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ABSTRACT

This document is a general consensus report from the college and university teachers who took part in a workshop on entry-level undergraduate courses in science, mathematics, and engineering. The workshop was in response to an assessment made by a Sigma Xi National Advisory Group (NAG) in its 1989 report on undergraduate education in science, mathematics, and engineering. That report identified entry-level courses in these areas to be the "watersheds" that determined the place of science, mathematics, and engineering in the lives of those who go to college and determined the vitality of the academic departments in these disciplines. The participants in both NAG and the workshop were selected so as to achieve maximum diversity in disciplines, types of academic institutions, and the U.S. population (including the traditionally underrepresented). The intent was for these groups to identify and, to some degree, analyze problems and issues common to multiple disciplines and multiple types of institutions. Sections 2, 3 and 4 of this report present a collective participant perspective of: (1) the needs and problems of entry-level students; (2) the role of the faculty in delineating missions of entry-level courses, initiating change and bringing about change consistent with those missions; and (3) the role of institutions and their administrators in facilitating creative structuring and restructuring of curricula and creative teaching of entry-level courses. Section 5 deals with the role of assessment in undergraduate science courses. A list of participants, section 1 of the Sigma Xi NAG report, abstracts of papers presented at the workshop, a general education program built around the concept of evolution, and participant initiatives are appended. (KR)

ENTRY-LEVEL UNDERGRADUATE COURSES IN SCIENCE, MATHEMATICS AND ENGINEERING: AN INVESTMENT IN HUMAN RESOURCES

An Initiative of
Sigma Xi, The Scientific Research Society,
Committee on Science, Mathematics and Engineering Education

Supported by:
The National Science Foundation
and
The Johnson Foundation

Wingspread
Racine, Wisconsin
June 21-24, 1990

A workshop of college and university teachers of science, mathematics and engineering met at Wingspread, Racine, WI, June 21-24, 1990 under the auspices of the Johnson Foundation and the Division of Undergraduate Science, Engineering, and Mathematics Education, National Science Foundation Directorate of Education and Human Resources, to explore ways of serving students in entry-level courses better, and through the students, serving the professions and society better.

This general consensus report from the workshop addresses the participants' perceptions of student needs and problems, and of the role of faculties, academic institutions and supporting institutions in serving students better.

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8 January 1990

Dr. Luther S. Williams
Assistant Director
Directorate for Education and Human Resources
National Science Foundation
Washington, DC 20550

Dear Dr. Williams:

We are pleased to transmit to you and our colleagues in the research and academic communities a report resulting from a Sigma Xi-sponsored workshop on entry-level courses in science, mathematics, and engineering. Convened with support from the Foundation, and the cooperation of The Johnson Foundation, the workshop met at the Wingspread Conference Center in Racine, Wisconsin, on 21-24 June 1990.

In the report that follows, Dr. Anna Harrison, Chair of Sigma Xi's Committee on Science, Mathematics and Engineering Education, presents the outcomes and recommendations of a workshop at which college and university teachers of science, mathematics, and engineering explored appropriate missions of entry-level courses for undergraduates; these missions were examined in view of the needs of students, society, and the professions. More importantly, the report proposes mechanisms to fulfill these missions, presents recommendations that are well-founded and appropriate, and courageously proposes needed change in the undergraduate educational system.

Sigma Xi believes that this report is a fair and unbiased presentation on the major problems in undergraduate education and, in particular, on the issues involved in entry-level courses. For example, the report demonstrates a deep understanding of the special problems in undergraduate education faced by women, minorities, and individuals with physical disabilities.

As the honor society of research scientists, Sigma Xi has a special responsibility to ensure creative and dynamic growth of the research community and the attainment of an informed public. We believe that Dr. Harrison's report is a significant step in identifying fundamental issues that need to be addressed in order to create a dynamic system of undergraduate education in science, mathematics, and engineering that benefits everyone.

Sigma Xi will continue to pursue its responsibilities in this area. We look forward in this effort to further discussions with you and with other leaders concerned with undergraduate education in science, mathematics, and engineering.

Sincerely yours,

Fred Shair

Fredrick H. Shair
President

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"The great challenge in teaching is to engage the student effectively in structuring and restructuring his or her own mental constructs." (page 10)

"Broadly stated, entry-level courses should provide the foundation that enables all students to continue their education in science, mathematics and engineering, both formally and informally." (page 8)

"The primary goal of change is to evolve a more open system of education that fosters the continuous evolution of entry-level courses consistent with the changing needs of students and society and the continuous expansion of science, mathematics, engineering and technology." (page 10)

"An institution that encourages, supports and rewards creativity in undergraduate teaching in much the same way it encourages, supports and rewards creativity in research fosters the synergism of teaching and research." (page vi)

"The nature and quality of undergraduate entry-level courses can be influenced, directly or indirectly, by any organization that supports college and university science, mathematics and engineering in any way and at any level, or assesses the quality of programs in science, mathematics and engineering." (pages 19-20)

Findings in Brief

Background

This document is a general consensus report from the college and university teachers who met June 21-24, 1990, in a workshop on entry-level undergraduate courses in science, mathematics and engineering. The workshop was in response to an assessment made by a Sigma Xi National Advisory Group (NAG) in its report (1989) on undergraduate education in science, mathematics and engineering. That report identified entry-level courses in these areas to be the "watersheds" that determined the place of science, mathematics and engineering in the lives of those who go to college and determined the vitality of the academic departments in these disciplines.

Participants

Problems and Issues

The participants in both NAG and the workshop were selected to achieve maximum diversity in disciplines (social sciences, natural sciences, mathematics and engineering), diversity in types of academic institutions (2-year colleges through research universities), and the diversity in the U.S. population including the traditionally under-represented (women, minorities and persons with physical disabilities). The intent was for these groups to identify and, to some degree, analyze problems and issues common to multiple disciplines and multiple types of institutions — the problems and issues not specific to a discipline and not specific to an institution, or even to a type of institution. The problems and issues identified are thought to be generic to higher education in these areas.

Higher Education

We propose that these problems and issues are best addressed as problems and issues of higher education by the entire undergraduate education complex and others interested

- in the nature and quality of undergraduate education in science, mathematics and engineering and
- in the manner in which education in these areas serves students -- and through the students serves society.

The Report

The problems and issues surrounding entry-level courses are remarkably complex for anything that seems as simple and elementary as undergraduate entry-level courses. Sections 2, 3 and 4 of this report present a collective participant perspective of

Students

Faculty

Institutions

- the needs and problems of entry-level students,
- the role of the faculty in delineating missions of entry-level courses, initiating change and bringing about change consistent with those missions, and
- the role of institutions and their administrators in facilitating creative structuring and restructuring of curricula and creative teaching of entry-level courses. This includes not only colleges and

universities but also all of those other institutions that support science, mathematics and engineering in any way in colleges and universities or assess the nature and quality of undergraduate education in colleges and universities.

Many changes are taking place in attitudes toward and perceptions of undergraduate education. Two very significant changes are:

Broader Concept of Education

- the traditional concept of education in science, mathematics and engineering as the study of accumulated knowledge is giving way to a broader concept, reducing the emphasis on accumulated knowledge and expanding the attention given to and experience with the processes of investigation that are science, mathematics and engineering, and

Accessibility

- much greater value is being placed on ready accessibility to all students of meaningful experience with science, mathematics and engineering.

Dynamic Systems of Education

The confluence of these changes in perceptions and values collides with a largely inflexible system of undergraduate education. We conclude from this that initiatives for change in entry-level courses should lead to the development of a dynamic system of undergraduate education free to respond to changing needs of students and of society, the expansion of knowledge, and the development of pedagogical methodologies and technologies.

By adapting to the needs of students, such a system may be a much more effective and natural mechanism of recruiting students, both white males and the traditionally underrepresented (women, minorities and persons with physical disabilities), to careers in science, mathematics and engineering than the current practice of endeavoring to assist students to adapt to the current system of undergraduate education.

We further propose that key to the development of a dynamic system of undergraduate education is a faculty that has freedom, support and reward for creative teaching and for creative structuring and restructuring of courses. Two possible consequences of this freedom, support and reward are that fewer faculty may flee from involvement in entry-level courses and that the courses evolved may be more attractive to all students, particularly those from groups traditionally underrepresented.

Synergism of Teaching and Research

An institution that encourages, supports and rewards creativity in undergraduate teaching in much the same way it encourages, supports and rewards creativity in research fosters the synergism of teaching and research. This is a synergism that contributes to the quality of research, the quality of education at all levels, the professional development of the faculty, and the personal and professional development of both undergraduate and graduate students. It is the quality of a college's or university's teaching and research together with the accomplishments of its faculty and students that are major factors in determining its reputation among its peers and its image within the community it serves.

Infrastructure of Institutions

To develop and sustain a dynamic system of undergraduate education may require changes in the infrastructure of colleges and universities and also some changes in institutions that either support or assess the performance of colleges and universities. The potential return in terms of the development of human resources, the participation of an informed public in the resolution of societal issues, the nature and quality of precollege education, and the vitality of academic departments is both large and essential to the well-being of the nation.

Recommendations

The following recommendations are made by the workshop:

General Recommendation

TO ALL CONCERNED ABOUT THE NATURE AND QUALITY OF EDUCATION IN SCIENCE, MATHEMATICS AND ENGINEERING AT ANY LEVEL, we recommend recognition of the key roles of entry-level undergraduate courses in producing a knowledgeable public as well as educating future scientists, mathematicians, and engineers. We urge your participation in, or your support of, initiatives to provide more appropriate entry-level courses.

Sigma Xi

TO SIGMA XI we recommend:

- Inclusion of individuals in areas related to education in the annual Sigma Xi speaker list.
- Inclusion of research in education in the Sigma Xi research grants program.
- Expansion of the coverage of education in *American Scientist.*
- Establishment of an information resource center for initiatives in entry-level undergraduate teaching.

Sigma Xi Chapters and Clubs

TO SIGMA XI CHAPTERS AND CLUBS we recommend organization of workshops or other activities that enable faculty and academic administrators to explore critical issues involving entry-level courses and to plan creative solutions of identified problems.

Congress and NSF

TO CONGRESS AND THE NATIONAL SCIENCE FOUNDATION we recommend selection and support of programs essential to building and sustaining dynamic systems of undergraduate education accessible to all undergraduates and continuously responsive to expansions in knowledge, developments in both scientific and pedagogical methodologies and technologies, changing needs of students and society, and changing demographics of academic institutions and the workforce. Such programs include:

- Research on how undergraduates think and learn, and on evaluation of teaching methodologies.
- Development of technologies and methodologies appropriate to investigative laboratories and lecture exploration of the processes of investigation.
- Development of entry-level investigative laboratories that enable students to do science, mathematics and engineering and to experience the excitement of discovery.

• Development of entry-level courses for technically oriented students, and also entry-level courses for general education, that encompass carefully selected topics from accumulated knowledge and experience with processes of investigation. Such courses should explore the development and use of concepts, minimize memorization and actively engage the student in learning.

• Establishment of an information resource center for entry-level undergraduate course initiatives.

• Support of workshops and conferences that enable faculties and administrators to exchange information, identify issues and seek mechanisms of resolving those issues.

Colleges and Universities

TO ADMINISTRATORS OF COLLEGES AND UNIVERSITIES we recommend the implementation of policies and practices that create and sustain a dynamic system of undergraduate education in science, mathematics and engineering that enhances the synergism of education and research in your institution and makes accessible to all undergraduates meaningful entry-level courses. To achieve a dynamic system of education requires rethinking and revising the content of courses, the methodologies of teaching and the incentive-support-reward system for those who teach. We urge that your institution adequately encourage, support, and reward creative teaching.

Department Heads

TO DEPARTMENT HEADS IN COLLEGES AND UNIVERSITIES we recommend implementation of policies and practices that create and sustain entry-level undergraduate courses in science, mathematics and engineering that are attractive and rewarding to teach, and accessible and meaningful to all undergraduates. To achieve such courses requires rethinking and revising the content of entry-level courses, the methodologies of teaching and the incentive-support-reward system for those who teach. We urge that your department adequately encourage, support and reward creative teaching.

Foundations, Government Agencies and Corporations

TO ADMINISTRATORS OF FOUNDATIONS, GOVERNMENT AGENCIES AND CORPORATIONS we recommend evaluation of the total effect of policies and practices of your institution in supporting science, mathematics and engineering in colleges and universities on the policies and practices of those institutions in regard to undergraduate education—particularly entry-level courses.

Professional Societies

TO PROFESSIONAL SCIENCE, MATHEMATICS AND ENGINEERING SOCIETIES we recommend evaluation of the effect of the policies and practices of your society in attracting students to your profession and enhancing the undergraduate preparation of these students on the policies and practices of academic institutions in regard to entry-level courses for technically oriented students and also entry-level courses for general education.

Accrediting Organizations

TO ACCREDITING ORGANIZATIONS we recommend evaluation of the effect of your policies and practices of accreditation on the dynamics of undergraduate educational systems.

1 The Workshop

Background

This workshop on entry-level undergraduate courses in science, mathematics and engineering was based on the report of a Sigma Xi National Advisory Group (NAG)[1]. That report identified entry-level courses as "watersheds" that determine not only the place of science, mathematics and engineering in the lives of those who go to college, but also the vitality and productivity of undergraduate programs in colleges and universities.

The intent of this workshop was to enable a diverse group of college and university teachers, committed to improving entry-level undergraduate programs, to explore together:

- The missions of undergraduate entry-level courses appropriate to modern science, mathematics and engineering,
- The contemporary needs of students, the professions and society, and
- Feasible ways (mechanistic options) of fulfilling those missions.

Participants

The participants encompassed the social sciences, natural sciences, mathematics and engineering; the traditionally under-represented (women, minorities and persons with physical disabilities); the spectrum of institutions from two-year colleges to research universities; and the spectrum of experience from a few years beyond the graduate degree to the retired. This diversity was achieved by selection from among self-nominations and nominations made by others in response to advertisements in *Science* and *The Chronicle of Higher Education*, and an item in the *Sigma Xi Newsletter*.

Invited Papers

Four invited presentations contributed to the knowledge base upon which the deliberations proceeded. A long abstract of each of these presentations is given in Appendix 3.

Two presentations addressed higher order thinking and undergraduate student learning and reasoning: *Higher Order Thinking in*

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1 *An Exploration of the Nature and Quality of Undergraduate Education in Science, Mathematics and Engineering*, 1989. A copy can be obtained from Sigma Xi Headquarters by calling 800-243-6534. The first section dealing with the missions of undergraduate programs in science, mathematics and engineering, and the nature of these disciplines, is reproduced in Appendix 2 of the present report.

Mathematics and Other Disciplines, by Alan H. Schoenfeld[2], and *Student Learning and Reasoning* by Jack Lochhead[3].

Two described innovative endeavors in progress: *Using New Pedagogy and Technology to Teach Experience Based Entry-Level Science*, by Priscilla Laws[4], and *Integrated First-Year Curriculum in Science, Engineering and Mathematics* by Jeffrey E. Froyd[5].

A fifth invited presentation provided an update on the structure and undergraduate programs of the National Science Foundation Directorate of Education and Human Resources: *A Report from the National Science Foundation* by Edward W. Ernst[6].

More than fifty percent of the workshop was devoted to participant discussion in an alternating pattern of small working groups and plenary sessions. It is the intent of this report (among other things) to reflect the participants' search to understand the attitudes, perceptions and problems of students; their diligence in enhancing the quality of their teaching; their commitment in bringing about change and sustaining the benefits achieved by change; and their frustrations in dealing with a highly structured system of education and in securing support internally and externally for their endeavors.

Report

This report deals with the perspectives of the participants of the current state of entry-level courses and developments that would better serve the students — and through them the professions and society. The next three sections of the report address the student, the faculty, and the institutional aspects of entry-level courses. The primary focus is upon the roles of faculties and institutions in delivering to students educational services appropriate to the continuously evolving nature of science, mathematics and engineering and the continuously evolving needs of students and society.

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2 Professor of Education and Mathematics, Graduate School of Education, EMST, University of California, Berkeley.

3 Director, Scientific Reasoning Research Institute, Hasbrouck Laboratory, University of Massachusetts at Amherst.

4 Professor, Department of Physics, Dickinson College.

5 Associate Professor of Electrical and Computer Engineering, Rose-Hulman Institute of Technology.

6 Program Director, Division of Undergraduate Science, Engineering and Mathematics Education, Directorate of Education and Human Resources, National Science Foundation.

2 Entry-Level Courses and The Students

Student Options

For students, entry-level courses in science, mathematics and engineering are the access routes to many opportunities. Even though students are the only clientele for entry-level courses, they have very little influence on the design and delivery of these courses. Their only options are to take a course or not to take it. For many students, either option may be very costly. Taking a course may doom an inadequately prepared student to almost certain failure. Not taking the course may severely limit the student's opportunities even to the extent of forfeiting long-held professional goals.

In this section of the report we explore

- A simple model of learning helpful in understanding student problems with science, mathematics and engineering,
- Some of the aspirations and perceptions of students, and
- Some of the characteristics of entry-level courses that contribute to students' difficulties.

The Learning Model

Each student is an individual with a set of perceptions, a set of mental constructs, that encompasses the world and its cultures as he or she has encountered and perceived them. New experiences and information may be compatible with a student's constructs and easily incorporated into these constructs. That is the easy part of learning. However, some new experiences and information will be counter-intuitive in terms of a student's constructs. This is the hard part of learning — the challenge of learning. Ways must be found to accommodate this new experience or information into existing mental constructs or ways must be found to restructure existing mental constructs.

The Challenge of Learning

Counter-intuitive experience or information could be:

- Rejected as nonsense, because it is not consistent with existing mental constructs,
- Accepted, knowing (or not knowing) that it is not consistent with existing mental constructs, by structuring an alternate mental construct, or
- Accepted, knowing that it is not consistent with the existing mental constructs, by modifying existing mental constructs to accommodate the new experience or information.

All of the above are characteristic of active involvement in learning.

The 15% Cohort of Highly Motivated Freshmen

In his analysis of longitudinal studies of undergraduate students, Kenneth C. Green[7] reports that there is a cohort of academically-able and intellectually motivated students who enter college with genuine interest in the sciences expecting to major in science. In 1988 this cohort was approximately 15% of all first time entering freshmen in four-year colleges and universities. In these analyses Green uses the word "science" to encompass the natural sciences, mathematics and engineering. Data are not available for the social sciences. Throughout this report we shall use the phrase *15% cohort* to designate the group of academically-able and intellectually motivated students who enter college with genuine interest in majoring in "science" and the phrase *85% cohort* to designate all other entering students.

Green also reports that in recent years only approximately 50% of the talented and interested cohort of students aspiring to major in science (the 15% cohort) complete a major in science. The dropout is particularly troubling since science attracts a disproportionate number of academically-able freshmen. Much of this huge dropout occurs before the sophomore year, indicating that many entry-level programs in science do not compete well for the long-term commitment of half of the academically-able and intellectually motivated students who enter college expressing genuine interest in science.

It is important to learn how these students assess their college experiences with science. Many report the material to be dull, the classes to be boring, the experience to be unrewarding and the burdens of memorizing great quantities of material overpowering. They also report the laboratories to be dull and the human environment to be impersonal and in many cases hostile.

The 85% Cohort

What of the 85% cohort of freshmen? This is a very large heterogeneous group. Individual students within the group may have a very high level of one or two of the three identifying characteristics (academic ability, intellectual motivation and interest in majoring) but not all three. Nearly all of these students will be required to take some work in science and mathematics in college in support of career goals or in fulfillment of graduation requirements. Some may major in

7 This work has been reported in a number of places, including Appendix 4 of the Sigma Xi National Advisory Group Report and "A Profile of Undergraduates in the Sciences," *American Scientist*, vol. 77, Sept.-Oct., 1989, p. 476.

science, mathematics and engineering but past experience indicates that very few do. Some of these students are academically-able and well prepared by their secondary school programs to pursue academic work in science, mathematics or engineering[8].

This is, however, not characteristic of the group. Many have had traumatic experiences with precollege science and mathematics. Many have limited backgrounds in science and mathematics. Many will seek the least demanding course(s) to fulfill requirements without regard for any benefits that may accrue to them other than fulfilling the requirements for graduation. It is well to remember that this 85% cohort includes most of the students who will teach science and mathematics in the elementary schools and also most of those who will become the social, economic and political leaders of the nation. To the extent that these students minimize their education in science, mathematics and engineering, their academic institution is failing to fulfill its mission to serve its students and our society.

It is characteristic of many in this group that they are apprehensive about their abilities and backgrounds, and perceive themselves as being incapable of doing science, mathematics and engineering. The great majority of these students do not perceive entry-level courses in these areas as experiences from which they can derive benefit. As a consequence, they make decisions about their education that deprive themselves of the empowerment inherent in a background in these areas, and also deprive the nation of rich human resources in many areas. This is particularly true for females, the poor and members of cultural minorities. These students see little positive relation of science, mathematics and engineering to their own lives. They suffer from scientific and technological illiteracy and are prone to be a part of that large segment of the public alienated by science, mathematics, engineering and technology.

Characteristics of Entry-Level Courses

We turn now to a consideration of two characteristics of entry-level courses that add credence to the litany of student woes. The quantity of material that must be memorized may be horrendous. The human environment is frequently impersonal and it may be hostile.

Many entry-level courses are devoted almost exclusively to the

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8 It is these students that are the focus of the Sheila Tobias study *They're Not Dumb, They're Different: Stalking the Second Tier* supported and published by The Research Corporation (1990).

presentation of accumulated knowledge with very little attention being given to the processes of investigations that are science, mathematics and engineering. Students frequently come face to face with the tyranny of knowledge — the great quantity of accumulated knowledge crammed into a course — and the concomitant tyranny of testing. In such courses there may be very little to encourage or enable students to discover the nature of science, mathematics and engineering, or the excitement of investigation, or the relation of science, mathematics and engineering to their own lives. The impression may even be given that science, mathematics and engineering are static bodies of knowledge to be memorized.

In the preceding paragraph "accumulated knowledge" is used in the collective sense to include the data base (empirical knowledge), concepts (theories, models, principles, derivations, proofs), and the methodologies and algorithms of the various disciplines. Some of this is of historical value and fascinating from the standpoint of historical development — although not directly relevant to current problems and issues. The compulsion to overload courses is very strong — and well motivated.

Design of Courses for the 15% Cohort

In many disciplines, the entry-level courses have been designed for students who expect to major in that discipline, even though it is quite clear that only a very small percentage of the students taking the courses expect to major in that discipline. The great majority of students are there to support other professional goals or to fulfill distributive graduation requirements. Traditionally, again in some disciplines, such courses are designed to move the most able and most committed into the major sequence with an extensive body of knowledge and command of an array of calculational and laboratory techniques. Such courses are designed to be a part of major sequences. It is not thought to be necessary that these courses be balanced units within themselves. It is expected that students can discover later how exciting the processes of investigation are and also discover the relation of the discipline to other disciplines and to their own lives.

The intent to move the most able and most committed into the major sequence has very significant consequences. Entry-level courses are quality control mechanisms to remove the less able and the less committed. That coupled with the high emphasis on quantity of knowledge rewards the student willing to memorize. This is a mechanism that may also eliminate some very innovative students who enjoy making-do with whatever is at hand in solving problems and who are not enamored of memorization. Such a mechanism makes the system seem very cold, even hostile, to students.

The 85% Cohort

What of the entry-level courses for the 85% cohort? Universities provide an array of service courses and other courses that satisfy general education requirements. These may be pale copies of the entry-level courses for majors or specially designed topic courses frequently designed around societal issues. Colleges, on the other hand, with smaller and more homogeneous student bodies may offer only one entry-level course in a discipline.

Barriers to Student Success

It is indeed a challenge to serve students who arrive in college programmed for either flight from or disaster with science, mathematics and engineering by

- Their alienation to science, mathematics and engineering,
- Their perceptions of their own abilities, and
- Their mental and cultural constructs that are limited and frequently incompatible with the new experiences and information inherent in the college experience.

One of the great barriers to success in college is the array of misconceptions that students bring with them. In the opening lecture of the workshop, Alan H. Schoenfeld delineated common misconceptions of mathematics and problem solving:

- There is only one way to do it.
- Mathematics is passed out from above to be memorized.
- Mathematics is a solitary activity.
- All soluble problems can be solved in five minutes.
- Formal proof has nothing to do with real problems.

Such misconceptions must be identified and addressed directly.

Many students have yet to discover that colleges and universities, at their best, are environments in which seeking, questioning and learning are expected to be the norm for both students and faculty. As a consequence they may place false pressures on themselves and on the faculty. They fail to recognize that to not know and to ask questions is to learn, not to exhibit stupidity. By not asking questions students cut themselves off from help. Very intelligent students may never become engaged in the learning process and as a consequence may even fail.

The presentation of accumulated knowledge, important as that may be, is not in itself adequate to meet the needs of many students. Students must be enabled to become engaged in learning.

3 Faculty

Role of Faculty

Faculty design, develop and deliver the entry-level educational services of a college or university within the structure and practices of their institution. This section reports the collective participant perspective of the manner in which these educational services could better serve students, and through them, the departments, the institutions, the professions and the public.

Attitudes, Perspectives and Values

The participants were well aware of the problems associated with entry-level courses and many have made substantial commitments of time and energy in bringing about change in their own institutions (Appendix 5). They recognized attitudes, perceptions and values of the past as key to the current state of entry-level courses. Recent changes in attitudes, perspectives and values were seen as key to the potential willingness of academic communities to reassess entry-level courses and initiate significant change. These new and evolving perspectives make the present time particularly auspicious for the initiation and development of changes in entry-level courses.

Consistent with this evolving awareness the word "values" was added to one of the seven fundamental topics[9] identified by the National Advisory Group. That topic, "Attitudes, Perspectives and Values of Students, Faculties, Administrations and the Public" was ever present during discussions at the workshop and considered by this workshop to be the most important of the seven fundamental topics that should be addressed in charting policy for undergraduate education. We shall return repeatedly to various aspects of this topic.

Missions of Entry-Level Courses

The mission statement of the National Advisory Group (Appendix 2) for undergraduate education in science, mathematics and engineering was accepted by the participants as a starting point for consideration of entry-level courses. Broadly stated, entry-level courses should provide a foundation that enables all students to continue their education in science, mathematics and engineering both formally and informally. For those specializing in technical areas, this would in-

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9 The seven fundamental topics identified by the National Advisory Group were: Quality of Instruction; Quality of the Curriculum; Quality of the Human Environment; Quality of the Physical Environment; Accessibility and Flexibility of Curricula Essential for Student Mobility; Attitudes and Perceptions of Students, Faculties, Administrations, and the Public; and Promises and Special Needs of Traditionally Underrepresented Groups in Science, Mathematics and Engineering.

clude more advanced courses. For other students, this could mean admission to upper class courses for general education or it could mean continuing education through mechanisms such as the mass media throughout their life spans.

There was, however, a sense of need for a more detailed delineation of mission arising from an appreciation

- Of how little many entrance level students, even well prepared students, understand about the nature of science, mathematics and engineering; the relation of these areas to their own lives; and the personal empowerment inherent in education in these areas,

- Of how strongly alienated many entrance level students are from science, mathematics, engineering and technology and how strongly convinced they are that they cannot do science, mathematics and engineering, and

- Of how probable it is that an entry-level course may be the last academic experience a student will have with these areas.

Essentially the entire student population is involved and the detailed mission statement reflects the faculty perception of the manner in which entry-level courses can serve all students and through them society. These detailed missions include encouraging and enabling all students **to begin**

- To develop command of carefully chosen topics from accumulated knowledge,

- To understand science, mathematics and engineering as processes of investigation — as ways of knowing,

- To have hands-on experience with investigations and to discover the joy and satisfaction of discovery,

- To discover the aesthetics and human dimensions of science, mathematics, engineering and technology,

- To discover they can understand aspects of science. mathematics and engineering,

- To understand the powers and limitations of science, mathematics and engineering,

- To discover and appreciate the influence of science, mathematics, engineering and technology on our lives,

- To understand the synergisms among science disciplines and the synergisms among science, mathematics and engineering,

- To understand the mechanisms through which the public influences, even determines, the direction and rate of development of science, mathematics, engineering, and technology, and

- To understand the personal empowerment, from the standpoint of employment and also from the standpoint of personal community leadership, inherent in an academic background in science, mathematics and engineering.

The rigidity of current academic practices in engineering, mathematics and many scientific disciplines make it difficult, if not impossible, to implement these missions. This rigidity is exemplified by the text books that sell well for entry-level chemistry courses. All of these books are very much alike. All are overpowering in content, physical dimensions and mass. In many disciplines entry-level courses most commonly made available to students have become highly stereotyped.

The Tyranny of Stereotyped Curricula

We can only speculate about the source of such a high resistance to change in fields that are perhaps the most rapidly expanding fields of endeavor in the world with corresponding rapid expansions in accumulated knowledge. One factor is certainly the tyranny of knowledge — a tyranny derived from the compulsion to cram so much accumulated knowledge into each course. The pressure of accumulated knowledge has squeezed out much of the pleasure and excitement of learning. It also has squeezed out the freedom essential to innovation and creative experimentation in curricular development and in teaching. We now have the tyranny of stereotyped curricula. Taken together, the tyranny of knowledge and the tyranny of stereotyped curricula have greatly diminished the intellectual challenge and the excitement of both teaching and learning. Both teaching and learning often become dull chores and consequently deemed unworthy of personal endeavor.

Goal of Change

The primary goal of change is to evolve a more open system of education that fosters the continuous evolution of entry-level courses consistent with the changing needs of students and society and the continuous expansion of science, mathematics, engineering and technology.

Challenge In Teaching

The great challenge in teaching is to engage the student effectively in structuring and restructuring his or her own mental constructs. The magnitude of the challenge in teaching entry-level courses is enhanced by the diversity of the students — diversity in such things as interest in the subject, perceived congruence or dis-congruence of the subject with his or her cultural values, perceived relevance of the subject to his or her future, attitude toward science and mathematics in general, assessment of the adequacy of his or her preparation, assessment of the time and energy he or she can or is willing to invest in the course, and assessment of his or her capacity to be successful in the course. Such diversity in students argues for diversity in the approaches used in teaching entry-level courses.

Incorporation of Accumulated Knowledge and Processes of Investigation

Compulsion to present a maximum amount of accumulated knowledge fosters the presentation of an impeccably organized body of knowledge even to the extent of essentially neglecting the processes of investigation that are science, mathematics and engineering, and almost presenting concepts as facts to be memorized. A concern for the active participation of the student in his or her learning fosters the careful selection of manageable portions of accumulated knowledge and the utilization of approaches that enable the student to explore the processes of science, mathematics and engineering, to develop concepts and to build constructs essential to continued learning. Tests appropriate to content oriented courses reward memorization; tests appropriate to investigation oriented courses reward understanding of process and concepts.

Methodologies of Teaching

The search is on to learn how to use existing methodologies, develop other methodologies and devise courses that enable students to master carefully chosen portions of accumulated knowledge and also to become involved in the processes of investigation.

Lectures

Lecturing can be, and often is, a superb methodology for presenting knowledge. It is probably most effective with students who are already engaged in active learning, who are experienced in effectively structuring and restructuring their own mental constructs, and who have developed the habits of questioning, probing and correlating. But the traditional formal lecture, particularly one loaded with the presentation of facts to be memorized, isn't effective with many students. That argues for enhancing lectures with experiments and lecture demonstrations, for utilizing computer-video techniques to simulate or model experiments, and for using some lectures or portions of lectures for sessions devoted to formulating questions and formulating strategies to solve the problems posed.

Laboratories

The sciences and engineering are particularly fortunate in having laboratories associated with many of their courses, including entry-level courses. These laboratories can offer many opportunities for hands-on, active learning, for discovery, and for the thrill of finding that one can rapidly develop command of quantitative methodologies. The best laboratory programs can stimulate science and engineering students like no other single methodology. But the potential for laboratories has often been several levels above the usual practice, and entry level courses have often had pedestrian, cookbook laboratories that have contributed to the student flight from science. The challenge, both in the lecture hall and in the laboratory, is to use the various methodologies, to use the new as well as the tried and true technologies to capture the interest and stimulate the development of our students in all our entry-level courses.

Actively Engaging Students

There are a multiplicity of other ways to engage students in active learning. These include collaborative learning situations; appropriate utilization of contemporary technology; projection of science, mathematics and engineering as human endeavors; sketching phenomena and building models; construction of qualitative concepts before addressing the quantitative; exploration of the concrete before reaching out to the abstract; assessment of progress with immediate feed-back to students; confrontation of misconceptions; remediation; repetition; counseling and mentoring. The first three of the above — collaborative learning, use of modern technology and investigative laboratories — are explored further in the following pages.

Collaborative Learning

During the workshop, Jack Lochhead demonstrated collaborative learning by involving all participants, working in groups of two, in the solution of simple problems. It became immediately evident that the work could be structured in such a way that each participant has the experience of formulating and articulating questions, and the experience of formulating and articulating responses to questions. The ground rules were very simple. One of the pair assumed the roles of reading and answering questions, talking aloud throughout; the other assumed the role of asking questions. With the next problem the roles reversed. What a wonderful way for individuals to explore problem solving and at the same time explore their own mental constructs and confront misconceptions in a friendly environment.

Uri Treisman, Swarthmore College and the University of California Berkeley, reports success with students considered to be at risk in entry-level calculus by combining work in small groups with traditional lectures. The students register for the regular calculus course and also for a scheduled laboratory that meets for a two hour session twice a week. These laboratories are devoted to the investigation of problem solving with the students working in small groups under the supervision of a competent mathematician who understands how to select appropriate problems and assist small groups in their investigations of problem solving. This extension of time-on-task, working in small groups under supervision, enables students to have experience in doing mathematics and to recoup in part the deficit in problem solving experienced during the precollege years. The essential characteristics of collaborative learning are scheduled periods of working in small groups with other students on common problems in a supportive environment.

Modern Technology

Priscilla Laws very effectively demonstrated the use of modern technology to introduce qualitative concepts and quantitative analyses. Using a sonar detector and a microcomputer set up with data processing and overhead projection capability, she demonstrated an exploration of the linear motion of a "student" walking toward and away from the detector. Graphs of position and speed were displayed in real time, directly cnarting the student's movements.

Investigative Laboratories

Investigative laboratories are essential to the discovery of the nature of science, mathematics and engineering; the excitement of doing science, mathematics and engineering; and the powers and limitations of these areas of intellectual endeavors. Such laboratories are in marked contrast to laboratories frequently made available to many entry-level students. Here, too, we are confronted frequently by stereotyped laboratory programs dealing with the acquisition of techniques, routine observations and cookbook exercises. Such laboratories provide drill — not experience in investigation or in problem solving. To introduce change in laboratories is a challenge. The current system of laboratory instruction in many courses requires minimum planning and supervision. Investigative laboratories are difficult to develop and to supervise. Such laboratories fully involve not only the students but also those who teach them. The effort to develop them is justified by the recognition that many current laboratories divert many high potential students to other fields. Investigative laboratories are very significant investments in the development of human resources. From such laboratories students derive many of the pleasures and benefits characteristic of undergraduate research.

Satisfa."on and Pride

It is highly desirable for students to derive satisfaction from what they are doing and take pride in what they are accomplishing. It is quite possible for a student to make an A in a course and neither derive satisfaction nor take pride in his or her accomplishment — even in an honors course. Among the best students many are more interested in the comments written on a paper than they are in the grade.

Selection of Methodologies

The participants agreed that the missions delineated for entry-level courses were applicable to all types of academic institutions, but that the choice of course structures and methodologies used in teaching should be matters of local choice. Any method of teaching can be used inappropriately: no method is optimal for all students all of the time. A given methodology may be more appropriate for some mixes of students than for others. Interest and effectiveness are enhanced by using a variety of methodologies appropriate to the course material, student mix, instructor and institution. A multiplicity of approaches within a course can provide richer experiences for all students. Even experienced teachers must have assistance in learning new teaching methodologies. Teaching assistants, in particular, need support in gaining command of these new methodologies.

Disciplinary vs Inter-Disciplinary Courses and Programs

The participants at the workshop considered both disciplinary and inter-disciplinary courses to be appropriate entry-level courses. In either case, it is important that students have the opportunity to develop an understanding of the synergisms among scientific disciplines and also the synergisms among science, mathematics and engineering. No discipline is an entity unto itself. Disciplinary courses can be presented from an interdisciplinary point of view. Truly inter-disciplinary, as compared to multi-disciplinary, courses and programs are very attractive educationally. They do, however, demand a high level of collaboration to develop and may be fragile to sustain or transport to other institutions. Such courses are highly dependent on the talents and interests of the faculty who develop and sustain them.

Examples

Invited papers (Appendix 3) presented at the workshop provide an example of a single entry-level physics course for majors and for general education at Dickinson College, and also an example of a 12-credit inter-disciplinary program in science, mathematics and engineering required of all freshmen engineering students at Rose-Hulman Institute. A background paper distributed before the workshop provides an example of a six-quarter inter-disciplinary general education sequence built around the concept of evolution in the natural world (Appendix 4).

One aspect of interdisciplinary courses not adequately discussed during the workshop was the wide array of combinations involving the social sciences with each other and with biological sciences, physical sciences, mathematics and engineering. Various combinations of these have great potential in courses built around societal issues.

The support of innovation and the transport of successful courses within institutions and to other institutions are addressed further in Section 4.

Values in Entry-Level Courses

We now turn to a topic of great concern to many workshop participants. This topic is the transmission of values to students by word or deed, either by deliberate intent or inadvertently, during the course experience.

Internal to science, mathematics and engineering an array of practices have evolved that ensure the integrity of these disciplines and respect for the contributions of others. These practices are encompassed in the processes of investigations that are science, mathematics and engineering, and the steps taken in all scholarly work to insure the protection of intellectual property. The values upon which they are based are an essential part of education, including entry-level courses.

Other value issues of particular concern have to do with the projection of personal values by faculty members to students. Certainly the projection of personal values such as respect and concern for the development of students as individuals, a willingness to help, a dedication to intellectual pursuits, and a sense of fairness in assessing student work are an essential part of good teaching and a supportive human environment. There can be, however, a down side to the projection of some personal values by some faculty in the classroom. Examples: There is great danger in the projection of values that underlie the act of demeaning perceived characteristics such as ability, achievement, motivation, commitment and professional goals of an individual student or an identifiable group of students such as women, minorities and persons with physical disabilities. There are also negative consequences to the self-glorification of one's own field and profession through the debasing of other fields and careers. The projection of such values can be as subtle as ignoring the individual or group, the tone of voice used, the questions asked and the time allowed for a response to a question. Such actions are detrimental to those demeaned; they teach or legitimize the "negative" values of the faculty member. Values projected in the classroom should be consistent with the values that underlie the missions of undergraduate education. As the mission of undergraduate education evolves from an almost complete focus on "selecting and advancing the most competent and most committed" to a focus on "encouraging and enabling all students to have a meaningful educational experience" we become increasingly concerned about the projection of values in the classroom that are not consistent with encouraging and enabling all students.

Other value issues arise in the consideration of the impact of technological options on the quality of life and the quality of the environment. These are very complex issues and students should come to understand that the expertise of scientists, mathematicians and engineers is essential in technological innovation and also in the evaluation of the probable benefits and burdens (risks) inherent in the implementation of that technological innovation. Students should also come to understand that the decision to allow or not to allow the implementation of a technological option is a value judgment. In a democratic society, value judgments having to do with the quality of life and the quality of the environment are the prerogative of the public and the surrogates of the public (those elected by the public and those appointed by those elected). This is, of course, one of the reasons there is so much concern about the level of scientific and technological literacy of the public. It is very important that individuals are capable of undertanding technical issues sufficiently to make decisions consistent with their values.

More Than Technical Competence

Teaching an entry-level course effectively requires an understanding of the nature of science, mathematics and engineering as well as technical competence. It also requires an understanding of the relation of these intellectual endeavors to society and its needs. Teaching is a creative enterprise essential to the development of human resources.

4 Institutions

Colleges and Universities

Administrations of colleges and universities delineate the parameters within which their respective college or university provides undergraduate educational services, including entry-level courses, to their students. Policies and practices of colleges and universities

1) Are derived from the attitudes, perceptions and values of administrators, and faculty, and

2) Are dependent upon the actions taken by

a) Accrediting organizations in delineating academic standards,

b) Local, state and national governments in making appropriations, and

c) Foundations, corporations and government agencies in making grants and contracts in support of science, mathematics and engineering in colleges and universities.

All of the above will be addressed here in terms of bringing about change for the better in entry-level courses and sustaining the benefits of change.

Bringing About Change

Individual faculty members can promote change within existing courses, promote the development of new courses to meet identifiable needs, and participate in the implementation of such initiatives within their institutions. Such activities are dependent upon the support of their academic institutions and an array of private and public institutions.

Barriers to Change

As difficult as it is to initiate change and bring about change in courses, it is progressively more difficult to bring about change in departments, academic institutions and the national educational structure. There are serious barriers: denial of the need to change, resistance to change, lack of institutional commitment, diffidence of faculty about personal capacities to adapt, and lack of faculty commitment to change. Even under the most favorable conditions, faculty and teaching assistants will require support in adjusting to new concepts and developing new skills.

Institutionalization of the Benefits of Change

It will be even more difficult to institutionalize the benefits brought about by the current flurry of activities. Concerns about the transportability of promising innovative programs within an institution and/or to other institutions may obscure the necessity for other more important transfers. These transfers are the diffusion of evolving attitudes, perceptions and values that are the bases of the innovations, and the diffusion of changing concepts of education and methodologies of teaching.

Transportability of Innovative Programs

We agree with the comment of Michael LaBarbera concerning the natural science sequence at the University of Chicago, "We would be pleased if this sequence were taken as a model by other institutions, but by no means encourage its transplantation; the strengths of the faculty at each institution should be taken into account in any attempt to design an analogous integrated sequence" (Appendix 4). It may be that some courses should not have lifetimes beyond the interests of the faculty and students who were a part of their creation. Such courses make substantial contributions to the intellectual climate of the institutions and are the essence of a dynamic system of education. Other courses will have long continuously evolving lifetimes.

If it is natural for a program to be transported from one institution to another, the transfer should, of course, be encouraged. The probability for a successful transport is greatest for institutions that are well matched in terms of the composition and interests of the students, and the interests and strengths of the faculties. Ideally faculty members of the acceptor institution should have the opportunity to work with the donor group.

We suggest that for agencies and foundations to set wide transportability as a goal in funding entry-level course developments may be self-defeating. Such a heavy burden on the initiators may doom the project to the production of a course less appropriate to the initiators' institution(s) and not really appropriate for wide transportability. The interests and strengths of the faculty in each institution are extremely important. We also suggest that successful approaches to curricula development for precollege education in sciences and mathematics may not be good models for the development of undergraduate education and could be counter-productive.

Resource Center

There is a real need for a resource center for entry-level course research and course initiatives. Some teachers seek programs they can adapt. Others involved in course development seek to identify faculty involved in similar innovative endeavors. There will be a continuing need for such a center. We are not going to do research on learning and develop better entry-level courses and be done with it — any more than we are going to do research and development in sciences, mathematics and engineering and then be done with such research and development. Teaching and research are both processes with continuously evolving methodologies and changing foci.

Long term vitality of undergraduate education, including entry-level courses, is best insured by infrastructures of colleges and universities that

Infrastructures of Colleges and Universities

- Extend to the faculty the freedom to be experimental in their approach to teaching,
- Provide the support essential to develop new programs,
- Provide the resources necessary to teach, and
- Reward adequately creative teaching.

Educational programs within such infrastructures can be expected to be self-correcting in much the same way research is self-correcting. Teaching can again become an exciting, creative endeavor that attracts faculty at all academic ranks. Students and junior faculty will both have the benefit of the experience and perspective of talented senior faculty. Academic institutions will be recognized for academic programs that produce inquisitive and imaginative graduates as well as for research programs that are creative and effective in producing knowledge. The ideal is a faculty made up of individuals who derive satisfaction from and take pride in their involvement in both teaching and research. An essential part of monitoring the effectiveness of the infrastructure of an institution in making education in science, mathematics and engineering education accessible to all undergraduates is periodic assessments of the student experience with entry-level courses through exit interviews.

Challenges to Colleges and Universities

The challenge to colleges and universities is to develop infrastructures that insure a dynamic system of undergraduate education. With such a system the probability of again having stereotyped curricula is greatly diminished. Just exactly what transformations in infrastructure would be required of the institution involved is by no means clear. If sufficient numbers of faculty, academic administrators, leaders of supporting institutions and representatives of the public are committed to bringing about a quiet evolution toward a dynamic system of undergraduate education, it undoubtedly can be done. It is essential that undergraduate education, including entry-level courses, becomes a dynamic system consistent with the expansion of knowledge, the changing demographics of our colleges and universities and the needs of society.

Supporting Institutions

The nature and quality of undergraduate entry-level courses can be influenced, directly or indirectly, by any organization that supports college and university science, mathematics and engineering in any way at any level, or assesses the quality of programs in science, mathematics and engineering. This includes grant and contract programs in education and in research, appropriations, accreditation programs, and even recruitment programs. The types of organizations involved include private foundations; corporations; local, state and national governments and their agencies; professional societies; and accrediting organizations. Colleges and universities are strongly dependent upon these institutions.

Our primary concern is that the administrators of these institutions may not be aware of the cumulative effect the policies and practices of their institution have on the nature and quality of something so seemingly simple and remote as undergraduate entry-level courses. It is highly probable that administrators, as individuals, would support the missions for undergraduate education and entry-level courses delineated in this report. The policies and practices of some institutions also support the fulfillment of these missions but the side effects of the policies and practices of some others may be diametrically opposed. In the long run, some of the cumulative consequences of their practices may be contrary to the intent.

Examples: Accreditation programs may narrowly define an elite and condemn that elite to the pursuit of the technicalities of the discipline without the benefits of a broad perspective of science, mathematics and engineering. The manner in which research is supported may negate the value and creativity involved in teaching and the development of human resources. Research fellowships that free graduate students from teaching may deprive those students of the acquisition of a broad perspective of science, mathematics and engineering, and also deprive them of the opportunity to develop competence and confidence in their capacities to teach.

The Challenge to Supporting Institutions

The challenge to institutions that support science, mathematics and engineering in any fashion is to examine the long-term effects of their policies and practices on undergraduate education. Entry-level courses, in particular, are essential to the development of an informed public, precollege science and mathematics teachers, and a technically competent work-force as well as the scientists, mathematicians and engineers who will become the leaders in the extension of knowledge and development of new technologies.

5 Assessment

Entry-level courses are an integral part of the development of a system of undergraduate education in science, mathematics and engineering that

- Is dynamic,
- Serves all undergraduate students well and through these students serves society well, and
- Fosters continued learning throughout the lifespan of these students.

The first characterizes a system of education that adapts readily to change, such as the expansion of knowledge, the development of new technologies, changing needs of students, changing demographics of colleges and universities, and changing societal needs. The second is essential to the development of students as individuals and the development of human resources. The third is an investment in adult scientific literacy and the involvement of an informed public in the resolution of societal issues.

We take the position that it is a role of initiatives in the development of entry-level undergraduate courses to contribute to a system of undergraduate education that has these characteristics.

To achieve these characteristics at least two fundamental topics should be addressed in establishing policy for the development of entry-level courses in science, mathematics and engineering:

- A concept of entry-level courses in which entry-level courses are accessible and rewarding to a high proportion of undergraduate students, and
- The identification and overcoming of barriers to creative structuring and teaching of entry-level courses.

Both of these topics have been discussed at some length in the preceding sections of this report. The first, a concept of entry-level courses which are accessible, is in marked contrast to the common practice in some disciplines of using entry-level courses as a quality control mechanism to exclude all but the most academically-able and the most committed from the pursuit of a major. The second, the identification and overcoming of barriers to creative structuring and teaching of entry-level courses, has been explored in terms of the tyranny of knowledge (the compulsion to cram excessive quantities of accumulated knowledge into an entry-level course), the tyranny of stereotyped curricula (the excessive conformity of courses to the same content and methodologies of teaching) and the infra-structures of institutions that discourage creative restructuring of courses and creative approaches to teaching.

It is quite possible that the rigidity of the current system of undergraduate education is responsible, at least in part, for the flight of so many faculty members from teaching entry-level courses and is also responsible, in part, for the difficulty of recruiting students, including those from traditionally underrepresented groups (women, minorities and persons with physical disabilities) into science, mathematics and engineering. Instead of expecting individuals, either faculty or students, to adapt to a rigid and somewhat archaic system of education, it is tir e the system does more of the adapting. One step in this adaptation .s marketing to students the concept that an understanding of and a background in science, mathematics and engineering are empowerment. Each course beyond the entry-level course contributes to building a significant edge in activities such as business, management, elementary school teaching, politics, communications and community involvement.

Recommendations from the workshop are given on pages viii-x.

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Appendix 2
Section 1 Of The Sigma Xi National Advisory Group Report

An Exploration of the Nature and Quality of Undergraduate Education in Science, Mathematics and Engineering

MISSIONS OF UNDERGRADUATE EDUCATION IN SCIENCE, MATHEMATICS AND ENGINEERING

Missions

Undergraduate programs exist in order to provide environments that encourage and enable students to accomplish something. These "somethings" are the missions of the programs. Just exactly what these missions are depends upon the perceptions of academic administrators and departmental faculty members of factors such as 1) the needs and goals of students and 2) the needs and goals of society.

Undergraduate missions of departments of science, mathematics and engineering include encouraging and enabling undergraduate students:

1) to pursue careers:

   a) in science, mathematics, engineering and related endeavors;

   b) in school (K-12) science and mathematics education; and

   c) in scientific and technological aspects of law, mass communications and management;

2) to discover the nature of science, mathematics and engineering;

3) to discover the aesthetic and human dimensions of science, mathematics, engineering and technology (the order and beauty of many natural systems and many products of technology, the ingenuity of the human mind in creating models to rationalize the properties of systems and in creating technological options for the production of goods and services and the resolution of societal issues); and

4) to become informed participants in the democratic processes through which value-laden issues involving science, mathematics, engineering and technology are resolved.

Practices in science, engineering and mathematics education indicate that those who develop curricula and teaching materials, those who teach, and those who structure examinations may at times lose track of what science, engineering and mathematics are.

The Nature of Science

Science is a process of investigating phenomena—physical, biological, behavioral, social, economic and political phenomena.

Process, as used here, is an inclusive term encompassing:

- The selection of the phenomenon to be investigated,
- The selection or development of an appropriate methodology,
- The selection or development of appropriate instrumentation,
- The delineation of an appropriate protocol (procedure),
- The execution of the protocol and the collection of data,
- The reduction of data and the assessment of the uncertainty of the results,
- The correlation of the results with existing knowledge, and
- The analysis of the theoretical implications of the results.

Any phenomenon for which methodology and instrumentation can be developed and validated is within the domain of science (the process). Science as a process of investigation of phenomena is frequently alluded to as "science as a way of knowing."

The Nature of Scientific Knowledge

The legacy of science, the process of investigation of phenomena, is a body of scientific knowledge consisting of:

- A data base,
- An array of methodologies,
- An array of concepts, and
- An array of theories and models.

Many issues concerning curricula have to do with the relative weighting given in various courses to 1) the process of investigation of phenomena, and 2) the body of scientific knowledge and, within the time allotted to the body of scientific knowledge, the relative weighting given to a) data bases, b) methodologies, c) concepts and d) theories and models.

The Nature of Engineering

Similarly, engineering is the process of investigating how to solve problems such as making a plastic cup that meets delineated specifications, or designing and building a communication satellite that meets delineated performance requirements, or designing and instituting police services that meet specified needs of a given community. In each case the first step in the process is accepting the problem and the final step is validating that the product, process or service meets all of the specifications and performs the required function.

The Nature of Engineering Knowledge

The legacy of engineering, the process of investigating how to solve engineering problems, is a body of engineering knowledge consisting of a data base, an array of methodologies, an array of concepts, and an array of theories and models.

Although there are many parallels between science and engineering, the goals of science and engineering are fundamentally different. Science is the process of investigating phenomena with the goal of creating understanding; engineering is the process of problem-solving with the goal of creating a product, device, facility or system, subject to constraints such as economics, safety, aesthetics, and environmental impact.

The Nature of Mathematics

Tremendous changes during the past twenty-five years in how mathematics is done have imposed upon mathematicians the necessity to rethink the nature and the definition of mathematical science. Today, mathematical science is defined loosely as the science of patterns. The role of patterns in mathematics is by no means new. Newton perceived patterns in astronomical data, formulated principles consistent with those patterns and used those principles to deduce other patterns, some known and some unknown, of behavior for planetary systems. What is new is a millionfold expansion in the number of patterns investigated by mathematicians brought about through the use of computers. The new definition 1) subsumes and unites many aspects of statistical sciences, core (pure) mathematics, and applied mathematics, 2) acknowledges the dependency of mathematics on the data bases of science and engineering, and 3) delineates a leadership role of mathematics in the evolution of science and engineering. The symbiosis of mathematics, science and engineering becomes increasingly apparent. The computer-assisted topography (CAT) scanner is just one technological product derived through this synergism.

Symbiosis of Science, Mathematics and Engineering

Applications based upon comparisons of fit of patterns with observations of natural phenomena are now central to many scientific investigations and technological developments. Dramatic uses of concepts from pure mathematics in unexpected applications are occurring with increasing frequency. Even so, the symbiosis of mathematics, science and engineering is not necessarily effectively exploited. Many scientists and engineers have not explored mathematics beyond the calculus, analysis and differential equations taught to them as students and, in many institutions, modernization of curriculum has been repressed by inertia and accreditation systems.

Failure of Undergraduate Education to Fulfill Missions

Evidence mounts that undergraduate education in science, mathematics, and engineering is not fulfilling its missions. A high proportion of freshmen who enter college planning to major in these fields either change their minds during entry-level courses, drop out later, or reluctantly complete their programs rather than "waste" the investments of time, energy and money already made. More than fifty percent of freshmen intending to major in science, mathematics, or engineering fail to complete bachelor's degree programs in these fields, to say nothing of the many future teachers, communicators, managers, lawyers, political activists, public officials, and socially concerned citizens who are rendered permanently allergic to these fields by unfortunate experiences in introductory courses. Too many entry-level courses, whether geared to majors or to students satisfying general education requirements, fail to stimulate and involve students—much less educate them. Students complain that the courses are largely irrelevant to their lives and that the effort required far exceeds the benefit reaped.

In accord with these findings, the National Advisory Group identified the crisis as applying equally to entry-level courses for science, mathematics, and engineering majors and for students majoring in other fields.

Roots of the Crisis

In searching for the roots of the crisis in undergraduate education, members of the National Advisory Group hit repeatedly upon the theme of accessibility for students: access to instruction that generates enthusiasm and fosters long-term learning; access to a curriculum that is relevant, flexible and within their capabilities; access to a human environment that is intellectually stimulating and emotionally supportive; and access to a physical environment that supports the other three dimensions. These crucial components are strongly interrelated; weakness in any one diminishes the quality of undergraduate education.

Promoting these aspects of accessibility requires an appreciation of the intellectual readiness and psychological needs of the students—it calls for undergraduate educators to evolve approaches that enable and encourage students to progress from where they are to desirable levels of intellectual competence and maturation. College facult; may echo the sentiments of the Vermont farmer who advised the traveler: "If I wanted to get to where you're going, I wouldn't start from here." Yet, as much as adjusting entry-level courses to the students' level of knowledge may be contrary to the faculties' beliefs about what constitutes college-level work, to do otherwise is to abandon many potential majors as well as other students who take such courses for general education purposes to lifelong ignorance of the beauty and capabilities of science, mathematics and engineering. The necessity to adapt entry-level courses to the pre-college preparations of students is to recognize the fact that, in many cases, such preparation is deficient.

Appendix 3
Abstracts Of Papers Presented At The Workshop

HIGHER ORDER THINKING IN MATHEMATICS AND OTHER DISCIPLINES

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This presentation has three main goals:

1. To outline a theoretical view of what it means to "think mathematically" (and by implication, what it would mean to think like a physicist, or a chemist, or a biologist...);

2. To discuss aspects of my courses in mathematical problem-solving, which focus on the development of specific higher order skills;

3. To suggest ways in which aspects of those courses might appropriately be modified to become components of mainstream entry-level college courses in mathematics and science.

1. On Thinking Mathematically (or thinking in any problem-solving domain)

There is, by now, a well-established theoretical frame for the characterization of intellectual competencies in problem-solving domains (See Collins, Brown and Newman, 1989; Schoenfeld, 1985, in press). With minor variations, authors put forth four or five aspects of intellectual competency:

A. Resources, or domain knowledge

B. Problem-solving strategies (heuristics)

C. Executive control, or self-regulation

D. Belief systems

E. Practices.

A. Resources include facts and procedures—the "basics" of the subject matter. Studies into resources include the organization of knowledge in memory, and how information is accessed for use. The one-line summary of recent research findings: even these "basics" are much more complex than one would tend to think, and the simple models of learning that underlie much of our current teaching practices are too simple (with sometimes harmful consequences). Such issues are domain-general, applying to learning in all domains.

B. Strategies. Examples of problem-solving strategies in mathematics are exploiting symmetry, considering simpler or analogous problems, looking for particular kinds of patterns. The general nature of such productive strategies has been known for a half-century, since Polya's (1945) *How to Solve It*. Advances over the past two decades provide the methodologies that enable us to delineate and teach such strategies, with success. Strategies tend to be domain-specific. That is, the strategies (a) need to be worked out and taught in fine detail, and (b) differ from discipline to discipline, so that the task of elaborating such strategies in domains other than mathematics is largely undone.

C. Control. The one-line summary here is: "It's not just what you know, it's how and when you use it (or fail to)." There is a large body of data indicating that much expert problem-solving success comes from the efficient and resourceful use of the knowledge in categories A and B; moreover, that much student failure comes not simply from lack of knowledge, but from ineffective or inefficient use of the knowledge they do have. This issue is, for the most part, domain-general.

D. Beliefs. One's set of understandings about a domain (roughly speaking, one's epistemological stance) influences the way he or she works within it. If a student thinks physics is simply the application of formulas "handed down" from experts, for example, then the student won't seek to understand the formulas or find coherence in the symbolic representations of the physical world. In mathematics (and other disciplines, I suspect), the vast number of students who, on the basis of their experience, have come to believe that "all problems can be solved in five minutes or less" will simply stop working on problems that require substantially longer investments of time and energy.

E. Practices. To quote from Lauren Resnick (1989, p. 58), "Becoming a good mathematical problem-solver—becoming a good thinker in any domain—may be as much a matter of acquiring the habits and dispositions of interpretation and sense-making as of acquiring any particular set of skills, strategies, or knowledge. If this is so, we may do well to conceive of mathematics education less as an instructional process (in the traditional sense of teaching specific, well-defined skills or items of knowledge), than as a socialization process." Such a reconceptualization suggests some radical shifts in our instructional practices.

2 & 3: My Problem-Solving Courses, and Implications for Instruction in Entry-Level Undergraduate Courses

My problem-solving courses have evolved, over the past fifteen years, to the point where they devote serious attention to all five of the aspects of mathematical thinking discussed in (1). The courses are offered at the lower division level, in order to provide (a) a dose of mathematical thinking—the only one they will get—for those who will not go on in mathematics, and therefore do not need the (oftimes sterile) techniques taught in the calculus sequence, and (b) a similar dose for those who may go on to be mathematics majors, because they often have to wait until their junior years before having the opportunity to engage seriously with mathematics.

Domain knowledge is considered in the following way: I choose problems for the course whose solutions involve important mathematical ideas or introduce important topics, or whose solutions illustrate important mathematical thought processes. Problem-solving strategies are explicitly mentioned and modeled; we take the time to work through problems, rather than working exercises following the demonstration of specific techniques. Since much problem-solving is done in small groups during class time, there is time for "coaching" related to matters of control, as well as discussions of the issue and modeling of appropriate control behaviors. Beliefs and practices are dealt with the same way: There is an explicit attempt to construct an environment in which the students are doing mathematics, and which supports the development of the appropriate mathematical perspectives in students. For example, to combat the belief "all problems can be solved in five minutes or less," students are explicitly told that some problems will take days or weeks to solve; problems are worked in class that take us days or weeks; and take-home examinations contain such problems. Other, more subtle beliefs, e.g., regarding the nature of mathematical proof, are dealt with by community exchange: "When do we believe a result someone proposes, and on what grounds?" is an explicit focus of course discussion. There is substantial documentation (Schoenfeld, 1985) that the courses are successful.

In one sense my courses, although at the entry level, are quite demanding and intellectually advanced. Students in one version of the course produced a publishable result; in another, they produced a number of minor results that were new to me. Yet, in a fundamental sense, my problem-solving courses are remedial. That is, if all mathematics courses were properly taught, there would be no need for courses like mine. I focus on strategies, control, beliefs and practices because no other courses do; in K-12, and in their other mathematics courses, my students' teachers have been so busy cramming subject matter down their throats that the result has been the exclusion of any possibilities for real thinking. Nothing done in my problem-solving courses is necessarily constrained to such courses; one might redesign almost all of mathematics instruction, particularly at the entry level, to allow students to grapple with the subject matter in serious ways, and to develop the thinking skills discussed above. And, of course, I assume there is nothing special about mathematics in that regard: As far as I can tell, there are parallel issues in all of the sciences.

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STUDENT LEARNING AND REASONING: IS IT UNDERSTANDABLE?

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...university teachers do not have to demonstrate professional competence in education—gifted amateurism is fully acceptable.

Herbert A. Simon (1986) p. 110

It may be fortunate that university faculty have tended to be amateurs in the craft of teaching. During the past one hundred years most educational experts have held to a psychological perspective, behaviorism, that, whatever its merits, has little useful to say about university level teaching, and in fact often suggests actions that could be detrimental to the goals of higher learning. But in the last five years the picture has changed drastically. As Lauren Resnick predicted in 1983 "... a new consensus on the nature of learning has begun to emerge...[that] has a direct bearing on how science and mathematics can be taught most effectively."

This new view of learning does not refute behaviorism but rather places limits on its range of appropriate application. We now know that the key processes in cognition and learning are more complicated than those that had been imagined previously. The essential new element is the idea that each of us constructs his or her own knowledge. We do this from our experience, including activities such as listening, reading and observing. But we also construct our knowledge of our experiences and thus experience itself must be shaped by what we already know or believe. New knowledge and new knowledge structures can be built only out of pieces of existing knowledge and organizational structures that we already possess. Thus our methods of observation and the reasoning we employ to process those observations are crucially influenced by what we already know or believe.

In many ways this constructivist perspective is as old as human history (von Glasersfeld, 1989). But its careful application to psychology and learning theory can be traced to Piaget. Furthermore, it is only in the past five years that it has had major influence on American psychology and education. Constructivism is inherent in modern physics, but its application to "ordinary objects" is not immediately obvious. In physics we understand that the most we can learn about quarks and electrons is whether a particular model that we have constructed accurately predicts behavior. The success of the deBroglie wave model does not imply that the electron is a wave, only that a wave model can make certain useful predictions about electrons. Nor is it possible to assume that, because we sometimes can measure the position of an electron, it is always localized in space. The objects of modern physics can never be seen or directly experienced. But what about objects that we do see (touch, smell, hear, imagine or dream), such as those used in a lecture demonstration? We know these objects through the nerve impulses generated in our optic fibers and interpreted by the many layers of our visual processing system. Is this experience significantly more direct than that we have of quarks? The constructivist position is that it is not. Knowledge is seen as being composed of models, models that each individual must construct in his or her own mind out of the currently available building blocks.

Constructivism is not solipsism. It makes no argument against reality; nor does it claim that each of us is trapped in an idiosyncratic world. Knowledge may be individually constructed, but this is done through a socially mediated process. Our constructions are influenced by the way in which other people react to them. These social influences can be complex and subtle, but in some cases their impact is clear. Every scientist at some time has changed his or her beliefs about some element of science, not through a direct analysis of the data or an understanding of the arguments, but rather because the idea had become socially acceptable. Recent examples include: the existence of black holes, continental drift, room temperature superconduction, cold fusion and the meteoric extinction of dinosaurs. It is the social mediation of scientific review and wide-scale scientific acceptance that gives the models of science their power and robustness. It also can make scientific progress slow and awkward.

One implication for education is that we ought to present science to students as a process of finding tentative explanations, all of which must undergo continual review and modification. The facts of science are absolute only in the sense that they constitute the common language which must be mastered in order to join the social communication currently in progress. While this is the manner in which most serious scientists view their work, it tends not to be expressed in teaching, at least not in a forceful enough manner to overcome the positivist perspective on science perpetuated in popular culture, the media and advertising. There are two practical benefits to placing a greater stress on this view of the scientific enterprise. First it is consistent with the manner in which we now believe knowledge is acquired, thus it encourages students to learn efficiently. Second there is strong evidence that it will make science attractive to many more top quality students (Tobias, 1990 and Light 1990).

The primary implication of constructivism for teaching is that we can never be quite sure how students will interpret what we tell or show them. The old theory of knowledge has been called a copy theory. Students were like photocopiers or tape recorders faithfully reproducing what we gave them. But knowledge is not formed by copying, and its acquisition cannot be demonstrated merely through faithful reproduction. A more accurate model would be something like a language translating facsimile mail system in which pages entered in English would be printed in French. In an ordinary fax system the message is sent out over a noisy telephone line. It is necessary to check each symbol that has been transmitted by having it reflected back from the receiver. This process is similar to that employed in cultures where students chant back words seconds after the teacher utters them. This insures that the correct words were received, but it does not establish how they were interpreted. If somewhere along the line the message is translated into another language, checking becomes very difficult.

Until about ten years ago it seemed reasonable to assume that if college students were hearing the right words they would also be getting the right message. This has proven not to be a safe assumption. Experiments with college level physics students (Clement, 1982 and McCloskey, 1983) showed that students can have the right words and even the right answers but nevertheless harbor the wrong ideas. Students who can successfully calculate the trajectory of a stone believe it is continualy propelled by the sort of impetus force physics discarded several hundred years ago. Similar phenomena have been observed in mathematics (Clement, Lochhead, Monk, 1981) where calculus students who can easily differentiate complex polynomials nevertheless believe that the equation $A = 7S$ implies that the S values are larger than the corresponding A values.

Students make unexpected interpretations not only of scientific facts and observations but also of the basic reasoning processes employed in science and mathematics. Analytical reasoning is a set of complex processes; and knowledge of these processes must be constructed by each individual learner. Some variations in how students define the rules must be expected, particularly since the rules and techniques themselves are rarely the subject of direct instruction. There are in fact a wide range of expert styles (Gardner, 1983) and we should expect no less from our students.

Constructivism is not an ideological position that claims students ought to learn through discovery. The construction of knowledge happens whether or not we would like it to.

There is no message in constructivist theory that states how education should be conducted, only a warning about the complexity of the process.

In science it is essential to question every observation and to examine every assumption. Constructivism suggests that we must view student knowledge in the same light. We must maintain a constant skepticism about the effect our instructional procedures are having. Our task is difficult. On the one hand we must recognize that each student will be building a unique set of models and that it is not reasonable or possible to insist that these models match our own. On the other hand it is essential to demand appropriate performance from student models. If students were able to test and refine models entirely on their own there would be no need for an education system.

Formal education would be impossible if every student generated a completely unique set of perspectives. The problem of tracking the manner in which each individual student received every message would be unsolvable. Fortunately research has shown that the large majority of students interpret events in a fairly small number of different ways. Once these options are known it is possible to design instruction that takes these possibilities into account. Examples of how this can be done are found in the work of Hestenes (1987) and Clement (1987).

But it is not possible or desirable to have faculty guide students through the construction of every important concept. Students must learn to do that for themselves. Here it is essential to remember that the goal of science is not to generate individually satisfying, idiosyncratic explanations, but rather communicable models which can be employed in the social discourse of science. To sharpen the skills needed for that enterprise students must work collaboratively in groups on tasks that ask them to devise a consensus explanation or description. Productive group work is not something that is wisely left to chance. Several useful techniques have been devised for structuring effective collaboration (Lochhead, 1985; Brown and Palincsar, 1989). For a group exercise to be cognitively constructive it must include confusion and conflict. These are not normal aspirations of education, and students may fail to perceive the benefits if they are not properly prepared to engage in such intellectual struggle.

One commonly expressed concern is that during group work students may reinforce any incorrect ideas they happen to share. This can happen, but what is far more likely is that the group will go well beyond the limits of each individual's knowledge, generating useful new insights into the phenomenon under consideration (Lochhead, 1979). Science has progressed in precisely this manner and there is no reason to assume students must operate differently. Furthermore research has shown repeatedly that the explanations given by faculty are often misunderstood and offer little or no protection against the propagation of divergent ideas (The College Board, 1990). The process of constructing a consensus turns out to be by far the most powerful method for conveying the scientific message (Damon, 1984).

During the past twenty years a new picture of the learning process has been constructed and in certain specific content areas researchers have formulated fairly detailed descriptions of the ways in which concepts may be formed. At the same time new instructional approaches have been designed, many of which involve group work. Nevertheless, despite years of research, teaching and learning remain crafts that are more similar to art than technology. Yet the time may be near when gifted amateurism will no longer satisfise[1] the demands of teaching.

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1 The term "satisfise" was coined by Herbert Simon to describe a search for adequate rather than optimal solutions. A brief description of the implications of Simon's theory is given in: The 1978 Nobel Prize in Economics, *Science*, 202, p. 858-861.

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USING NEW PEDAGOGY AND TECHNOLOGY TO TEACH EXPERIENCE BASED ENTRY-LEVEL SCIENCE

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At Dickinson College we have been attempting to draw upon our experiences and the insights of others to analyze the problems associated with the teaching of introductory science courses, to set new goals for the introductory physics program, and to achieve these goals by changing the way we teach.[1]

The goals for the Workshop Physics courses include:

(1) Acquisition of physics concepts and skills sufficient to prepare students to engage successfully in further study in physics, engineering and other allied sciences. The skills include those already emphasized in traditional introductory physics courses.

(2) Improvement of scientific literacy as defined by Arnold Arons.[2] Such literacy includes an understanding that scientific concepts are human creations, a comprehension of the distinction between observation and inference, and the development of enough knowledge in physics to allow intelligent study and observation to lead to formal learning without formal instruction.

(3) Exposure to contemporary research tools such as computers and other apparatus appropriate to the areas of study encountered by students.

(4) Motivation of students to learn more science either formally or informally.

We have transformed our introductory physics program from a lecture setting to a workshop environment. Instead of a weekly schedule of three lectures augmented by a three-hour laboratory session, students meet three times a week for two-hour sessions. The Workshop Physics classroom is outfitted with physics apparatus, 12 microcomputers, and work space to accommodate up to 24 students. Formal lectures are replaced by a series of activities and class discussions. In this environment students obtain direct experience with physical phenomena, engage in active collaboration with their peers, and use microcomputer hardware and software to help them organize and express their experiences in abstract mathematical terms and in words.

There are three critical differences between Workshop Physics courses and those taught in a traditional manner. First, we are using experiential learning sequences like those described in David Kolb's book, *Experiential Learning*[3] and the book by Osborne and Freyberg, *Learning in Science*.[4] The learning sequence includes prediction, observation, construction of formal theory, and finally, application of formal theories to new phenomena. Second, we have benefited from the insights of Uri Triesman and his colleagues at University of California, Berkeley, who have explored the power of peer learning in helping underprepared students succeed in their mathematics studies. Third, we have used microcomputers to accelerate the rate at which students can acquire data and develop mathematical descriptions of real phenomena. Computer use centers around the use of both generic software including standard spreadsheet and graphing routines for data handling and display, and the use of drawing and word processing software for the preparation of formal laboratory reports. We have worked with Tufts University to develop specifications for an electronic device known as the Universal Laboratory Interface (ULI) that is capable of transforming the microcomputer into a data acquisition system. Software has been written at Dickinson and Tufts to allow the use of the ULI with a collection of sensors on the Macintosh computer.

Since the fall of 1986 over 200 students have worked under the guidance of six instructors to complete Workshop Physics courses. Although the assessment of the program is not yet complete, we have shown demonstrable gains in several areas:

(1) Student attitudes toward the study of physics have improved dramatically.

(2) A greater percentage of students have mastered concepts considered difficult to teach because they involve classic misconceptions.

(3) Student performance in upper-level physics courses and in solving traditional textbook problems is as good as or better than that of students taking our traditional lecture courses.

(4) We know by observation that students who complete Workshop Physics are considerably more comfortable working in a laboratory setting and working with computers.

(5) There is preliminary evidence that students are acquiring an expanded vision of the observational basis of physics and the connections between concepts.

In addition to the demonstrable gains, we have encountered two significant problems. Although our surveys indicate that the average number of hours spent out of class on the course is typical to that reported by physics students at other institutions, a number of students feel that the course is complex and demands too much time. A small percentage of students thoroughly dislike the active approach and would prefer a return to lectures.

We feel that the Workshop Physics concept should be improved and extended both to other institutions and to other disciplines. Ronald Thornton at Tufts University and Priscilla Laws at Dickinson College are collaborating to extend the capabilities of the microcomputer-based laboratory (MBL) hardware and software. We have been joined by a Dickinson Colleague, Robert Boyle, to work with consultants Arnold Arons from the University of Washington and Edwin Taylor from the Massachusetts Institute of Technology to revise the activities for the calculus-based course so that the sequence of material is more logical, develops a more compelling "story line," and better prepares students for the subsequent study of contemporary physics.

Under the auspices of a new grant from FIPSE, colleagues at Dickinson College and Tufts University are working actively with counterparts at the University of Oregon, Boise State University, Ohio State, and Rutgers University to extend the workshop concept to physics courses at larger universities. We are collaborating with mathematicians at Dickinson and elsewhere to develop a sequence of introductory Workshop Mathematics courses. The Dickinson College Biology Department is experimenting with the use of the MBL to do real time experiments in human physiology in the introductory biology courses. Finally, two summer seminars were held at Dickinson College during the summer of 1990 for college teachers, using funds from NSF and FIPSE.

Our enterprise has been an exhilarating one, for it represents a blending of time-honored ideas about learning with new laboratory tools and educational technology. It is consonant with the early twentieth century educational philosophies of William James, John Dewey, and Alfred North Whitehead. Its philosophy is epitomized by a quote from Aristotle that is over 2000 years old: "What we have to learn to do, we learn by doing" and by a modern proverb which serves as our course motto:

I hear, I forget.
I see, I remember.
I do, I understand.

The Workshop Physics environment has given students unprecedented power to examine their "common sense" understandings of science and connect those understandings in a more formal, mathematical framework.

References

1 The Workshop Physics project began officially in October 1986 with a three-year grant from the U.S. Department of Education Fund for Improvement of Post-Secondary Education (FIPSE). Developers of the program included Priscilla Laws, John Luetzelschwab, Robert Boyle, and Neil Wolf of the Department of Physics and Astronomy at Dickinson College and Ronald Thornton of the Tufts University Center for the Teaching of Science and Mathematics.

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INTEGRATED, FIRST-YEAR CURRICULUM IN SCIENCE, ENGINEERING, AND MATHEMATICS

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In November of 1986, a group of faculty at the Rose-Hulman Institute of Technology conceived the idea of an integrated curriculum for first-year students that would be designed with two objectives. First, thematic concepts, concepts that span two or more scientific disciplines, would be stressed instead of individual topics. Second, emphasis would be shifted from numeric and symbolic manipulation to problem formulation, problem-solving strategies, and solution interpretation. A preliminary syllabus has been developed for the entire first year, NeXT workstations and physics laboratory stations have been purchased, and activities are now being finalized for the sixty (60) students who will begin the new curriculum in August 1990.

1.0 PRESENT CURRICULUM

In general, the present, first-year curriculum in science, engineering, and mathematics at Rose-Hulman Institute of Technology consists of the following courses:

Calculus I, II, and III (15 credits)

Mechanics or Engineering Statics (4 credits)

Electricity and Magnetism (4 credits)

General Chemistry I, II (8 credits)

Graphical Communication (2 credits)

Introduction to Design (2 credits)

Computer Programming I (2 credits).

Together, these courses represent 37 credits. In addition to these courses, students take courses in military science, literature and writing, and electives in humanities and social science.

1.1 Overemphasis on Manipulation

Conversations among the faculty revealed two widely-perceived weaknesses in the current curriculum. First, there is too much emphasis on numeric and symbolic manipulation, especially the latter. Methods of integration can focus on finding closed-form anti-derivatives for varieties of integrals without developing intuition about the concept of integration. Physics and chemistry courses often allow success with the following problem-solving strategy: Find the formula which contains the symbols which match the values given in the problem statement. Students write pages of algebraic manipulation without discerning the nature of the problem or developing an estimate of the solution that is required, or interpreting the result which is obtained. From their perspective, courses require that they memorize many collections of special techniques whose intellectual and scientific content remains obscure. Overemphasis on manipulative skills suppresses student curiosity and fails to develop required problem formulation and solution interpretation skills.

Emphasis on manipulative skills at the expense of concepts and problem-solving strategies would be forgivable if technology to perform the manipulative tasks were not available. However, the technology is available, and curricula must address the issues of content, problem formulation, and solution interpretation.

1.2 Compartmentalization

The present curriculum presents students with discipline-oriented "containers of knowledge" called "courses." Each course focuses on topics, techniques, and applications which arise in the discipline. Integrating concepts is left entirely to students who are never given formal instruction on how to recognize and apply relationships across the boundaries of different disciplines. Students learn each new topic presented in each different course without developing a framework in which these topics may be integrated to create broad, thematic concepts which are more powerful and more generally applicable. Failure to recognize relationships and to integrate topics produces less efficient instruction and less effective problem-solvers at a time when our curriculum is experiencing enormous pressure to add more material.

Now that the problems have been targeted, solutions are required.

2.0 PROPOSAL FOR AN INTEGRATED, FIRST-YEAR CURRICULUM

2.1 Structure

Design of the new curriculum followed four guiding principles:

- Interdisciplinary
- Efficient
  - modern technology
  - designed, coherent redundancy to reinforce and relate concepts common to a number of disciplines
- Adaptable — identify, codify, and introduce fundamentals as science and technology advance
- Visibly relevant and interesting

The resulting structure is a three-course sequence (quarter system). Each course is twelve credits.

2.2 Concepts

One of the greatest challenges for science, engineering, and mathematics education posed by exponential knowledge growth and rapidly advancing technology is to identify a small number of broad, powerful concepts which must be communicated to students. At the risk of adopting an overused word, these concepts are the fundamentals. Today, there are no fundamentals. Or rather, each person has his or her own set of fundamentals and the intersection of the sets of seven or more people is nearly empty. Educators must identify fundamentals and select topics to reinforce these fundamentals instead of arbitrarily deciding which topics will be taught and which topics will not be presented.

To counter compartmentalization, a small number of concepts were identified as the focal points in the curriculum. These concepts were organized into three categories:

1. Basic Building Blocks
2. Thematic Concepts
3. Problem-Solving Strategies.

2.2.1 Basic Building Blocks

Basic building blocks are the concepts upon which science, mathematics, and engineering are based. These must be communicated early and reinforced throughout the curriculum. Four basic building blocks have been identified:

1. Function
2. Vector
3. Three-Dimensional Visualization
4. Physical Abstraction.

The first three are self-explanatory. The fourth requires some explanation. Physical abstractions are quantities which scientists invent to describe and explain observed behavior. They include length, mass, temperature, energy, entropy, etc. Students need to realize that physical abstractions are not concrete; instead, they have been made up and are used simply because of past success in describing behavior in the physical world around us. Also, students must learn and use the units associated with the physical abstractions.

2.2.2 The Thematic Concepts

Thematic concepts are links which span two or more different disciplines. Three have been identified.

1. Rate

   The rate at which a quantity is changing, both average and instantaneous, is important. The concept of rate appears in reaction kinetics, velocity, acceleration, the derivative, and in Newton's Second Law where force is set equal to the rate at which linear momentum is changing. «IP»

2. Accumulation

   Accumulation is the notion that the value of a quantity can be calculated by summing individual contributions. Further, the accuracy of the value can be increased by summing a greater number of smaller pieces. Areas under curves are calculated by summing areas of rectangles or trapezoids. Total mass, center of mass, and moment of inertia are calculated by summing contributions of infinitesimal pieces of mass. Work is calculated by summing individual pieces of work, and, in the limit, work is calculated by using a line integral. In the limit, rate and accumulation are related by the fundamental theorem of calculus.

3. Conservation

Observations of physical phenomena indicate that there are physical abstractions whose total amount in the universe remains constant with respect to time. Such physical abstractions are said to be conserved. Often, realization that there is a quantity which is conserved generates a new physical abstraction. If an abstraction is conserved, and if in your system the quantity of the abstraction is either increasing or decreasing, then the quantity of the abstraction in the environment must be decreasing or increasing. Conservation laws are invaluable in formulating problem statements which can be solved. Quantities which are conserved are:

Amount of elements (in the absence of nuclear reactions)—In a chemical reaction, the amount of hydrogen is constant.

Linear momentum—Two systems exchange linear momentum through an abstraction called force.

Angular momentum—Two systems exchange angular momentum through an abstraction called torque.

Charge

Mass

Energy

(Entropy—Even though the total amount of entropy in the universe is not constant, it is non-decreasing. Therefore, it is worthwhile to list this physical abstraction.)

2.2.3 Problem Solving Strategies

Problem-solving strategies are what we use when we do not see how to solve the problem. Strategies can be as simple as "draw a picture of your problem" or "consider the units in the problem." They may be more complex: "first, identify the goal; second, decide how you plan to reach the goal; and third, implement your plan." First-year mathematics, science, and engineering students have very few problem-solving strategies because they have worked through very few problems in which the solution was not immediately apparent to them. They are ill-equipped to attack multi-step word problems in physics, chemistry, and calculus, not because of their failure to grasp the concepts involved, but because they do not immediately see how to solve the problem and therefore, they become convinced that they do not understand the material.

In the new curriculum, teachers will present and model problem-solving strategies for the students. Students will be required to elucidate their problem-solving strategy when they submit their problem solutions.

3.0 IMPLEMENTATION

The new curriculum will be offered for the first time to sixty (60) students during the 1990-91 academic year. Participants will be selected from students who have volunteered to become a part of the new curriculum. To date, over two hundred students from an incoming first-year class of approximately 360 students have indicated they want to participate in the integrated curriculum. Participants will be selected by 15 July 1990.

To shift emphasis from numeric and symbolic manipulations to problem formulation and solution interpretation, The Rose-Hulman Institute has purchased seventy (70) NeXT workstations and equipped them with WingZ (a spreadsheet), and FrameMaker (a document preparation system). Also, each NeXT comes bundled with Mathematica, Interface Builder (a graphical tool for user interface and software development), and Objective-C programming environment (compiler, editor, and debugger), Digital Librarian, Webster's Dictionary, and WriteNow (an easy-to-use word processor). Also, the Institute has purchased sixteen (16) physics laboratory stations with an air table, sonic ranger, rotational table, and a Zenith 286-LP computer to support data acquisition and analysis.

In the 1991-92 academic year, the integrated curriculum will be taught with 120 students. On the basis of the two years' experience, the Institute will decide to expand the curriculum to the entire first-year class, offer the curriculum to a portion of the first-year class, or discontinue the integrated curriculum.

4.0 ACKNOWLEDGMENTS

Six faculty prepared the preliminary syllabus for the integrated, first-year curriculum in the summer of 1988. Their work was supported by The Lilly Endowment, Inc., Grant Number 870643.

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Appendix 4
A General Education Program Built Around The Concept Of Evolution

In the publication, *The Natural Sciences Sequence at the University of Chicago*, Michael LaBarbera, Associate Professor, Department of Organismal Biology and Anatomy, delineates a successful six-quarter sequence built around the concept of evolution in the natural world. Excerpts from his introduction to the 86-page publication and the catalog statement of the sequence are given below.

The students are drawn exclusively from disciplines outside the natural sciences; self-reporting documents that a plurality enter these sequences indifferent or actively hostile to the study of the natural sciences. Student evaluations of the "evolution" sequence indicate that the students leave the sequence with an appreciation of the relevance of the natural sciences to their personal lives and to public policy questions, students commonly indicate that, although they have no interest in pursuing careers in the natural sciences, they can appreciate why others might find such study engaging.

The lecturers in the "evolution" sequence meet twice a year (early in the fall and late in the spring quarters) to discuss their experiences in the past year and their plans for the upcoming year; changes in course content and emphasis are extensively discussed. The "evolution" sequence exercises are largely custom-designed for an audience of non-scientists. Although the common wisdom among university faculty would have one believe that students, especially non-scientists, dislike laboratory exercises, I believe that the large laboratory component in the "evolution" sequence is vital in bringing home to the students the reality of the topics discussed in lecture. These exercises have been crafted to avoid the "cookbook" nature of many introductory laboratories; the intellectual challenge that they offer to the students more than offsets the labor they involve.

We offer this example of how the natural sciences can be made accessible to students majoring in other disciplines, but do not wish to give the impression that there is anything "magic" about this particular sequence of courses or the topics involved. Although we believe that the integration of this sequence accounts for much of its success, the particular theme we have chosen could be replaced by any number of others (i.e., energy, order [entropy], "powers of 10", information). Regardless of the theme chosen or the content of each course, no such sequence is likely to be successful without a strong laboratory component, a major commitment on the part of the faculty involved to maintain communication among themselves, and the active support and encouragement of the institution's administration.

NatSci 101 - 106. Evolution of the Natural World.

This is an integrated six-quarter sequence which emphasizes the evolution of the physical universe and of life on earth, and that explores the interrelationships between the two. The courses must be taken in sequence, with the first year (101-103) a prerequisite for the second (104-106). This sequence satisfies the Common Core requirements in the physical and biological sciences for students in the humanities and social sciences. Registration is open only to freshmen, sophomores, and first-year transfer students, with preference given to freshmen. Prerequisites: Completion of pre-calculus mathematics or placement into a calculus course.

NatSci 101. Evolution of the Universe.

The origin, evolution, and large-scale structure of the universe will be considered in this course. The course will examine models of the present universe as the result of physical events that happened in the first minutes of the big bang. Topics to be covered include curved space and the expansion of the universe, the early evolution of the universe from a primordial soup of elementary particles through nucleosynthesis, and the subsequent formation of galaxies and stars. Laboratory.

NatSci 102. Evolution of the Solar System and the Earth.

This course will begin with an examination of the physical and chemical origins of planetary systems, the role of meteorite studies in this context, and a comparison of the earth with neighboring planets. It will then turn to chemical and physical processes leading to internal differentiation of the earth. Further topics to be considered include the thermal balance at the earth's surface (glaciation and the greenhouse effect) and the role of liquid water in controlling crustal geology and evolution. Laboratory.

NatSci 103. Evolution: Chemical to Biochemical.

The course opens with a consideration of the organic molecules found in space and what is known about the prebiotic terrestrial environment. It continues with attention to the kinds of molecules that are characteristic of living systems and attempts to delineate the minimum requirements for systems to be termed living. The course then traces the evidence for the origin of the simplest living things via a chemical evolution from nonliving materials and considers evidence relating to the origins of higher levels of organization and the formation of cell organelles. Laboratory.

NatSci 104. Biological Evolution.

An introduction to evolutionary processes and patterns in present-day organisms and in the fossil record, and how they are shaped by biological and physical forces. Topics covered, emphasizing evolutionary principles, include DNA and the genetic code, the genetics of populations, the origin of species, evolution above the species level, and major events in the history of life, such as the origin of complex cells, invasion of land, and mass extinctions. Laboratory.

NatSci 105. The Design and Function of Organisms.

This course will focus on the constraints that physics and chemistry impose on organismal-level design in biology. General biological problems (e.g., movement, support, internal communication) and their solutions will be explored, with examples drawn from both botany and zoology; evolutionary implications will be emphasized. Laboratory.

NatSci 106. Organisms to Ecosystems.

This course will consider the mechanisms and processes by which organisms interact with their environments. It will also examine the organization and function of major categories of terrestrial ecosystems including arctic and alpine tundras, hot and cold deserts, forests, woodlands, and grasslands. There will be an analysis of the impact of human activities on the global ecosystem. Laboratory.

Appendix 5
Participant Initiatives

TEAM-TAUGHT NEUROSCIENCE

L. Joseph Achor, Baylor University

At Baylor University *Introduction to Neuroscience* is an entry-level course team-taught by five professors. In addition to addressing subject-specific aspects of this field, goals for this course include enhancing scientific literacy, facilitating understanding of the scientific method and its applications, encouraging scientific skepticism and critical thinking, and developing understanding and compassion for people whose experiences and behavior are different from our own. Each professor brings to the course his or her own expertise in one or more areas of neuroscience, and each teaches a three-week unit. Computer exercises simulating important scientific procedures and observations facilitate learning. To enhance the flow of information and to aid students in making the transition from one professor to another, instructors provide lecture outlines and brief notes. This course meets one of the three laboratory science requirements for both science and non-science majors. Approximately 250 students enroll in the course each year.

COMPUTER-MANAGED GENERAL BIOLOGY COURSES

Anne Donnelly, SUNY College of Agriculture & Technology

Students at SUNY College of Agriculture & Technology at Cobleskill may elect to take general biology in a flexible, computer-managed format. Two sequential courses integrate lectures, printed study guides, audio and video tapes, lab exercises, and interactive computer work to accommodate the needs, schedules, and learning styles of a diverse population of students. In these self-paced courses, students are responsible for attending scheduled labs and lectures, and for using the computer to generate homework assignments. The computer provides grades, correct answers, and explanations, as well as optional remediation or enrichment on certain topics. Grading is done by mastery testing (computer generated from banks in excess of 6,000 questions). Computer-managed learning has been used for these courses since 1975 and currently serves 300 students per semester. Software is discipline-independent and versatile, being used in varied ways for entry-level courses in biology and chemistry, and soon for math, accounting, and the Skills Development Center.

STUDENT-ORIENTED COURSE IN CHEMISTRY

Anna J. Harrison & Edwin S. Weaver, Mount Holyoke College

A continuing effort to make chemistry more accessible to and rewarding for students with limited backgrounds in mathematics and the sciences naturally generates a student oriented course. Our intent is to help students develop interest in chemical phenomena and confidence in their abilities to understand things chemical. The selection of chemical systems, concepts, laboratory activities, and problems is guided by our perception of their contribution to the development of 1) an understanding of the nature of science and 2) a body of knowledge conducive to lifetime learning through the mass media. The introduction of topics is guided by perceptions of what these students can cope with next and how far they can go in processing information on first encounter. Depth and breadth of concept are pursued through repeated encounters achieved by later orchestration with related topics. A text, *Chemistry: A Search to Understand*, based upon our experience in working with these students was published by Harcourt Brace Jovanovich in 1989.

AMERICAN SCIENCE, TECHNOLOGY, AND SOCIETY

Norriss S. Hetherington, University of California, Berkeley

Many students, particularly those who do not major in science, seem to view science as a set of facts to be memorized, not as a process of investigation. A course at the University of Kansas effectively challenged this view. This otherwise standard lecture course actively involved students via assignments designed to explore and test generalizations raised in readings and lectures. For example, students tested the hypothesis that early American science consisted of observations without theoretical framework by each taking a series of early volumes of the *Philosophical Transactions of the Royal Society of London* and characterizing reports by American authors as either entirely anecdotal or theoretically based. Students left the course with skills empowering them to formulate testable hypotheses, test the resulting hypotheses, organize their results, and present their conclusions. The hands-on experience of doing research can significantly raise the intellectual level, enthusiasm, and enjoyment of a course.

HISTORY OF ASTRONOMY

Norriss S. Hetherington, University of California, Berkeley

Both science and the history of science are best viewed as activities, not as collections of data. A major goal of this course at the University of Kansas was to have students read with critical understanding actual scientific papers (in translation, when necessary) and to formulate reasoned, organized essays based entirely on the primary source. A sample assignment follows: Assess the relative importance of philosophical considerations and observational evidence in the expanding model of the universe for Hubble in his paper "The Problem of the Expanding Universe", *American Scientist*, 30, 1942, 99-115. Initially, virtually none of the students could do the assignments. On the day each paper was turned in, assigned passages were gone over word by word, sometimes several times, until students finally saw meanings they had been struggling to grasp and to convey in their essays. Near the end of the course, however, attention spans were longer, critical reading skills sharper, and intelligent, organized essays conveying sophisticated understanding were being produced.

THE GRADING SYSTEM

Jay A. Johnson, University of Washington

The Center for Quantitative Science at the University of Washington offers a wide range of applied mathematics courses for students in natural resources management. Decision making in these fields relies on quantitative analysis, requiring mastery of fundamental mathematics. Yet, students entering these fields are not generally fond of mathematics. To encourage the development of mathematical skills in calculus and differential equations courses, we devised the following grading system: Each student earns three grades, for homework, mid-term exam, and final exam. The final grade is based on the sum of 40% of the highest grade of the three, 35% of the median grade, and 25% of the lowest. As the three grades are percentages, the weighted average is also a percentage. Numerical grades (4.0 system) are prorated, with 70% = 0.7 and 96% = 4.0. The operating principle is straight forward: Do the homework. Because there are no surprises on the exams, mastering the homework insures good performance on exams. Students are rewarded for what they do best.

COMBINED COURSES IN CALCULUS, PHYSICS, AND WRITING
Edward A. Martin, Monroe Community College

Tight schedules and rigid course sequences characterize many engineering programs. This is particularly so at two-year institutions, where students may be obliged to take calculus and physics concurrently. In these programs, concepts may be needed in physics before they are covered in calculus. This scheduling problem likely contributes to the difficulty that many engineering students experience in entry-level physics courses. To address this problem, Monroe Community College offers special combined sections of calculus and physics. For each of the first two semesters, combined sections are team taught by professors of mathematics and physics. The two professors remain in the class room at all times. Applications of calculus are presented as they are needed for physics; theories behind these applications come later. Writing, in the form of a journal, is used as a tool to encourage clear thinking and to develop understanding.

INTER-DISCIPLINARY COURSE IN QUANTITATIVE REASONING
David Peak & Michael Frame, Union College

Order and Chaos: Art and Magic is an entry-level course in quantitative reasoning taught by a physicist and a mathematician at Union College. Participants (typically upper-class humanities and social science majors) have no prior experience with calculus. This course emphasizes the power of mathematical modeling in trying to sort out the complexities of the physical, biological, and social worlds. It stresses thinking in pictures rather than relying on classical analysis, and it uses the compelling imagery of fractal geometry and nonlinear dynamics as the primary vehicle for discussion. Students utilize the computer as an essential tool in aiding their understanding. Weekly laboratory sessions engage students in the process of discovery and bring to life otherwise formal aspects of the course. A term project allows students to exercise their creative energies; examples contributed so far include poetry, musical compositions, paintings, analyses of geological structures, computer image constructions, and investigations of the dynamics of arms races.

MATHEMATICS WORKSHOPS
Carol Scheftic, Carnegie Mellon University

Establishing study groups to work together on assignments may contribute to the success of women and minority students. Calculus students at Carnegie Mellon University gained experience in collaborative learning, following a model developed by P. Uri Treisman at the University of California, Berkeley: Some students were assigned to workshops, rather than to normal recitations. Workshops met for twice as much time, were smaller, and worked on problem sets (alone or in small groups). A graduate student and an experienced undergraduate mingled with groups, listened to their discussions, helped them identify important issues, and asked leading questions. Workshops are not remedial: They strengthen the interest and understanding of students who would get average or above-average grades on their own. After one semester, workshop students scored higher than a matched group assigned to recitations. All students (including white males) benefited from workshops, but workshops were more helpful for black students and especially helpful for women.

CASE STUDY PHYSICS

Alan Van Heuvelen, New Mexico State University

Overview, Case Study Physics, developed at New Mexico State University, provides a flexible format to help students construct a knowledge hierarchy on a foundation of conceptual understanding. The program places equal emphasis on acquisition and construction of conceptual knowledge and on development of analytical techniques to use that knowledge to analyze and solve problems in the real world. Students receive repeated exposure to concepts over an extended period and in a variety of contexts. They are actively involved in their instruction and are motivated by developing understanding and by applying knowledge to interesting phenomena. Preliminary trials of this method have produced gains in qualitative understanding and problem-solving ability, and in the number of students successfully completing their study. These gains are achieved with easily adoptable materials, including a study guide, a set of problem sheets, and an instructor's guide, all of which supplement any standard physics text. (Sponsored by the Fund for the Improvement of Post-Secondary Education.)

CREATIVE MATHEMATICS

Alvin White, Harvey Mudd College

There is a discontinuity between the free, creative play of children and mature scientists on the one hand, and the routine of learning rules in the class room on the other hand. Mathematics students at Harvey Mudd College encounter several exercises designed to bridge this gap. Classes are divided into teams of three to five students. Each team is asked to invent two problems related to the homework: one should be interesting. The other should be impossible to solve. Each team then challenges the others to solve its problems. The class discusses solutions, or—if a problem is impossible—why it is so. Both team and class discussions give insight into the nature of mathematics and the students' knowledge. Another invitation to creative thought is an assignment to perturb a formula or concept beyond the meaning that is commonly encountered. (For example: Assign a meaning to n! when n is a fraction.) Students find it interesting that most of their outrageous proposals can be given meaning via more advanced mathematics, which this exercise encourages them to pursue.