [Special Issue]. *Cooperative Learning, 14*(1). Santa Cruz, CA: International Association for the Study of Cooperation in Education.

Harmin, M. (1994). *Inspiring Active Learning: A Handbook for Teachers.* Alexandria, VA: Association for Supervision and Curriculum Development.

Hiebert, J. (Ed.). (1986). *Conceptual and Procedural Knowledge: The Case of Mathematics.* Hillsdale, NJ: Lawrence Erlbaum Associates.

National Council of Teachers of Mathematics. (1989). *Curriculum and Evaluation Standards For School Mathematics.* Reston, VA: NCTM.

National Council of Teachers of Mathematics. (1991). *Professional Standards for Teaching Mathematics.* Reston, VA: NCTM.

Noddings, N. (1990). *Constructivism in mathematics education.* (Journal For Research in Mathematics Education, Monograph No. 4). Reston, VA: National Council of Teachers of Mathematics.

Ross, R. & Kurtz, R. (1993, January). Making manipulatives work: A strategy for success. *Arithmetic Teacher, 40* (5), 254–257.

Simon, M.A. (1995). Reconstructing mathematics pedagogy from a constructivist perspective. *Journal for Research in Mathematics Education, 26*, 114–145.

Sowell, E.J. (1989). Effects of manipulative materials in mathematics instruction. *Journal for Research in Mathematics Education 20*, 498–505.

Steffe, L. P. (1990). *On the knowledge of mathematics teachers.* (Journal for Research in Mathematics Education, Monograph No 4). Reston, VA: National Council of Teachers of Mathematics.

Science References (John Layman)

American Institute of Physics. (1990). Operation physics—heat. *Operation Physics.* One Physics Ellipse, College Park, MD. AIP.

Andersson, B. (1979). Some aspects of children's understanding of boiling point. In W. F. Archenhold , R.H. Driver, A. Orton, & C. Wood-Roginsion (Eds.), *Cognitive Development Research in Science and Mathematics.* Leeds: University of Leeds Printing Service.

Arons, A. B. (1990). *A Guide To Introductory Physics Teaching.* (1st ed.) New York: John Wiley & Sons, Inc.

Arons, A. B. (1993, May). Guiding insight and inquiry in the introductory physics laboratory. *The Physics Teacher, 31*, 278–282.

Driver, R. & Bell, B. (1986, March). Students' thinking and the learning of science: A constructivist view. *School Science Review, 67* (240), 443–456.

Driver, R. (1992). Research in physics learning: Theoretical issues and empirical studies. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), *International Workshop on Research in Physics Learning: Theoretical Issues and Empirical Studies.* (pp. 403–409) Kiel: University of Kiel, IPN/Institute for Science Education.

Garfalo, F. & LoPresti, V. (1993, May). Evolution of an integrated college freshman curriculum. *Journal of Chemical Education, 70* (5), 352–359.

Greeno, J. G. (1992). Mathematical and scientific thinking in classrooms and other situations. *Enhancing Thinking Skills in the Sciences and Mathematics.* (pp. 39–61). Hillsdale, NJ: Laurence Erlbaum Associates.

Gunstone, R. F. (1992). Constructivism and metacognition: Theoretical issues and classroom studies. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), *Research in Physics Learning: Theoretical Issues and Empirical Studies.* (pp. 129–140). Kiel: University of Kiel, IPN/Institute for Science Education.

Halpern, D. (1992). A cognitive approach to improving thinking skills in the sciences and mathematics. *Enhancing Thinking Skills in the Sciences and Mathematics.* (pp. 1–14). Hillsdale, NJ: Laurence Erlbaum Associates.

Hewson, P. & Hewson, M. (1992). The status of students' conceptions. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), *Research in Physics Learning: Theoretical Issues and Empirical Studies,* (pp. 59–73). Kiel: University of Kiel, IPN/Institute for Science Education.

Hewson, P. W. & Thorley, N. R. (1989). The conditions of conceptual change in the classroom. *International Journal of Science Education, 11* [Special Issue], 541–553.

McDermott, L. C.& Shaffer, P. S. (1992). Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies. *American Journal of Physics 60*(11), 1003–1013.

Mestre, J. (1987, Summer). Why should mathematics and science teachers be interested in cognitive research findings? *Academic Connections,* 3–11.

National Research Council. (1996). *National Science Education Standards.* Washington, DC: National Academy Press.

Needham, R. & Hill, P. (1987, June). *Teaching strategies for developing understanding in science.* Children's Learning in Science Project, Center for Studies in Science and Mathematics Education. Leeds: University of Leeds.

Pfundt, H. & Duit, R. (Eds.). (1991). *Bibliography: Students' Alternative Frameworks and Science Education.* Kiel: University of Kiel, IPN/Institute for Science Education.

Posner, G. J., Strike, K. A., Hewson, P. W. & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66, 211–227.

Resnick, L. B. (1987). *Education and Learning to Think*. Washington, DC: National Academy Press.

Scott, P. H., Asoko, H. M. & Driver, R.H. (1992). Teaching for conceptual change: A review of strategies. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), *Research in Physics Learning: Theoretical Issues and Empirical Studies.* (pp. 310–329). Kiel: University of Kiel, IPN/Institute for Science Education.

Scott, P. H., Dyson, T. & Gater, S. (1987, June). *A constructivist view of learning and teaching in science.* Children's Learning in Science Project, Center for Studies in Science and Mathematics Education. Leeds: University of Leeds.

Tiberghien, A. (Ed.). (1980). Modes and conditions of learning. An example: The learning of some aspects of the concepts of heat. *Cognitive Development Research in Science and Mathematics.* Leeds: University of Leeds Printing Service.

Tobias, S. (1990). *They're Not Dumb, They're Different*. Tucson, AZ: Research Corporation.

Watson, B. & Konicek, R. (1990, May). Teaching for conceptual change: Confronting children's experience. *Phi Beta Kappan*, 681–685

General References

Brandt, R. (1992, April). On research on teaching: A conversation with Lee Shulman. *Educational Leadership*, 14–19.

Brooks, J. G. & Brooks, M. G. (1993). *In Search of Understanding: The Case for Constructivist Classrooms.* Alexandria, VA: Association for Supervision and Curriculum Development.

Elmore, R. F. (1992, April). Why restructuring alone won't improve teaching. *Educational Leadership*, 44–48.

Leinhardt, G. (1992, April). What research on learning tells us about teaching. *Educational Leadership*, 20–25.

Rosenshine, B. & Meister, C. (1992, April). The use of scaffolds for teaching higher-level cognitive strategies. *Educational Leadership*, 26–33.

Appendix II

HIGHLIGHTS OF NATIONAL RECOMMENDATIONS

The excerpts below emanate from recent, national efforts to delineate standards for mathematics and science education, and to establish guidelines for school reform based on learner-centered principles. These were selected, annotated, and distributed to all MCTP participants as part of a collaborative-wide effort, led by Genevieve Knight and John Layman, to define "guiding principles" for MCTP courses. (Note: When distributed in 1995, the materials from the National Research Council and the American Psychological Association were in draft form. The excerpts below are from the final products.)

Included are excerpts from:

- The National Council of Teachers of Mathematics (NCTM): *Professional Standards for Teaching Mathematics* and *Curriculum and Evaluation Standards for School Mathematics*
- The National Research Council (NRC): *National Science Education Standards*
- The American Psychological Association (APA): *Learner-Centered Psychological Principles: Guidelines for School Redesign and Reform*

Highlights from The National Council of Teachers of Mathematics (NCTM) Professional Standards for Teaching Mathematics (1991) and Curriculum and Evaluation Standards for School Mathematics (1989)

The *Professional Standards for Teaching Mathematics* rest on two assumptions:

- Teachers are key figures in changing the ways in which mathematics is taught and learned in schools.
- Such changes require that teachers have long-term support and adequate resources.

(NCTM, 1991, p. 2)

The NCTM teaching standards explicitly describe how the environment of mathematics classrooms must change to support active learning. There must be major shifts to:

- Classrooms as mathematical communities—away from classrooms as simply a collection of individuals;
- Logic and mathematical evidence as verification—away from the teacher as the sole authority for right answers;
- Mathematical reasoning—away from simply memorizing procedures;
- Conjecturing, inventing, and problem solving—away from an emphasis on mechanic answer-finding;
- Connecting mathematics, its ideas, and its applications—away from treating mathematics as a body of isolated concepts and procedures.

(NCTM, 1991, p. 3)

The development of teachers of mathematics is a life-long activity; standards for professional development rest on assumptions including the following:

- Teachers are influenced by the teaching they see and experience.
- Learning to teach is a process of integration of theory, research and practice.
- The education of teachers of mathematics is

an ongoing process; their growth requires commitment to professional development.

- There are level-specific needs for the education of teachers of mathematics; the learning needs of elementary, middle, and secondary school students must be addressed when considering teachers' knowledge of students and teaching.

(NCTM, 1991, p. 124–125)

The following quote is particularly relevant to MCTP's philosophy and goals:

> *Prospective teachers must be taught in a manner similar to how they are to teach—by exploring, conjecturing, communicating, reasoning and so forth. . . . all teachers need an understanding of both the historical development and current applications of mathematics. Furthermore, they should be familiar with the power of technology.*

(NCTM, 1989, p.253)

Highlights from
The National Research Council (NRC)
***National Science Education Standards* (1996)**

The goals for school science that underlie the *National Science Education Standards* are to educate students who are able to:

- Experience the richness and excitement of knowing about and understanding the natural world;
- Use appropriate scientific processes and principles in making personal decisions;
- Engage intelligently in public discourse and debate about matters of scientific and technological concern; and
- Increase their economic productivity through the use of knowledge, understanding, and skills of the scientifically literate person in their careers.

(NRC, 1996, p. 13)

Two of the guiding principles behind the *NSES* have been central to MCTP:

- Science is for all students.
- Learning science is an active process.

(NRC, 1996, p. 19)

The standards for science teaching are grounded in the following assumptions:

- What students learn is greatly influenced by how they are taught.
- The actions of teachers are deeply influenced by their perceptions of science as an enterprise and as a subject to taught and learned.
- Student understanding is actively constructed through individual and social processes.
- The actions of teachers are deeply influenced by their understanding of and relationships with their students.

(NRC, 1996, p. 28)

To guide and facilitate learning, teachers:

- Focus and support inquiries while interacting with students.
- Orchestrate discourse among students about scientific ideas.
- Challenge students to accept and share responsibility for their own learning.
- Recognize and respond to student diversity and encourage all students to participate fully in science learning.
- Encourage and model the skills of scientific inquiry, as well as curiosity, openness to new ideas and data, and skepticism that characterizes science.

(NRC, 1996, p. 32)

To engage in ongoing assessment of their teaching and of student learning, teachers:

- Use multiple methods and systematically gather data about student understanding and ability.
- Analyze assessment data to guide teaching.
- Use student data, observations of teaching, and interactions with colleagues to reflect on and improve teaching practice.

(NRC, 1996, p. 37–38)

To provide students with time, space, and the resources needed for learning science, teachers:

- Structure the time available so that students are able to engage in extended investigations.
- Create a setting that is flexible and supportive of science inquiry.
- Ensure a safe working environment.
- Make science tools, materials, print resources, media, and technological resources accessible to students.
- Identify and use resources outside the school.
- Engage students in designing the learning environment.

(NRC, 1996, p. 43)

To develop communities of science learners that reflect the intellectual rigor of scientific inquiry and the attitudes and social values conducive to science learning, teachers:

- Display and demand respect for the ideas and skills of all students.
- Enable students to have a significant voice in decisions about the content and context of their work and require students to take responsibility for the learning of all members of the community.
- Nurture collaboration among students.
- Facilitate ongoing formal and informal discussion based on a shared understanding of rules of scientific discourse.

(NRC, 1996, p. 46)

Highlights from
The American Psychological Association (APA)
***Learner-Centered Psychological Principles: Guidelines for School Redesign and Reform* (1995)**

The following 14 principles are intended to deal holistically with learners in the context of real-world learning situations. Thus, they are best understood as an organized set of principles; no principle should be viewed in isolation. These principles are intended to apply to all learners—from children, to teachers, to administrators, to parents, and to community members involved in our educational system (APA, 1995).

Cognitive and Metacognitive Factors

- *Nature of the learning process.* The learning of complex subject matter is most effective when it is an intentional process of constructing meaning from information and experience.
- *Goals of the learning process.* The successful learner, over time and with support and instructional guidance, can create meaningful, coherent representations of knowledge.
- *Construction of knowledge.* The successful learner can link new information with existing knowledge in meaningful ways.
- *Strategic thinking.* The successful learner can create and use a repertoire of thinking and reasoning strategies to achieve complex learning goals.
- *Thinking about thinking.* Higher order strategies for selecting and monitoring mental operations facilitate creative and critical thinking.
- *Context of learning.* Learning is influenced by environmental factors, including culture, technology, and instructional practices.

Motivational and Affective Factors

- *Motivational and emotional influences on learning.* What and how much is learned is influenced by the learner's motivation. Motivation to learn, in turn, is influenced by the individual's emotional states, beliefs, interests and goals, and habits of thinking.
- *Intrinsic motivation to learn.* The learner's creativity, higher order thinking, and natural curiosity all contribute to motivation to learn. Intrinsic motivation is stimulated by tasks of optimal novelty and difficulty, relevant to personal interests, and providing for personal choice and control.

- *Effects of motivation on effort.* Acquisition of complex knowledge and skills requires extended learner effort and guided practice. Without learners' motivation to learn, the willingness to exert this effort is unlikely without coercion.

Developmental and Social

- *Developmental influences on learning.* As individuals develop, there are different opportunities and constraints for learning. Learning is most effective when differential development within and across physical, intellectual, emotional, and social domains is taken into account.
- *Social influences on learning.* Learning is influenced by social interactions, interpersonal relations, and communication with others.

Individual Differences

- *Individual differences in learning.* Learners have different strategies, approaches, and capabilities for learning that are a function of prior experience and heredity.
- *Learning and diversity.* Learning is most effective when differences in learners' linguistic, cultural, and social backgrounds are taken into account.
- *Standards and assessment.* Setting appropriately high and challenging standards and assessing the learner as well as learning progress—including diagnostic, process, and outcome assessment—are integral parts of the learning process.

References

American Psychological Association. (1995). *Learner-Centered Psychological Principles: Guidelines for School Redesign and Reform.* [Online]. Available: http://www.apa.org/ed/lcp.html [1997, Dec 18].

National Council of Teachers of Mathematics. (1989). *Curriculum and Evaluation Standards for School Mathematics.* Reston, VA: NCTM. Also available: http://www.enc.org/reform/journals/ENC2280/280dtoc1.htm [1997, Dec 18].

National Council of Teachers of Mathematics. (1991). *Professional Standards for Teaching Mathematics.* Reston, VA: NCTM.

National Research Council. (1996). *National Science Education Standards.* Washington, DC: National Academy Press. Also available: http://www.nap.edu/readingroom/books/nses/ [1997, Dec 18].

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