The Liberal Art of Science: Agenda for Action

The Report of the Project on Liberal Education and the Sciences

American Association for the Advancement of Science
Founded in 1848, the American Association for the Advancement of Science is the world’s leading general scientific society, with more than 132,000 individual members and nearly 300 affiliated scientific and engineering societies and academies of science. The AAAS engages in a variety of activities to advance science and human progress. To help meet these goals, the AAAS has a diversified agenda of programs bearing on science and technology policy; the responsibilities and human rights of scientists; intergovernmental relations in science; the public’s understanding of science; science education; international cooperation in science; science education; international cooperation in science and engineering; and opportunities in science and engineering for women, minorities, and the disabled. The AAAS also publishes Science, a weekly journal for professionals, and Science Books & Films, a review magazine for schools and libraries.
CONTENTS

Preface vii

THE STATEMENT

Statement of the Study Group of the Project on Liberal Education and the Sciences xi

THE RECOMMENDATIONS

Agenda for Action 3

Responsibility of Natural Science Faculties 3
Resource Commitment 3
  Time Commitment to Science 3
  Faculty-Student Ratio 3
Teaching Materials and Technologies 4
Appropriate Assessment Instruments 4
Science Teachers 4
The Underrepresented in Science 5
The Disabled 5
Science and Engineering Majors 5
Institutional Support 5
External Support 6

THE REPORT

Introduction 9

Endnotes 13

Aspects of Scientific Understanding 15

The Nature of Scientific Explanation 16
  Scientific Values and Ways of Knowing 17
  Methods of Collecting, Analyzing, and Classifying Information 17
  Scientific Laws, Theories, and Models 18
  The Language of Science 18
  The Role of Mathematical Concepts in Understanding Science 19
  The Limits of Scientific Understanding 20
Integrative Concepts in Science 21
  Causality and Consequence 22
  Scale and Proportion 22
  Dynamic Equilibrium 23
  Change and Evolution 23
<table>
<thead>
<tr>
<th>The Context of Science</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical Development and the Intellectual and</td>
<td></td>
</tr>
<tr>
<td>Cultural Contexts of Science</td>
<td></td>
</tr>
<tr>
<td>Ethical, Social, Economic, and Political Dimensions of</td>
<td></td>
</tr>
<tr>
<td>Science</td>
<td></td>
</tr>
<tr>
<td>Postscript</td>
<td>25</td>
</tr>
<tr>
<td>Endnotes</td>
<td>26</td>
</tr>
</tbody>
</table>

**Prolegomenon to a New Pedagogy**

- Science As Taught/Science As Practiced                      | 28 |
- Pedagogical Techniques                                       | 30 |
  - Goal-Oriented Instruction                                   | 31 |
  - Engendering Subject Matter Understanding                    | 31 |
  - Laboratory and Field Experiences                            | 33 |
  - Lectures and Texts                                         | 35 |
  - Group Discussion and Projects                               | 37 |
  - Writing Activities                                          | 38 |
  - Integrating Mathematics                                    | 39 |
  - Appropriate Assessment of Scientific Understanding          | 40 |
- Subject Matter                                              |    |
  - Integrating Multidisciplinary Content                       |    |
  - Subject Matter Organized Around the Conceptual Framework of |    |
  - the Discipline                                              |    |
  - Subject Matter Organized Around Problems, Issues, or Case  |    |
  - Studies                                                    |    |
  - Subject Matter Organized Around Themes                      |    |
  - Subject Matter Organized Around the History of Science      |    |
  - Conclusion                                                 | 47 |
  - Endnotes                                                   | 47 |

**Programmatic Approaches to Liberal Education in Science**

- Curricular Matters                                           | 51 |
  - Consensus on Goals                                          | 52 |
  - Data on Goal Attainment                                     | 53 |
  - Designing Coherent Programs Through Intellectual Integration| 54 |
- Administrative Support                                        |    |
  - Faculty Development                                         |    |
  - Reward Structure                                            |    |
  - Program Maintenance                                         |    |
  - Endnotes                                                    | 59 |

**Liberal Education in Science for Special Groups**

- Future Science Teachers                                       | 61 |
- The Underrepresented in Science                               | 62 |
- The Disabled                                                 | 64 |
- Science and Engineering Majors                                | 64 |
  - Endnotes                                                    | 66 |

**Afterword**

**THE APPENDIXES**

- Introduction to the Appendixes                                | 73 |
- Appendix A: Programs Involving the Core Curriculum            | 75 |
Integrated Liberal Studies Program (University of Wisconsin-Madison) 76
Introduction to the Natural Sciences (Lehman College) 77
Learning Science Through Inquiry: Natural Science Division I Requirement (Hampshire College) 78
The Liberal Arts/Mathematics-Based Alternative (Lambda) Core (Case Western Reserve University) 79
Science in Modern Life I and II (Brooklyn College) 80
Scientific and Technological Literacy (Iona College) 81
The Technology Cluster (Syracuse University) 82

Appendix B: Programs Constituting a Major 83
The Curriculum in Science and Culture (Purdue University) 84
History, Philosophy, and Social Studies of Science and Medicine (The University of Chicago) 85
Liberal Arts and Science Program (Utah State University) 86
Science in Society Program (Wesleyan University) 87

Appendix C: Full-Year Courses and Course Sequences 89
Chemistry of Our World (Wright State University) 90
Foundations of Science (Hunter College) 91
Physical Science Program (West Virginia University) 92
The Theory and Practice of Science (Columbia University) 93

Appendix D: One-Semester Courses 95
The Century of Genius: Science, Philosophy, and Social Change, 1543–1687 (University of San Diego) 96
Communications Technology (State University of New York at Stony Brook) 97
Science influences every aspect of contemporary American life, yet the United States has been described as a nation of scientific illiterates. The appraisal of leaders in government, education, and the private sector is that the welfare of the nation and the individual will be improved when all citizens have sufficient understanding of science to make soundly based personal, civic, and professional decisions. This national goal can be achieved only through the radical reform of science education at all levels. Of critical concern is education in the natural sciences at the undergraduate level.\(^1\) *The Liberal Art of Science: Agenda for Action* addresses this concern.

This report presents the conclusions and recommendations of the Study Group of the American Association for the Advancement of Science (AAAS) Project on Liberal Education and the Sciences. The members of the Study Group deliberated about the level of scientific understanding required for optimal participation in life in the 21st century and about the nature of undergraduate education in the natural sciences necessary to achieve a proper level of understanding. As a result of their inquiry, the members of the Study Group reaffirm the value of liberal education for all undergraduates, set goals for the natural sciences in liberal education, and recommend mechanisms for their attainment.

The AAAS Project on Liberal Education and the Sciences was initiated in response to recommendations contained in the report of the Carnegie Forum on Education and Economy, *A Nation Prepared: Teachers for the 21st Century* (1986), and in *Tomorrow's Teachers: A Report of The Holmes Group* (1986). Both reports recommended that the undergraduate education major be eliminated and replaced by a major in the liberal arts. However, they did not discuss the nature of the new major. Because implementation of this recommendation depends on defining the characteristics of the new major, the Carnegie Corporation of New York invited the AAAS to organize a study of the education of prospective teachers in the natural sciences.

The AAAS accepted the invitation, but expanded the study to include the role of the natural sciences in the liberal arts curriculum for all students. Understanding science as a liberal art will be equally important for all undergraduates when they become America's future leaders in the private sector, education, and government.

Plans for the scope and direction of the project were made with the help of members of the AAAS Coalition for Education in the Sciences, a consortium of scientific and educational associations. The members of the project's Advisory Board and Study Group were selected in consultation with the leaders of these associations (see Appendix E for a list of these groups). Six representatives of the scientific, engineering, and educational communities and of the private sector comprise the Advisory Board. The 15 members of the Study Group represent diverse disciplines and share a firm commitment to strengthening undergraduate education in the natural sciences.

\(^1\) This report is limited to the role of the natural sciences in undergraduate education. Comments on the mathematical, engineering, and other sciences are made only insofar as they contribute to understanding the natural sciences.
The project's strategy—assembling a multidisciplinary team to discuss the issues—was based on the assumption that consensus reached by such a team on the place of the natural sciences in liberal studies would be a valuable resource for stimulating discussion of the issues at the national level. Joining this group of senior scholars were graduate students and young professionals, identified by Study Group members, who served as Study Group Associates and joined in the group's deliberations. One purpose of this experience was to develop in the group of young academicians an interest in and an understanding of issues in higher education.

The Liberal Art of Science: Agenda for Action contains the Study Group's recommendations of goals for liberal education in the sciences as well as the multidisciplinary curriculum and teaching strategies necessary to achieve them. It reaffirms the importance of the natural sciences in the liberal arts curriculum and recommends that the study of the natural sciences be multidisciplinary. Cross-disciplinary teaching that involves faculty from the humanities, the social sciences, and the practical and fine arts is encouraged. The Study Group also recommends teaching science as it is practiced. This means incorporating the philosophy, values, and methods of science into instruction in the natural sciences.

The Study Group recognizes that implementation of its recommendations is the prerogative of faculty members in the nation's colleges and universities and trusts that they will consider this report in light of the needs and circumstances of students in their particular institutions.

Furthermore, the Study Group recognizes that implementing these recommendations will require the commitment of many resources and cannot be accomplished by institutions of higher education without assistance from the state and federal governments, the private sector, and professional associations. The issues involved are of such national importance that resources from all these sectors should be committed to support the necessary activities.
The Statement
Science is one of the liberal arts and should be taught as such.

Human survival and the quality of life depend on liberally educated citizens who are able to make informed assessments of the opportunities and risks inherent in the scientific enterprise. Yet there is every indication that present levels of scientific understanding, even among those who are otherwise well educated, are inadequate for life in the 21st century. In spite of the importance of science and the ubiquity of its applications, science has not been integrated adequately into the totality of human experience. Therefore, it is the central premise of this report that science must be taught as one of the liberal arts, which it unquestionably is.

Without the study of science and its relationships to other domains of knowledge, neither the intrinsic value of liberal education nor the practical benefits deriving from it can be achieved. Science, like the other liberal arts, contributes to the satisfaction of the human desire to know and understand. Moreover, a liberal education is the most practical education because it develops habits of mind that are essential for the conduct of the examined life. Ideally, a liberal education produces persons who are open-minded and free from provincialism, dogma, preconception, and ideology; conscious of their opinions and judgments; reflective of their actions; and aware of their place in the social and natural worlds. The experience of learning science as a liberal art must be extended to all young people so that they can discover the sheer pleasure and intellectual satisfaction of understanding science. In this way, they will be empowered to participate more fully and fruitfully in their chosen professions and in civic affairs.

Understanding science and its influence on society and the natural world will require a vast reform in science education from preschool to university. This report focuses on the need for curricular reform at the college level. It addresses goals for all students—science majors and nonscience majors alike—for science majors also must understand science as a liberal art in order to be responsible and reflective professionals.

Science should be taught as science is practiced at its best.

Education in science is more than the transmission of factual information: it must provide students with a knowledge base that enables them to educate themselves about the scientific and tech-
nological issues of their times; it must provide students with an understanding of the nature of science and its place in society; and it must provide them with an understanding of the methods and processes of scientific inquiry. To achieve these goals, science should be taught as science is practiced at its best.

Our recommendations are addressed primarily to natural science faculty who must take responsibility for a major reform of science education. To initiate and implement the changes recommended, it is essential to enlist the vision, commitment, and participation of faculties in other disciplines, administrators, and external agencies. The report includes an appendix that contains examples of individual and institutional initiatives which are under way already. We propose that the academic community go beyond these isolated efforts and adopt a coherent national agenda to strengthen all aspects of science education. This can and must be done.

ASPECTS OF SCIENTIFIC UNDERSTANDING

All sciences share certain aspects of understanding—common perspectives that transcend disciplinary boundaries. Indeed, many of these fundamental values and aspects are also the province of the humanities, the fine and practical arts, and the social sciences. Students, no matter what their ultimate career goals, should take from their college science education understanding, knowledge, skills, and attitudes concerning the aspects of science listed below. We believe that all of the following components should constitute an integral part of every student’s education for they represent and embody the goals of liberal education in science.

A. The Nature of Scientific Understanding

1. Scientific Values and Ways of Knowing
Students should learn that science is the art of interrogating nature, a system of inquiry that requires curiosity, intellectual honesty, skepticism, tolerance for ambiguity, and openness to new ideas and the sharing of knowledge.

2. Collection, Organization, and Classification of Information
Students should learn through experience that collecting information demands careful observation, sound experimental design, the identification of significant variables, and precise, accurate, and reliable measurements. To make sense of the natural world, students need to be aware that understanding and explanation are impossible without the organization of data.

3. Discovering Scientific Laws, Devising Models, and Developing Theories
Students should have the opportunity to learn the nature of the "scientific method" through participation in discovering (or at least rediscovering) the laws implicit in data, constructing and testing hypotheses, and challenging the predictive power of theories and models. Whatever the scientific discipline, attention
should be paid to the relationship between the concrete and the abstract and the concept of falsifiability of a scientific explanation.

4. The Limits of Scientific Knowledge
A liberal education in the sciences requires not only an understanding of what science knows, but also of what science does not know. It is essential that students realize that scientific knowledge is not absolute, but tentative, approximate, and subject to constraints and revision.

5. The Vocabulary and Terminology of Science
One of the greatest barriers to scientific literacy is the specialized vocabulary of science and its relationship to concepts. Students must recognize the importance of this language and learn the basic terminology for accurate communication and shared understanding. They must understand and use the major terms, formulas, and equations of the area being studied. Instructors are urged to be selective in the use of specialized vocabulary and place it in a context that is meaningful to students.

6. The Role of Mathematical Concepts in Understanding Science
Mathematics is concerned with abstraction, not merely quantification or formalization. Mathematical concepts can help scientists to construct and manipulate mental objects and processes to explain scientific phenomena and capture them analytically. Much of nature can be modeled and described in mathematical terms. No matter what the course or the level of mathematical preparation of the student, he or she should take away some understanding of how mathematics helps inform the study of nature and the ability to use some forms of mathematical reasoning to solve problems. We think it particularly important that all students be able to think logically, make reasonable approximations and estimates, and apply simple statistical principles.

B. Integrative Concepts

1. Scale and Proportion
A sense of the scale and proportion of the universe should be conveyed in science courses and illustrated through the use of mathematics and analogies. There is wonder in the simple fact that our human dimensions are approximately 14 orders of magnitude greater than the diameter of an atomic nucleus and approximately 25 orders of magnitude less than the distance to the farthest quasars observed thus far.

2. Change and Evolution
There can be no understanding of science without understanding change and the fact that we live in a directional, though not teleological, universe. Among the many illustrations are changes in position and velocity, in physical state and form, in chemical properties and composition, and in biological identity and speciation.

3. Causality and Consequences
The idea of cause and effect is fundamental to science—indeed, to making sense of existence. Students should be engaged in determining causal relations and in seeking explanations and mechanisms for such linkages.

4. Dynamic Equilibrium
An understanding of science is incomplete without both knowledge of this pervasive concept and its application in some specific
cases. Essential to this understanding are the definition of system, the establishment of boundary conditions, the study of the interaction of constituent units, and the discovery of rules governing the system.

C. The Context of Science

1. The Historical Development and Intellectual and Cultural Contexts of Science
   The teaching of science must explore the interplay between science and the intellectual and cultural traditions in which it is firmly embedded. Science has a history that can demonstrate the relationship between science and the wider world of ideas and can illuminate contemporary issues.

2. The Ethical, Social, Economic, and Political Dimensions of Science
   Liberal education in the sciences must provide students with linkages to the real world by exploring the values inherent in science and technology, by examining the institutions that set directions for science and technology, and by stressing the choices scientists, citizens, and governments make about science in human lives. Because those choices increasingly have impacts on a global scale, the international context of science and technology should be included.

TEACHING SCIENCE AS SCIENCE IS PRACTICED

This report espouses high goals of scientific understanding which will require new instructional strategies. Liberal education in the sciences must be provided to all students, ranging from those exhibiting high levels of achievement and interest to students with weak precollege preparation in science and fear of mathematics and science learning. Such problems are exacerbated for both minorities and women because they are already encumbered by many social and economic biases and stresses. We are confident that teaching science as it is practiced will improve science instruction vastly. Moreover, if the full range of students is to achieve the understanding in science proposed in this report, the natural science faculty must become conversant with research on how people learn science and integrate that knowledge into their science teaching. College instruction must reflect strategies that exhibit the following characteristics:

1. Goal-Oriented Instruction
   The coherence of an active research program in science is provided by the overarching goal that brings meaning to the day-to-day problems encountered by scientists. In like fashion, science courses should be organized around achievable objectives made explicit to the students. The intent is to make science learning meaningful to students from the start by engaging them in actual scientific investigation and in scientific reasoning.

2. Experiential and Laboratory Activities
   Curiosity about natural phenomena is one of the strongest motivators for the study of science. Therefore, liberal education in
science should include an experiential or laboratory component to give students a concrete, "hands-on" sense of the actual activities of scientists. Such experiences ought to be designed to explore the complexity of interpreting and evaluating data from various environments and to discover the limitations of scientific knowledge.

3. **Activities Promoting Independent Learning and Analysis**
   To prepare students to deal with scientific issues that arise after they have left formal education, science courses should develop skills for finding, reading, and analyzing information from a variety of sources. Individual research projects provide a mechanism for acquiring the skills and habits essential for functioning as an independent learner and citizen.

4. **Group Discussion and Projects**
   Liberal education in the sciences should make extensive use of group efforts in discussion sections and in projects in order to demonstrate the dependence of the scientific enterprise on teamwork as well as on individuals. To clarify the interactive nature of scientific inquiry, instructors should design problem-solving activities that include group research projects. Students often learn effectively through participating in group discussions and by designing and working on group projects or problems. Collaborative projects also contribute to the development of effective communication skills.

5. **Writing Activities**
   Liberal education in the sciences must require student writing because effective communication is an essential part of the scientific enterprise. Students should be expected to write reports of projects and exercises, papers on assigned or self-selected topics, and essays in response to examination questions.

6. **Cross-Disciplinary Content**
   Liberal education in the sciences should demonstrate the inherent cross-disciplinary connections that emerge when practical problems are addressed. The teaching of the natural sciences should utilize interconnections among the sciences themselves. Moreover, in order to prevent the isolation of science from the other liberal arts, instruction should include relevant relationships to the humanities, the fine and practical arts, and the social sciences.

7. **Mathematics in Science Courses**
   Mathematics is crucial to much of science. Science courses, especially for nonscience majors, should integrate mathematics with the study of those scientific topics whose explanations are based on mathematical concepts. Learning the relevant mathematics can be accomplished in several ways, but most of today's prerequisite courses are not appropriate, even for science majors.

8. **Assessment of Scientific Understanding**
   Assessment should reflect the stated goals of scientific understanding. Students should be tested for their abilities to analyze scientific problems, to generate reasonable hypotheses, to evaluate evidence, and to raise questions about science and technology in their own lives and in the society in which they live. Scientific understanding cannot be measured adequately by true-false, multiple-choice, or other similar tests. In fact, these formats are detrimental to achieving the goals we espouse. Papers, projects, essay tests, oral presentations, and other forms of assessment
must be used to judge whether the desired levels of scientific understanding have been achieved.

Assessment systems must reward curiosity, intellectual honesty, skepticism, tolerance of ambiguity, openness to new ideas, and the willingness to share knowledge. When students work together in groups, different people make different kinds of contributions. As with scientific collaboration, the assessment of each individual should derive, at least in part, from evaluation of the work of the entire group.

The goals of liberal education in the sciences cannot be attained without a major reform of national achievement and professional licensure tests.

9. Teaching Materials and Technologies
Without innovative instructional materials, the goals of this report cannot be realized. Unfortunately, faculty and students in traditional science courses are tyrannized by textbooks—many are very conventional and antithetical to our aims. Authors and publishers should be encouraged to create and distribute texts that address our recommendations; faculty should consider their adoption. Professional societies and granting agencies should underwrite promising, but financially risky projects. At the local level, course-specific, instructor-originated texts and computer-generated learning aids can be produced. The discriminating use of these and other electronic teaching materials may counter the overdependence on published textbooks.

SPECIAL CONCERNS

While the preceding sections have focused on the characteristics of science courses that are appropriate for all students, special populations require special attention. The future of science depends on attracting more students, including members of underrepresented groups, to science and science education. This section calls for special efforts to prepare teachers, improve representation in all programs, provide access for the disabled, and increase the number of science and engineering professionals.

1. School Teachers
The recommendations in this report have particular implications for teachers in grades K through 12. Future teachers will be critical to the proposed upgrading of scientific understanding. Vigorous initiatives will be required within institutions of higher learning in order to strengthen the quality of teaching. Teachers should be prepared in ways consistent with the recommendations of this report and equipped to use the same teaching strategies with their own students. Within five years, a new cadre of teachers taught in this manner should be in classrooms. Achieving this will require cooperation between scientists and educators and more stringent science requirements for future teachers. Specifically, secondary and middle school science teachers and elementary school science specialists should major in a natural science.

2. Underrepresented Groups
The goal of widespread public understanding of science cannot be attained when many groups are discouraged from its study
early in their education. As long as science is associated with some groups and not others, this condition will continue. We recommend that institutions begin to remedy this situation by setting specific goals for increasing the numbers of science graduates from minority and disadvantaged groups in the natural sciences. At the very minimum, these goals should be in proportion to numbers in the general population, either regional or national. Implementation needs to include provisions for special recruitment and retention strategies and significant involvement at the elementary and secondary levels by colleges and universities, professional societies, private foundations, and governmental agencies.

3. The Disabled
Access to and opportunities in the natural sciences are of special concern for the disabled student. As currently designed, many laboratory and field experiences are not accessible to this population. Faculty members must recognize the needs of disabled students and take the initiative to work with them to overcome the obstacles that prevent them from full participation.

4. Science and Engineering Majors
Concerted attention must be paid to reversing the longstanding decline in the number of college students choosing to major in science or engineering. We believe this can be accomplished if education for science and engineering majors is reformed according to the recommendations in this report. Training in analysis, independent thinking, and awareness of social and political contexts must not be relegated to a special segment of their curriculum, taught by faculty who are not scientists or engineers. Instead, the ability to see science and technology in context must be conveyed and assessed through the science and engineering courses themselves. Even for engineers, science courses taught merely as building blocks for engineering skills should be replaced or supplemented by liberal education in the sciences.

Implementing the principles and goals stated here will entail academic and administrative changes in thinking and in doing. The proposed reforms also will require significant increases in the financial support of teaching. We offer the following specific recommendations to guide faculties and administrators in developing implementation strategies.

1. Time Commitment to Science
Fifty percent of the instruction in a baccalaureate degree should be devoted to liberal education; at least one quarter of this portion should be devoted to liberal education in the natural sciences. In most institutions, this will be the equivalent of 15 or 16 semester hours of instruction in science for all students. The same percentages should apply to two-year associate degree programs. The most expeditious route to incorporating the characteristics of liberal education recommended in the previous section will be through newly conceived curricula or science courses.

2. Programmatic Approaches to Liberal Education in the Sciences
The goals of science in liberal education cannot be accomplished in a single course or in a few, isolated science courses. What is
needed is a coherent integrated program of liberal studies, designed and implemented by the entire institution. The science courses themselves will require reconceptualization, as will the current structure of the curriculum. The traditional survey course and concern about "coverage" have no place in the new curriculum described here. Rather, it is critical that liberal education in the sciences become a well-integrated part of a broader liberal education program.

3. **Collaboration of Science with Other Liberal Arts Faculties**
Faculty from the humanities, fine and practical arts, and social sciences are essential collaborators with scientists in framing the definition of "scientific literacy" and designing curricula to provide it. Nothing will happen unless their goodwill and commitment are forthcoming. Natural science faculties must take the initiative by assembling relevant data, generating dialogue, and fostering collaboration among faculty throughout an institution. In addressing issues of technology in society, the natural science faculty will need to work with faculty in the social sciences, humanities, and with engineering faculties on campuses that have them.

4. **Institutional Leadership**
An institution should establish clearly identified mechanisms to review current curricula, design programs, encourage the development of courses, and provide ongoing monitoring and assessment. The most valuable resource for conceiving and developing new curricula is a willing faculty with good ideas. Administrators should support faculty interest in these innovations and facilitate collaborative endeavors.

5. **Institutional Support**
The commitment of an institution to curricular reform must be demonstrated by administrative support and by recognition of faculty who contribute to the effort. We recommend that institutions strongly consider the following incentives and support mechanisms:

- Increased and continuing financial commitments will be necessary in order to implement the innovations proposed in this report.
- Teaching and scholarship in liberal education programs must be recognized in promotion and tenure decisions and in salary determinations. Departmental and administrative support for this policy is crucial. A program of awards and prizes for innovations in curricular development should be instituted.
- Faculty involved in a new program or in course development should be released from other duties and/or provided with graduate and undergraduate student assistants.
- A variety of development opportunities should be available to faculty participating in new programs and special preparation should be provided for all instructional personnel involved in liberal education in the sciences.
- An appropriate mix of senior and junior faculty should be constituted to create and implement new curricula.
- Procedures should be devised to rotate faculty duties in order to encourage changes and revisions in courses and to avoid burn-out.
A campus agent or agency should be designated to provide faculty and administrators with announcements of available funding sources and guides to consulting services.

6. **External Support**

Improving science education is a national imperative. High priority should therefore be given to start-up programs and experimental course design. Although colleges and universities should be prepared to commit institutional resources for this purpose, external funding also will be required. The extent and nature of the changes proposed here will demand significant funding from outside sources over a considerable period of time. Without financial support from federal and state governments, professional and scientific societies, and corporate and philanthropic sources, it is unlikely that science education will be improved substantially.

We therefore urge widespread and vigorous support of the goals of this report through the following initiatives:

- Scientific, professional, and educational societies should provide statements of support, disciplinary leadership, staff and member involvement, and financial support for special projects.

- Accrediting agencies should adopt standards and long-range plans that foster implementation of this report.

- The federal government should institute grant programs to provide start-up funds to those institutions with a long-term commitment to implementing the principles of the recommendations in this report.

- State governments should direct funds to colleges and universities for the development of liberal education in the sciences.

- Private foundations should promote the liberal arts goals of science education. Foundations and corporate-giving programs can make a significant investment in the nation's future by directing their attention to science education-related initiatives.

We have here proposed a plan of action for addressing the serious national concern about the nature and quality of science education at the college level. Providing on a large scale the liberal education in the sciences envisioned in this report is no small task. The moral and practical imperative of this undertaking demands immediate and concerted action.
The Recommendations
AGENDA FOR ACTION

Reforming undergraduate education in the natural sciences merits the highest priority on the national education agenda. The teaching of science to all college students must be imbued with a dynamic new philosophy. Science must fulfill its essential role as one of the liberal arts and it must be taught as it is practiced at its best.

Reform is essential if the level of scientific literacy of the nation's college-educated population is to reach the heights needed for personal, professional, and civic life in the 21st century. To achieve the requisite level of scientific understanding demands the conceptualization, design, and implementation of coherent programs of liberal studies that will result in the desired level of literacy. These activities require the commitment of considerable resources. They can be accomplished only through the concerted efforts of institutions of higher education acting in cooperation with scholarly and professional societies and supported by the private and public sectors. Specific recommendations for a national agenda to accomplish the aims of liberal education in science follow.

RESPONSIBILITY OF NATURAL SCIENCE FACULTIES

The commitment of natural science faculties is essential to achieving the goals of liberal education in the sciences. Science faculties must take the initiative to engage their colleagues from the humanities, social sciences, and fine and practical arts in reconsidering the place of science in liberal arts programs.

RESOURCE COMMITMENT

Time Commitment to Science

Fifty percent of the instruction in a baccalaureate degree program should be devoted to liberal education; at least one quarter of this portion should be devoted to liberal education in the natural sciences. In most institutions, this is equivalent to 15 or 16 semester hours of instruction in science for all students. The same percentages should apply to two-year, associate-degree programs.

Faculty-Student Ratio

Lectures to hundreds of students supplemented by an hour of recitation with a graduate teaching assistant are not sufficient to
of the faculty members who contribute to the effort. Incentives and support mechanisms to exhibit commitment should include:

- increased and continuing financial support to implement the innovations proposed;
- recognition and reward of teaching and scholarship in liberal education by the administration and by departments in promotion and tenure decisions as well as in salary adjustments;
- establishment of programs of awards and prizes for innovations in developing curricula for liberal studies in science;
- reduced teaching load and assistance from undergraduate and graduate students for faculty involved in program or course development;
- opportunities for faculty to develop skills and knowledge essential for developing programs and courses for liberal education in science;
- a balanced mix of senior and junior faculty members to plan programs and to create and implement new curricula; and
- a system whereby faculty assignment to courses promotes improvement in curriculum.

EXTERNAL SUPPORT

Improving science education is a national imperative. High priority should be given to new programs and to the design of experimental courses carried out with existing institutional resources. However, the extent and nature of the innovations needed call for significant and continuing funding that can come only from outside sources. Without additional funding from federal and state governments, professional and scientific associations, and philanthropic foundations, and corporations, it is unlikely that science education will be improved substantially. Widespread and vigorous support of the goals of liberal education in science requires that:

- scientific, professional, and educational societies provide statements of support for liberal education in science, disciplinary leadership, member and staff involvement, and financial support for special projects;
- institutional- and program-accrediting agencies adopt more meaningful standards and develop long-range plans that foster implementation of the innovations needed;
- the federal government establish grant programs to provide funds to institutions that commit themselves to implementing the principles of liberal education in science and to direct funds to colleges and universities for the development of appropriate courses;
- state governments direct funds to colleges and universities for the development of programs to teach the natural sciences in the tradition of liberal studies; and
- private foundations and corporations encourage and promote the goals of liberal education in science and make a significant investment in the nation's future by turning their attention to science education-related initiatives.
The Report
Despite the pressing need for citizens who understand science, the public's current levels of scientific understanding are inadequate for life in the 21st century.
Science pervades all aspects of human existence. The global ecology, the nation’s economy and security, and the quality of individual lives all depend on the public’s awareness of the opportunities and risks afforded by developments in the sciences. Nevertheless, many Americans, even those who are otherwise well educated, have little understanding of science or how it affects their standards of living.\(^1\) Nor do they possess the intellectual skills to act effectively on scientific matters that they encounter in their personal, professional, or civic experiences.

These and other deficiencies in the knowledge and intellectual skills of the American public are recounted in the more than 300 reports on American education that have been issued since the publication of *A Nation at Risk* in 1983.\(^2\) Generally, these reports are critical of the state of American education. Although many of them have called for broad and fundamental changes in science education, little attention has been paid to the nature of the scientific understanding that the nation’s schools and colleges are expected to engender or to methods for attaining it.

This report describes the kind of scientific comprehension that will enable those in the college-educated population to meet the challenges of the 21st century and proposes methods for nurturing scientific familiarity during the undergraduate years. The recommendations are addressed primarily to college-based natural scientists. Because of their responsibility for the character and quality of collegiate education in the natural sciences, members of the natural science faculties are in a strategic position to contribute to strengthening the entire science education system. Members of the natural science faculties shape the college-educated population’s understanding of and attitudes toward science. They provide education in the natural sciences to future civic leaders—people who will determine the resources available to schools for the teaching of science—and to the nation’s science teachers who determine the scientific understanding and enthusiasm for science of high school graduates.

Improvements at the school level will be felt, in turn, at the collegiate level.\(^3\) High school graduates who have studied science with enthusiastic and knowledgeable teachers will be confident in their ability to learn science and, consequently, will be more likely to pursue advanced studies in science. These changes can be expected to increase the numbers of students choosing to study science and would free college faculty from teaching remedial courses for poorly prepared undergraduates.\(^4\)

In order for the college-educated population to achieve the level of scientific understanding that is essential for high-quality life in the 21st century, the Study Group advocates an approach to collegiate science education that recognizes science as a liberal art and that incorporates the values and methods of science into strategies for teaching science. The approach embodies two principles:
Science should be taught as it is practiced at its best.

Science is a liberal art and should be taught as such.

This approach is based on the following premises:

1. Methods of teaching science that reflect the intellectual values of the scientific community and the practice of scientific inquiry correspond in many respects to the conditions under which science is learned most effectively.

2. Liberal education is the most practical form of education.

3. Ideally, liberally educated persons are open-minded; relatively free from provincialism, dogma, preconceptions, and constraining ideology; conscious of their opinions and judgments; reflective of their actions; and aware of their place in the natural and social world.

4. Science is one of the liberal arts. Without the study of science and its relationships to other domains of knowledge, neither the intrinsic values of liberal education nor the practical benefits derived from it are likely to be attained.

5. Science, like all the liberal arts, contributes to the satisfaction of the human desire to know and understand.

For the purpose of this report, liberal education is defined in terms of the characteristics associated with a liberally educated person and the kind of curriculum that might impart these characteristics. The liberally educated person possesses not only knowledge and intellectual skills, but especially, the inclination and ability to apply them to appropriate ends. Ideally, the knowledge is both deep and broad. In practice, depth derives from sustained work in a single discipline or area of study. Breadth results from serious engagement with all the major domains of knowledge and human endeavor. A liberal education encompasses all the scholarly disciplines that inquire into the natural world and the human condition as well as the fine arts and the practical arts. Their interrelationships, multiple perspectives, traditions, and significance for contemporary society are the conceptual links that integrate the liberally educated person's knowledge into a coherent whole.

Many writers have essayed definitions of the intellectual skills that characterize the liberally educated. Those skills most commonly identified with and most pertinent to this report's recommendations are the intellectual skills that make possible self-reflection and articulate communication. 5

Self-reflection—that is, consciousness of one's opinions, judgments, and the role of humans in the natural world—derives from the ability to analyze one's arguments, determine the factual basis for information, evaluate the quality of evidence, and identify and assess one's premises and values. Self-reflection can free the individual from egocentrism, intellectual provincialism, and an anthropocentric view of the world.

Articulate communication—the ability to present ideas in a clear, effective way—derives from skills in conceptuali-
The goals of liberal education in science are defined here in terms of the understanding of science that characterizes liberally educated people. This understanding encompasses:

- the nature of the scientific endeavor, concepts, principles, and theories that describe the natural world;
- unifying concepts that integrate the sciences with other disciplines; and
- how scientific knowledge influences and is influenced by the intellectual tradition of the culture in which that knowledge is embedded.

Each of these elements of scientific understanding is described in this section.

All intellectual endeavors share a common purpose—making sense of the bewildering diversity of experience. The natural sciences search for regularity in the natural world. The search is predicated on the assumption that the natural world is orderly and can be comprehended and explained.

The regularities discovered are expressed in scientific laws, theories, and models. These interpretations are products of reasoning processes—characteristic of the members of the scientific community—that operate on observations of the natural world. To be admissible to scientific discourse, evidence must conform to the scientific community’s standards for acceptability. With few exceptions—astronomical events, for example—observations are expected to be replicable. In all cases, both the evidence and the arguments linking observation with explanation are subject to debate. The expectation of verification through replication makes scientific knowledge different from other forms of human knowledge.

Appreciating natural science as a liberal art means being well informed about science, possessing science-related intellectual skills, and being disposed to apply the knowledge and skills within and beyond the academic setting. Elements of science that all students should take from their undergraduate education are described in the subsections that follow. At a minimum, all students should be knowledgeable about each element. Ideally, by the time they complete their undergraduate experience, students should have mastered science-related skills and be disposed to apply them in the conduct of their daily lives.

THE NATURE OF SCIENTIFIC EXPLANATION

Liberally educated people discern the distinctive features of science as a way of knowing. This extends to familiarity with the values that guide the scientific enterprise, its methods of inquiry, and the ways that results are communicated.
A true understanding of the natural sciences requires comprehension and appreciation of the values that characterize the scientific enterprise, many of which are shared with other disciplines and professions. These values are so basic and so ubiquitous that their contributions to scientific understanding may often be overlooked.

The behaviors of scientists engaged in scientific inquiry reflect the values of the scientific enterprise. Commitment to understanding the natural world, intellectual integrity, curiosity, skepticism, tolerance for ambiguity, and openness to new ideas are attributes of the working scientist that science education should seek to engender. These qualities also characterize the liberally educated person. The undergraduate experience should afford students the opportunity to internalize scientific values. When appropriate, students should exhibit the behaviors of working scientists not only in their academic studies, but also in their personal, professional, and civic roles. A goal of all science courses should be to instill in students the values, dispositions, and habits of mind that characterize working scientists. Having completed such courses, students should be aware that science is the art of interrogating nature—that is, it is a system of inquiry that is predicated on a set of values and that requires mastery of systematic problem-solving techniques, the power of reason, and the art of abstraction.

The quantity of information in the natural world is vast and diverse. Collecting and organizing data, determining what is relevant, defining boundaries, and analyzing information in meaningful ways are essential for making sense of phenomena in the natural world. Knowledge of and skill in using scientific methods of data collection and management are basic to developing a conceptual understanding of science and to appreciating scientific processes.

The liberally educated person should realize that gathering information takes place within predetermined boundaries and demands the identification of significant variables, careful observation, and precise, accurate, and reliable measurements. He or she should know that, once collected, data must be organized and summarized to make understanding and explanation possible.
As a result of the undergraduate experience, the student should come to appreciate the importance of well-designed experiments, the potential and limitations of the quality of results that well-designed experiments yield, and the human aspects of inquiry that are involved in every step of the scientific process from the initial questioning of nature through final interpretation. Experiences with data collection, organization, and analysis should enable the student to develop a sense of the degree of accuracy appropriate for various measurements, the ways in which accuracy is reflected by significant figures, the limitations imposed upon overall reliability by the least accurate data, and how instrumentation extends human powers of observation.

Classification systems are conceptual tools that provide powerful heuristics for organizing knowledge and for further scientific inquiry. The development of classification systems such as for minerals and geological strata on the basis of chemical composition and process of formation, the categorization of plants and animals on the basis of structural characteristics, and the organization of the elements on the basis of chemical and physical properties contribute much to understanding the regularities of the natural world. Experiences with these classification systems increase conceptual understanding of a discipline's knowledge base and contribute to the development of new knowledge.

Scientific Laws, Theories, and Models

Scientific laws, theories, and models are representations of nature. Scientific laws express the regularities in nature. Scientific theories unite and explain seemingly diverse phenomena. Scientific models represent metaphorically structural and functional relationships in natural systems.

Understanding the nature of scientific laws, theories, and models, the processes of their formulation, and their explanatory and predictive powers contributes to an appreciation of the uniqueness of scientific knowledge. Possessing the intellectual skills necessary for the application of scientific laws, theories, and models to diverse situations empowers the individual. These skills include the ability to develop hypotheses, construct models, and evaluate contending theories as well as the capacity to induce relationships between the concrete and the abstract, between phenomena and theory, and to avoid errors of reification.

The Language of Science

Scientific communication uses a distinctive vocabulary as well as mathematical symbols and formulas to represent phenom-
ena, events, and causality. Articles in scientific journals, presentations at scientific meetings, and science textbooks use the specialized language of science, thereby often making science inaccessible to the uninitiated.

Ideally, the liberally educated student should gain enough knowledge about the characteristics of good scientific communication to enable him or her to judge the scientific merit of articles and lectures. Although at the completion of the undergraduate experience a student may not have become capable of making judgments about articles in specialized journals, he or she should be able to make such judgments about science textbooks, popular science journals, and the media.

Familiarity with scientists' usage of specialized vocabulary is another goal of liberal education in science. The use of a specialized or technical vocabulary in science contributes to the precision and clarity of scientific communication. Technical terms have rich meanings. For example, when one geologist speaks to another about the "Dakota Formation," each is aware of the structural characteristics of the formation, its geographical locations, the conditions under which it was formed, and the geological era with which it is identified. The simple phrase "Dakota Formation" conveys hundreds of bits of information to the person who "understands" the term.

Students often misinterpret scientific communication—both oral and written—because they are unaware that scientists frequently use familiar everyday words in specialized ways. Some examples of such words are work, velocity, and inertia. In everyday language, for example, velocity and speed are synonymous. However, the scientist distinguishes speed from velocity. Even when speed and velocity are defined in textbooks and in lectures, the student who is unaware of the specialized nature of scientific vocabulary may continue to treat the terms as synonymous and thereby misinterpret the information being conveyed.

Conversance with the features of scientific communication—the structure of discourse and the use of technical terms—and the ability to apply knowledge of these features to interpreting scientific writing should be goals for all courses in the natural sciences.

*Mathematics is the foundation of science and technology. Without strong mathematics, there can be no strong science.*
*(Everybody Counts)*

Mathematics contributes to understanding the natural world in many ways. Scientists use mathematics to manage and interpret data, express formal relationships, and model natural systems. The system of mathematical notation, methods of
statistical analysis, and processes of mathematical modeling are essential tools of science.

"Modeling [is] representing worldly phenomena by mental constructs, often visual or symbolic, that capture important and useful features."² Mathematical modeling in the sciences is a synthesis of mathematical and scientific thinking. Scientists use mathematical concepts and processes to construct models of natural systems. These models are used to analyze interactions in a system and thereby make it possible to explain and predict the system's behavior. For instance, Kirchhoff's and Ohm's laws describe the quantitative relationships among electrical potential, resistance, and current in electrical circuits.

The relationship of mathematics to science is such that understanding science requires the ability to think logically, to make reasonable approximations and estimates, and to apply mathematical tools in both formal and informal circumstances. Moreover, understanding science requires familiarity with mathematical notation, basic statistical analysis, and probability theory as well as awareness of the contributions of mathematics and mathematical modeling to the development of the natural sciences.

The extent and sophistication of the mathematics employed vary from discipline to discipline in science. Nevertheless, no matter what the course or the level of mathematical preparation of the entering student may be, he or she should take away some understanding of how mathematics helps to inform the study of nature and to promote the ability to use different and appropriate forms of mathematical reasoning to analyze scientific problems. A semiquantitative approach to science may be adequate in some courses, but, in most cases, more specialized knowledge of algebra, geometry, trigonometry, calculus, and computer programming is necessary to achieve a sufficient depth of understanding.

The Limits of Scientific Understanding

Scientific knowledge is not absolute; rather, it is tentative, approximate, and subject to revision. It is limited by the properties of the natural world, the instruments available to extend human senses, the paradigms that guide scientific inquiry, and by socially imposed missions. Being liberally educated requires an awareness not only of the power of scientific knowledge but also of its limitations.³

Some limitations to scientific understanding are inherent in nature. Quantum indeterminacy, for instance, does not allow exact simultaneous measurement of a particle's position and velocity. Other limitations are imposed by the type of problem. There are some problems that traditional science is not prepared to solve. They are too complex, too difficult, or unresponsive to the methodology of science.
In some cases, scientific knowledge is limited by instrumentation. For example, observations of very small or very distant objects are restricted by the resolving power of microscopes or telescopes. Associated experimental limitations on scientific knowledge are factors that constrain the quality of data; some aspects of reality cannot be measured or reproduced. Limits on accuracy, precision, reliability, and repeatability of measurements require the application of statistical and probability theory to interpret data and to establish the limits of reliability.

Prevailing paradigms are metaphorical or analogical abstractions that guide scientific inquiry. Because paradigms or theories are products of the human mind, they are constrained by attitudes, beliefs, and historical conditions. Current theories are taken to be “true,” the way the world is believed to be, according to the scientific thinking of the day. These beliefs focus attention in certain directions and determine what scientists choose to observe. Observations are interpreted to fit the prevailing model. Those that obviously do not fit are ignored until another theory is developed that can incorporate them.

Finally, science is limited by practical considerations. Today, the costs of doing scientific work are met by public and corporate funds. Often, major areas of scientific endeavor are determined by the mission-oriented goals of government, industry, and the corporations that provide the funds, which differ from the goals of science. This socially imposed selectiveness introduces a bias on the interpretation of nature that modern science is constructing.

An understanding of how each of these factors limits scientific knowledge should be a goal of all science courses. The liberally educated student should come to appreciate that the investigation of the unknown and the solution of complex problems are the essence of science. He or she also should gain a sense of the pleasure that scientists take in making the unknown known.

Certain ideas transcend disciplinary boundaries and are essential to understanding the intellectual relationships among all the disciplines in science. Developing an awareness of transdisciplinary concepts and their common features broadens the liberally educated student’s perspective on the unity of knowledge and also facilitates learning. Knowing about the existence of transdisciplinary concepts sensitizes the student to their possible appearance in other areas of study and motivates the search for them. Finding an instance of a familiar idea in a new context allows the student to relate what is
sions are set in a historical context and that all the issues addressed will and should continue to be debated.

ENDNOTES


3. For example, the types of questions that science can address and the part of reality that science illuminates are strictly limited. Certain aspects of human experience—such as esthetics, justice, and honor—are not amenable to scientific description or explanation: Science may seek to explain the color of a rose, but not the reason for its beauty. Clark, M. E., & Holler, L. D. (1986). Teaching science within the limits of science. Journal of College Science Teaching, 16(1), 8–9, 56–57.

4. For a discussion of the importance of understanding scale and proportion, see Hofstadter, D. R. (1982). On number numbness, or why innumeracy may be just as dangerous as illiteracy. Scientific American, 246(5), 20–34.
The teaching of science must be imbued with a dynamic new philosophy.

Prolegomenon
to a New Pedagogy
conditions that are radically different from those experienced by graduate students.

However, teaching science as it is practiced at its best does not mean that students must rediscover all scientific knowledge themselves. Rather, it means that, in the process of learning scientific principles, students also should learn the values and methods governing the discovery of scientific knowledge and their acceptance by the scientific community. Students should be taught to treat new ideas with skepticism and to engage in empirical work to discover, not to confirm.

It is unfortunate that many conventionally taught science courses do not reflect the practice of science at its best. Science taught as it is practiced would be presented as open-ended rather than closed and investigative rather than merely confirmatory. Science progresses through creativity and innovation—asking pertinent and impertinent questions—but science students are seldom expected to do more than answer questions and follow instructions. If the teaching of science were driven by real problems rather than by contrived textbook exercises, it would be truer to the spirit of science and considerably more interesting for most students. Because the methodology employed by scientists involves sharing ideas with others, group discussions mirror that practice better than traditional lectures can. Finally, when science is taught as it is practiced, students are brought to the important realization that scientific knowledge is not absolute, as many mistakenly believe, but tentative and subject to refinement and revision.

Bringing the spirit of scientific inquiry to the teaching of science at the undergraduate level will require changes in pedagogical techniques and in the selection and organization of subject matter. Pedagogical techniques and subject matter structures capable of bringing the spirit of scientific inquiry to undergraduate studies are described in the sections that follow. Programs and courses that exemplify this spirit are presented in the text as well as in Appendixes A through D. These examples are but a small selection of the courses and programs of this type that have been implemented at institutions of higher education across the nation.

PEDAGOGICAL TECHNIQUES

Pedagogical techniques that employ the methods and embody the values that guide the scientific community in its search for knowledge and that are effective in improving the study of science are described in this section. It should be noted that many of the courses exemplify more than one desirable characteristic. Their placement in one category is not intended to indicate that their benefit is confined to that category. Indeed, descriptions of the same courses appear in more than one category because they illustrate more than a single desirable quality.
The coherence of an active research program is provided by an overarching goal which brings meaning to the scientist's daily activities. In like fashion, the goals of liberal education in science should provide coherence to collegiate programs and the courses that comprise them. This can occur only if students are aware of how each course contributes to their overall program of study. Within each course, students should be made aware of how the day-to-day activities that engage them—assignments, lectures, laboratories, the ideas that develop, and the evidence that accumulates—are directed toward achieving the course's goal.

The study of science must be made meaningful to students from the start. They should be allowed to do some actual scientific investigation and should participate in the kind of scientific reasoning often denied them in a conventional setting. Each goal should be tractable, yet challenging. Students must be able to do the work and reach the goal within the time span of the particular course or program. Reaching the goal should yield a sense of accomplishment that will motivate students to use their newly acquired knowledge and skills in other contexts long after the course has ended.

Often, the failure of students to understand the subject matter can be traced to commonsense beliefs about the natural world brought to the study of science. These beliefs, which derive from personal experience, influence interpretations of lectures, demonstrations, and laboratory work. When commonsense beliefs are consistent with scientific interpretations of nature, they facilitate understanding of the subject matter. However, when the commonsense beliefs are different (misconceptions), they are highly resistant to change by conventional instruction. Consequently, when students complete courses, their knowledge about scientific principles often coexists with the same commonsense beliefs they had when they started the course.5

Pedagogical techniques that make students aware of their beliefs and provide them with the opportunity to test them empirically are proving more effective than conventional methods in changing misconceptions. When students

---

5 For examples of programs and courses that incorporate goal-oriented instruction according to the report's recommendations, see Appendix A: Learning Science Through Inquiry (Hampshire College); Appendix D: Medical Technologies and Critical Decisions (Wellesley College).

b For examples of programs and courses that engender subject matter understanding according to the report's recommendations, see Appendix A: Learning Science Through Inquiry (Hampshire College).
have opportunities to propose explanations for natural phenomena, to examine the plausibility of alternative explanations in group discussions, and to test the alternatives empirically, they achieve a broader and more canonical understanding of scientific principles. Group discussions aimed at reaching consensus on explanations are a powerful way of revealing students' misconceptions. Conflicting explanations provide motivation for the design and conduct of experiments to test the alternative explanations, thus engaging students in the process of discovery.

---

**Introduction to Physics**

*Arizona State University*

The method of paradigm problems is used at Arizona State University in some of its introductory physics courses. This three-step, pedagogical technique is designed to develop scientific and subject matter understanding by creating and resolving the cognitive conflict between students' commonsense beliefs and scientific explanations of natural phenomena. In addition, this method provides students with a foundation in modeling theory and with techniques for solving problems.

The method of paradigm problems involves three components: systematic design and selection of paradigm problems for intensive study, a dialectical teaching strategy, and a gradual introduction to modeling theory and techniques. Paradigm problems evoke and challenge typical misconceptions and serve as models for the solution of other problems in the subject area. Only 5 to 10 problems are chosen so that ample time is available to study each one thoroughly.

A dialectical teaching strategy is used to provoke the students into a state of cognitive conflict between scientifically verified conceptions and misconceptions, to resolve that conflict by rational means, and to teach objective procedures and criteria for evaluating beliefs about the physical world. Students consider systems of explicitly formulated commonsense beliefs, usually contributed by the participants themselves. They check their beliefs for consistency with empirical evidence and for mutual consistency among beliefs. Then, based on these and other criteria, they compare conflicting beliefs and belief systems, including relevant scientific beliefs, and decide which have scientific credibility. A similar dialectical strategy is used to solve problems. Students provide relevant information, tactics, and strategies for solving the problem; then, using group discussion, they select from the ideas presented the ones they believe are appropriate for solving the problem.

The introduction of modeling theory and techniques in this course is based on the premise that the structure of knowledge is supplied by models and theories and that a scientific theory is a system of design principles for modeling real objects and events. The students are taught that: the key to solving a typical physics problem is the development of a model from the information given; the problem cannot be understood fully until a model has been constructed; the information given in a problem is invariably insufficient, even for understanding the problem; the information given must be supplemented by theoretical knowledge in order to construct a model; and
a solution occurs when the special properties and implications of the model have been worked out. The instructors try to relate everything discussed to the appropriate modeling stages and to show the students how models are used to "understand" empirical phenomena. The students are encouraged to employ the modeling strategy in analyzing what they read in their texts.

Laboratory and field experiences serve three important functions in the development of scientific understanding. One is to make explicit the empirical basis of scientific theories; another is to develop an understanding of the practice of science; and the third is to develop skills in manipulating equipment, collecting data, and analyzing results. The conventional approach to laboratory and field work—the confirmation of facts and principles that have been or will be presented in lectures—does not serve any of these functions adequately.

Empirical studies of the effects of conventional laboratory and field work on learning science illuminate the conceptual challenges that inexperienced science students face in relating observations made in the laboratory or in the field to scientific ideas presented in lectures. A study conducted at the University of Chicago, designed to discover what makes learning science difficult, found that even distinguished university professors from disciplines other than science had difficulty relating their observations of physics demonstrations to the theory that the demonstrations were meant to illustrate. Senior university professors attended lectures presented by eminent physics professors with reputations as excellent teachers. The professors/students, all of whom were unfamiliar with physics, reported that it was difficult for them to determine which of the many possible observations they might make were the ones that the physics professors had intended them to make. Other studies find that less mature learners, for example, high school physics students, systematically make observations that are more consistent with what they believe should happen than with what can be observed objectively. These students often are not aware of the inconsistencies be-

---

For examples of programs and courses that incorporate laboratory and field experiences according to the report's recommendations, see Appendix A: Integrated Liberal Studies Program (University of Wisconsin-Madison), Learning Science Through Inquiry (Hampshire College), Science in Modern Life (Brooklyn College), Scientific and Technological Literacy (Iona College); Appendix B: Curriculum in Science and Culture (Purdue University), Liberal Arts and Science Program (Utah State University); Appendix C: Foundations of Science (Hunter College); Appendix D: The Century of Genius (University of San Diego), How People Move (Hampshire College), Intermediate Technology (Brown University), Medical Technology and Critical Decisions (Wellesley College), Role-Playing Laboratories in Analytical Chemistry (St. Olaf College), Science and Technology in the Modern World (Kean College of New Jersey), Science, Poetry, and the Imagination (Macon College), Technical Applications of Light (Wellesley College), Ways of Knowing (Macalester College).
tween what they report they have observed and the scientific principles they are learning.

Thus, use of the confirmatory approach in the laboratory and in the field does not contribute to the development of strong conceptual links between the natural world and the scientific theories developed to explain and predict it. Nor does this approach leave students with an accurate view of the practice of science. Rather, it contributes to the notion that the purpose of experimentation is the verification of hypotheses rather than their refutation. This conception of laboratory and field experiences does not reflect the conduct of science. In practice, scientists enter the laboratory or the field to test a hypothesis with well-considered expectations about what data will be consistent with the hypothesis and some general ideas about what data would be inconsistent with it.

When laboratory and field activities are conducted in ways that are more congruent with the practice of science, students will be prepared for these experiences intellectually. The ideal, of course, is original undergraduate research. Short of that, the approach recommended is that students be involved in the design of experiments, including deciding what hypotheses will be tested, what data will be collected, and how the data will be reduced, analyzed, and interpreted. Maximum benefit can be derived from laboratory and field experiences by having students work in groups and share their ideas, perceptions, and conceptions. Group design and interpretation of laboratory work are also effective strategies for exposing and changing misconceptions. In addition, students should prepare written reports describing the rationale for the experimental design, the data, and their interpretations. Ideally, these reports would be reviewed critically by peers under the instructor's guidance in a seminarlike setting, and then revised accordingly.

Much more time will be required for each laboratory or field activity using the approach proposed. However, the improvement in student performance should compensate adequately for any loss of activities due to time constraint.

To achieve the objectives of liberal education in the sciences, the Study Group recommends that all science courses contain laboratory and field activities. Activities will vary among the disciplines, but all courses should include opportunities to engage in the activities of practicing scientists, such as designing experiments; manipulating equipment; collecting, reducing, and analyzing data; exploring the complexity of the processes of interpreting and evaluating data from natural and simulated environments; developing principles or models from data; and discovering the limitations of scientific knowledge.

Role-Playing Laboratories in Analytical Chemistry
St. Olaf College

The Role-Playing Laboratories in Analytical Chemistry at St. Olaf College are a set of three, laboratory-based courses designed
to replicate the environment of analytical laboratories and the work of analytical chemists. The approach emphasizes the interdependence of individual student investigators through role-playing. All students are involved in various aspects of the discovery process. They work in groups of four, with each student assuming responsibility on a rotating basis for project management (organization, implementation, and communication), chemical management (procurement and preparation of reagents, standards, and solutions), hardware management (assembly and operation of instrumentation), and software management (creation, linking, and/or operation of any computer software required). The experiments include developing analytical methods and solving management dilemma problems.

Learning Science through Inquiry
Hampshire College

Hampshire College’s Learning Science Through Inquiry program involves students in experimental design. Students, as part of their science requirement, pose a research question based on readings, laboratory, or field experiences, review the literature, including primary sources, and submit a proposal describing an experiment to investigate the question, its purpose, and the methods that will be employed. In a course on the physiology of human movement, for instance, all the research questions are related to human kinesiology. The experimental design—choosing specific muscles, determining machine settings, standardizing procedures, and so forth—is left to the ingenuity of the students and is refined through a series of proposals presented to faculty. Generally, students are required to do a pilot run of their experiments. Then, they work on their own in the laboratory, discussing their progress with the instructor on a regular basis. The results are written up as a research report that has a focused question or hypothesis and that uses evidence from the students’ own laboratory experiments and the literature. Students assess the methods and the appropriateness of both the methods and the data. The report, or sections of it, may go through several drafts in response to faculty comments.

The importance of direct experience with data derived from the natural world in the development of scientific understanding and reasoning skills cannot be overstated. However, as noted previously, this should not be interpreted to mean that students must rediscover all scientific knowledge for themselves. Obviously, such rediscovery is not possible, reasonable, or even desirable. Lectures and texts are valid means of providing the information necessary for the development of scientific understanding. However, the spirit of scientific inquiry

---

d For examples of programs and courses that incorporate lectures and texts according to the report’s recommendations, see Appendix A: Introduction to the Natural Sciences (Lehman College), Learning Science Through Inquiry (Hampshire College); Appendix D: How People Move (Hampshire College), Ways of Knowing (McAlester College).
must pervade their use. Whenever possible, lectures and texts should be supported by readings from primary sources.

Students must learn to interact critically with lectures and reading materials, mentally interrogating the speaker or the writer, seeking answers to such questions as: What is the empirical evidence for the author's or speaker's conclusions? Is the argument well constructed? Are the assumptions correct?

Faculty members serve as role models for these processes. When lecturing, they must present scientific information and theories in ways that reflect the processes and values of science. They should challenge students constantly by asking: How do we know . . . ? Why do we believe . . . ? What is the evidence for . . . ? Lectures should include the empirical basis for theories and should develop arguments that link observations explicitly with hypotheses and theories; here, faculty may find using actual arguments from the history of the science useful. In addition, faculty members should make clear the criteria for examining the content and structure of arguments. When lecturing in this way, the professor is both presenting scientific ideas and modeling proper analytical skills, thus fostering the students' ability to learn how to assess scientific information themselves. These are complex skills that require practice. They are developed most effectively in small groups with experienced mentors who can make constructive comments.

**EXAMPLES OF LECTURES AND TEXTS**

**How People Move**

**Hampshire College**

In Hampshire College's course, *How People Move*, students learn to interact critically with original research papers. The professor models proper analytical skills and helps the students learn how to assess lectures and texts. An important component of the course involves learning how to read and critique primary sources, although secondary sources are used to provide background information.

In this course, the students are assigned a research paper which has to be read at least three times: once for the general structure, once to focus on words they do not understand, and, finally, to prepare themselves to discuss the experiments with their classmates.

The professor guides the discussions, focusing on procedures and results. The professor readily admits when he or she does not understand aspects of the report and encourages the students to be open about what they do not know or understand, suggesting that they use one another as resources to gain understanding, whenever possible. The students share ideas and resources and winnow good ideas from bad. Discussions are provoked and sustained by inviting students to generate lists of the hypotheses and of the data from the paper and to talk about the connections. This process helps the students discover that some hypotheses and assumptions may be unsupported and that there may be loose ends in the data. Then the professor asks what the major hypothesis of the paper is and it is discussed until a clear statement of it is obtained. The class reviews
the other studies that might be done, the factors that were not controlled adequately, how the study was biased by its sample, its methods, and so on. Finally, the structure of the paper's arguments and its flaws and strengths are examined. The students are encouraged to see both the limitations and the power of the techniques used.

Ways of Knowing
Macalester College

In Ways of Knowing, a freshman seminar at Macalester College, students learn to work critically with scientific information. Historical case studies of three intellectual revolutions in science (the overthrow of the geocentric cosmos, the development of the theory of evolution, and the role of relativity theory and quantum mechanics in the creation of a newly perceived physical reality) are presented as conflicts between and among ways of knowing. Both the immediate causes of these revolutions and their intellectual and cultural effects are considered. The claims of science are weighed relative to those of other branches of knowledge and the original receptions of these revolutionary ideas, as well as their current significance, are discussed. Throughout the seminar, students are asked to address two central questions: “How do we know anything?” and “How can we understand and explain ourselves, our fellow human beings, and the world we inhabit?”

The approach in Ways of Knowing, like its teaching faculty, is multidisciplinary. Students learn about the content and methodology of science through reading original works and selected secondary sources. The broader dimension comes from assigned readings in history, philosophy, theology, and literature. A relevant work of fiction is included for each case study. Discussion of these readings and related issues is an important part of the course structure. Frequent writing assignments challenge students to develop and demonstrate their analytical and synthetic skills.

The development of scientific knowledge takes place in a social context. The scientific community sets standards for the kinds of evidence that are admissible to its debates and for the ways in which that evidence is interpreted. Similarly, students learn best about the development of scientific ideas and develop skills in the evaluation of evidence and in the ability

* For examples of programs and courses that incorporate group discussion and projects according to the report's recommendations, see Appendix A: Learning Science Through Inquiry (Hampshire College), The Liberal Arts/Mathematics-Based Alternative Core (Case Western Reserve University); Appendix B: History, Philosophy, and Social Studies of Science and Medicine (The University of Chicago); Appendix C: Physical Science Program (West Virginia University); Appendix D: The Century of Genius (University of San Diego), How People Move (Hampshire College), Intermediate Technology (Brown University), Medical Technology and Critical Decisions (Wellesley College), Role-Playing Laboratories in Analytical Chemistry (St. Olaf College), Science and Technology in the Modern World (Kean College of New Jersey), Science, Poetry, and the Imagination (Macon College), Technical Applications of Light (Wellesley College), Ways of Knowing (Macalester College).
to compose a logical argument when they collaborate on projects or problems under a teacher's guidance.

Cooperation on joint projects requires effective communication. Students must express their ideas clearly, listen carefully to their peers, and revise their original thoughts and understandings in light of new knowledge and alternative interpretations. These processes help students not only to sharpen their understanding, but also to develop the skills necessary for assessing the validity of evidence and for composing logical arguments.  

### Physical Science Program

**West Virginia University**

West Virginia University had a program in the physical sciences that used both group discussions and group projects to help students acquire the problem-solving skills demanded of enlightened citizens in today's society. In addition to group discussions, laboratory work, lectures, and library research, the students engaged in guided design projects. While completing the projects, they acquired a basic understanding of the scientific concepts related to the issue under consideration and formed well-founded opinions. For example, students might examine how a hypothetical public interest research group would respond to a letter in a local newspaper advocating nuclear power as a source of safe energy. They would determine what facts were needed to evaluate the author's claims; gather information on various types of energy; discuss possible causes of the energy crisis; decide how they could respond to the letter; and prepare a comprehensive article presenting a complete assessment of the energy crisis and the potential of nuclear power to solve it.

### Writing Activities

Effective written communication is an important attribute of a liberally educated person, one that helps hone the individual's awareness and analytical and critical abilities. Competent communication is also essential for the conduct of science. Therefore, science education must promote writing as a technique for developing and checking personal comprehension and as a method for communicating and assessing. 

---

For examples of programs and courses that incorporate writing activities according to the report's recommendations, see Appendix A: Integrated Liberal Studies Program (University of Wisconsin-Madison), Introduction to the Natural Sciences (Lehman College), Learning Science Through Inquiry (Hampshire College), The Liberal Arts/Mathematics-Based Alternative Core (Case Western Reserve University), Science in Modern Life (Brooklyn College), Scientific and Technological Literacy (Iona College); Appendix B: Curriculum in Science and Culture (Purdue University), History, Philosophy, and Social Studies of Science and Medicine (The University of Chicago), Liberal Arts and Science Program (Utah State University); Appendix C: Foundations of Science (Hunter College), The Theory and Practice of Science (Columbia University); Appendix D: The Century of Genius (University of San Diego), How People Move (Hampshire College), Medical Technology and Critical Decisions (Wellesley College), Science and Technology in the Modern World (Kean College of New Jersey), Science, Poetry, and the Imagination (Macon College), The Sciences: Approaches to the Natural World (Curry College), Technical Applications of Light (Wellesley College), Ways of Knowing (Macalester College).
Students should be expected to write reports on laboratory and field experiences, projects, and exercises; papers on assigned or self-selected topics; and submit written answers to examination questions to demonstrate their analytical capacities and understanding.

**Learning Science Through Inquiry**

**Hampshire College**

Writing is a hallmark of Hampshire College’s program Learning Science Through Inquiry. Students write and refine proposals describing their research projects, their purposes, and their methodology. The written accounts of the projects are considered drafts; all aspects of the writing, from spelling to sentence construction to the use of references and effective presentation of data, are corrected. The students have to rewrite the papers as many times as necessary to pass the college’s requirement for demonstrating solid inquiry skills. Students also are expected to rely, when possible, on primary sources and to summarize and critique them orally or in writing.

Of all the liberal arts, mathematics is unique in its relationship to science. Mathematics is an essential tool for making sense of data, for representing scientific principles, and for modeling theories. This relationship of mathematics to science often goes unstated when the studies of science and mathematics are separated. Furthermore, making mathematics a prerequisite for science courses frequently prevents the mathematics-shy student from studying science. The integration of mathematics with the study of science should help students to understand better the function of mathematics in science, enable them to study science without having to satisfy mathematics prerequisites first, and perhaps entice the mathematics-shy student to the study of mathematics through science.

**The Theory and Practice of Science**

**Columbia University**

The Theory and Practice of Science at Columbia University addresses central themes in science by introducing appropriate mathematics and mathematical reasoning in science courses for the non-

---

* For examples of programs and courses that integrate mathematics according to the report’s recommendations, see Appendix A: Learning Science Through Inquiry (Hampshire College), The Liberal Arts/Mathematics Based-Alternative Core (Case Western Reserve University), Science in Modern Life (Brooklyn College), The Technology Cluster (Syracuse University); Appendix B: The Liberal Arts and Science Program (Utah State University); Appendix C: Chemistry of Our World (Wright State University), The Theory and Practice of Science (Columbia University); Appendix D: Intermediate Technology (Brown University), Medical Technology and Critical Decisions (Wellesley College), Science and Technology in the Modern World (Kean College of New Jersey), Science, Poetry, and the Imagination (Macon College).
science major. The first half of each of the course’s two semesters focuses on the most basic applications of mathematical quantification: measurement, error, scales of complexity, approximate calculation, and the relationship between empirical reality and mathematical proof. Students use these tools to initiate studies of modeling and prediction and of experimental design.

Appropriate Assessment of Scientific Understanding

Tests are instruments used to determine a curriculum’s effectiveness in stimulating learning. Conventional course-assessment strategies are limited to the measurement of students’ comprehension of scientific facts and concepts as well as their ability to apply scientific knowledge and reasoning skills to the solution of textbook-type problems. In conventional science courses, tests are often objective, usually involving multiple-choice, true-false, or fill-in-the-blank-type items.

Objective tests alone cannot assess adequately the mastery of science as a liberal art. Testing for the retention of factual information only is insufficient. Scientific understanding also includes the ability to analyze scientific problems and arguments, to generate reasonable hypotheses, to evaluate evidence and methodologies, and to raise questions about science and technology in one’s own life and in the society in which one lives. All these aspects of scientific understanding must be assessed.

Changing goals for science education will necessitate changes in assessment strategies. If two of the goals of science education are to develop science-related, intellectual skills and independent learning skills, then students’ intellectual skills and their “learning-how-to-learn” skills must be assessed—not merely their ability to recall facts.

Furthermore, assessment should provide students with opportunities to demonstrate their accomplishments in a variety of ways. Papers, projects, essay tests, oral presentations, and other forms of assessment should be used to judge whether the desired levels of scientific understanding have been reached. The basic principle is simple: assessment strategies should evaluate that which is important for students to know and retain throughout their lives about science and the scientific enterprise. The method and content of assessment com-

3 For examples of programs and courses that assess scientific understanding appropriately, according to the report’s recommendations, see Appendix A: Introduction to the Natural Sciences (Lehman College), Learning Science Through Inquiry (Hampshire College); Appendix C: Chemistry of Our World (Wright State University), The Theory and Practice of Science (Columbia University); Appendix D: How People Move (Hampshire College), Medical Technology and Critical Decisions (Wellesley College), Role-Playing Laboratories in Analytical Chemistry (St. Olaf College), Science, Poetry, and the Imagination (Macon College), Ways of Knowing (Macalester College).
municate to students what is considered important for them to know, but, as long as evaluation and grading systems emphasize superficial knowledge and the solution of academic problems, students will continue to learn only that which they think will be tested and graded.

*The Theory and Practice of Science*

*Columbia University*

Students in Columbia University's course on *The Theory and Practice of Science* are evaluated on weekly homework assignments, a midterm paper, and a final examination. The homework assignments combine traditional "mechanical" problems with conceptual and hypothetical questions, analytical (short answer or short essay) questions about specific passages in the original scientific papers they are reading, and essay questions about primary readings (papers, books, and essays). For example, students may be asked to summarize, dispute, or harangue, but not repeat, a chapter by Schroedinger, identify what is obscure about a "current straightforward" article in *Science*, or discuss conflicting views about the requirements for genetic material as imagined by Darwin and Mendel. The assignments require careful presentations, ample office hours by teaching assistants and instructors, and the understanding that the purpose of homework is not merely to answer questions so that the assignment is disposed of, but to learn and raise questions as well. The program director reports that the homework assignments have proved to be an "extremely effective (and, for the nonscience major, a very different, shocking, but oddly satisfying) way to keep students involved in the course and engaged with the course material."

In the physics and biology components of the course, the method of assessment is the same as the method of study—the scientific paper. At the end of each semester, students take a three-hour examination in which they are given a contemporary scientific paper from a journal like *Science* or *Nature* that they have not studied in class and are asked to analyze it. The questions implicitly test the type of scientific literacy the course was designed to engender: that students be able to read what scientists write, pick out a well-formulated question, identify the model or hypothesis being tested in the paper, identify and analyze the data, identify and evaluate the inferences drawn from the data, identify the conclusions reached, and be able to speculate on the next question to be asked or the next test to be undertaken.

*Chemistry of Our World*

*Wright State University*

Assessment for the laboratory component of *Chemistry of Our World* also illustrates the principle of appropriate assessment. The purpose of the laboratory activity is for students to develop an understanding of learning by observation. Students are graded on one- to two-page laboratory reports which include responses to four questions. First, students describe briefly what they observed; they must state what happened, not summarize the procedure. Second, they write an interpretation of what they observed. Third, they state what they did not understand about the experiment they performed or the observations they made. Fourth, they describe what they might have done—such as additional tests—to clarify what they did
not understand about the experiment, their observations, or their interpretation.

For example, in an experiment to analyze the composition of coal, a student might observe that the weight of the sample decreased after heating at low temperatures and decreased more after heating to a higher temperature. The student might interpret his or her observation by stating that water vaporizes at lower temperatures while hydrocarbons vaporize at higher temperatures. A student might wonder why heating the coal did not result in burning. Alternatively, if the student claimed to understand the experiment fully, he or she would be expected to explain why coal does not burn in the absence of oxygen. A student might propose heating the coal sample in the presence of air as a means of testing the effect of the air on burning in order to understand more fully why the coal did not burn in the first experiment.

Science is one of the liberal arts and should be taught as such.

Understanding science as a liberal art cannot be achieved solely through radical changes in pedagogical techniques. Careful attention also must be given to the nature and structure of the subject matter. The subject matter must be selected and organized in ways that contribute optimally to the perception of science as a liberal art. This perception requires that the subject matter be multidisciplinary. Furthermore, students must be made aware of the structural organization of the disciplines they study as well as the relationships among those disciplines.

Multidisciplinary content can be presented in a variety of ways that will contribute to attainment of the goals of liberal education in science. In addition to arranging subject matter according to a discipline’s conceptual framework, subject matter can be structured around the investigation of problems, issues, cases, or themes or the historical development of science and the scientific enterprise.

Science is intrinsically multidisciplinary. Understanding science as a liberal art means being familiar with its cross-dis-

---

1 For examples of programs and courses that integrate multidisciplinary content, see Appendix A: Integrated Liberal Studies Program (University of Wisconsin-Madison), Introduction to the Natural Sciences (Lehman College), Learning Science Through Inquiry (Hampshire College); Appendix B: Curriculum in Science and Culture (Purdue University), History, Philosophy, and Social Studies of Science and Medicine (The University of Chicago), Liberal Arts and Science Program (Utah State University), Science in Society Program (Wesleyan University); Appendix C: Foundations of Science (Hunter College); Appendix D: Communications Technology (State University of New York at Stony Brook), Medical Technology and Critical Decisions (Wellesley College), Science, Poetry, and the Imagination (Macom College), The Sciences: Approaches to the Natural World (Curry College), Technical Applications of Light (Wellesley College).
ciplinary nature—the relationships among the scientific disciplines as well as the relationships of the sciences to the humanities, social sciences, and practical and fine arts. The unifying themes described earlier are examples of one kind of relationship among the academic disciplines that all students should have the opportunity to learn. However, neither conventional science programs nor courses give students the opportunity to develop an appreciation of the multidisciplinary nature of science or to know the intellectual relationships among science and other academic disciplines. To provide this opportunity, the content of science programs and courses needs to be broadened to encompass aspects of the history, philosophy, sociology, politics, and economics of science and technology as well as topics from contemporary science. The cross-disciplinary coordination of mathematics with science is especially important.

Subject matter can be organized according to the conceptual framework or structure of a scientific discipline. Discipline structure refers to the ways in which a discipline’s concepts and theories are characteristically ordered. Aspects of this ordering can be inferred from the ways in which experts arrange texts, solve problems, and communicate about their discipline.

Organizing subject matter around the conceptual framework of the discipline allows students to develop a knowledge base similar in structure to that of experts in the field. A knowledge base structured in this way contributes to the successful application of such knowledge to the solution of problems and to the acquisition of new information.

The development of a well-structured knowledge base is seldom realized in conventional courses largely because the discipline’s structure is not explained to the students. Professors and textbook authors take the discipline’s structure for granted. Consequently, they do not bring the structural organization of the subject matter to the students’ attention. Furthermore, in conventional courses, evidence and arguments in support of concepts, as well as the discipline’s history, philosophy, and social and technological interactions, are not included in the subject matter that is taught.

Science as a Way of Knowing is a continuous project of the Education Committee of the American Society of Zoologists. The

1 For examples of programs and courses that organize subject matter around the conceptual framework of the discipline, see Appendix A: Science in Modern Life (Brooklyn College); Appendix C: The Theory and Practice of Science (Columbia University).
project's goal is to provide background materials to those who teach introductory biology courses in colleges and universities. Background materials are contained in volumes that address such topics as evolutionary biology, human ecology, genetics, developmental biology, form and function, cell biology, physiology, animal kingdom, and ecology.

The project's work is based on the proposition that conventional biology courses overemphasize factual information and neglect the conceptual framework of the biological sciences. Two of the project's goals relate directly to the structure of the biological sciences: they seek to lessen the factual load that characterizes so many biology courses and textbooks and to increase the attention given to the conceptual framework of science. These educational goals are achieved through the application of effective instructional strategies which include teaching the evidential basis for concepts and teaching the facts along with the conceptual framework they subend.

Subject matter also can be organized around contemporary or historical problems, issues, or case studies. Arranging subject matter in this way has the potential for developing a diverse and integrated knowledge base because understanding the problem, issue, or case requires understanding its historical, philosophical, social, political, economic, and technological contexts. However, courses whose subject matter is so ordered typically are offered only to nonmajors; consequently, such courses have the reputation for being superficial as far as their scientific content is concerned, lacking in rigor, and being exclusively qualitative. These weaknesses are not inevitable and courses structured in these ways have positive attributes. They have the potential for motivating students to study science, increasing understanding of the subject matter presented, enabling students to expand their abilities as independent learners, promoting the development of skills to assess the quality of scientific information, and sharpening recognition of the interactions between science and society.

**Medical Technology and Critical Decisions**

Wellesley College

Wellesley College's course entitled Medical Technology and Critical Decisions is an example of a course whose subject matter is

---

*For examples of programs and courses that organize subject matter around problems, issues, or case studies, see Appendix A: The Technology Cluster (Syracuse University); Appendix D: Medical Technology and Critical Decisions (Wellesley College), Ways of Knowing (Macalester College).*
structured around a single problem: the investigation of the issues a pregnant woman faces in trying to decide whether to undergo amniocentesis. The problem is related to the dramatic new options in medicine presented by technology. It motivates study of the scientific principles on which the technology rests and the mathematical principles of a methodology for making rational choices. The course introduces students to the underlying notions of genetics; the physical principles behind the ultrasound imaging technique used to position the needle that draws the fluid; the probability and statistics needed to understand the risks to the woman and the fetus of undergoing or not undergoing the procedure; and the methodology of decision analysis used increasingly by genetic counselors to help prospective parents incorporate their personal values into the decision-making process.

The Social Impact of Technology
Syracuse University

Students in The Social Impact of Technology course offered as part of The Technology Cluster at Syracuse University examine three or four cases of the social impacts of current technological issues. Case studies used include nuclear arms, manipulation of human genetics and human reproduction, large-scale accidents, and the prediction and control of natural and human-made hazards. For example, the nuclear arms case study focuses on the Strategic Defense Initiative (SDI). Several weeks are devoted to the science and technology of nuclear weapons, their effects, and their modes of deployment. Students also learn about political aspects of nuclear weapons such as deterrence, the arms race, and treaties to limit the threat posed by current nuclear arsenals. Discussions of technologies designed to counter nuclear weapons include consideration of costs and benefits, ethics, and whether development and deployment of SDI technology would actually decrease the likelihood of a nuclear exchange.

Another way of organizing subject matter is around themes. The theme may be a scientific concept—energy, for example—that can be taught in the context of any one of a number of contemporary issues, such as the environment, technology, or health. Alternatively, the theme might be a historical concept—scientific revolutions, for instance—that can be taught using any one of many historical illustrations. Regardless of the theme, this approach allows a science department or institution to achieve basic objectives while providing faculty members with the flexibility to adapt their particular expertise to the results desired.

1 For examples of programs and courses that organize subject matter around themes, see Appendix A: Scientific and Technological Literacy (Iona College); Appendix B: Liberal Arts and Science Program (Utah State University).
Scientific and Technological Literacy
Iona College

Iona College offers four science core sequences entitled Scientific and Technological Literacy. The content of each sequence is organized around both scientific themes and the sequential development of problem-solving skills. Each module (half-semester unit) in a series of four is devoted to a particular theme—the environment, health, energy, and commercial systems. In addition, each module addresses the development of problem-solving skills of increasing sophistication. The first module emphasizes scientific, problem-solving skills, with an accompanying review of basic and necessary scientific concepts and terminology. The second module includes the growth of scientific and technological knowledge and introduces quantitative methods and quantitative problem-solving skills. The third and fourth modules stress decision-making. Accompanying laboratory activities, which depend on skills acquired in the earlier modules, highlight the application of problem-solving skills to everyday problems.

The history of scientific understanding is another mode for the presentation of subject matter. Courses whose subject matter is organized around the history of science not only provide students with knowledge of the various intellectual and social contexts surrounding the development of the science, but also help them obtain a better grasp of the arguments and reasoning behind currently accepted, scientific explanations. In addition, students gain a sense of the process of science and the tenuous nature of knowledge. The historical approach has a distinct advantage in that it does not require much initial scientific knowledge or sophisticated mathematical skill. This approach allows for the gradual development of a scientific knowledge base and science-related skills. Organizing subject matter around a historical problem or case study has the added advantage of exposing students to original materials.

Introduction to the Natural Sciences
Lehman College

Introduction to the Natural Sciences is a two-semester course for liberal arts students which uses the history of science from antiquity to the present to set forth the basic concepts, major figures,

Faculty members are urged to assess their courses' pedagogy with respect to the values and practice of science. Are lectures dogmatic or do they reflect the scientific community's standards for evidence and argumentation? Do the laboratory activities and field experiences truly mirror the process of scientific investigation and discovery or are they merely exercises in following instructions? Is obtaining an expected answer judged superior to asking pertinent (and impertinent) questions? Do assessment methods encourage and reward independence and inquisitiveness? In short, does the teaching of science conform to the practice of science at its best?

Faculty also must assess the potential value of multidisciplinary content against subject matter that is narrowly defined. Because natural science faculties are responsible for the tenets of their disciplines, which include the value placed on intellectual integrity and depth of understanding, they may be concerned that neither they nor their colleagues in other disciplines are sufficiently knowledgeable about the history, philosophy, sociology, or technology of their disciplines to teach the natural sciences in their liberal arts context. Although these concerns may be well-founded, of greater concern is a nation whose leaders do not understand the multifaceted nature of science and the interactions of science and society. Overcoming this danger requires that natural science faculties take the initiative and seek creative solutions to the conundrum posed by the value of the multidisciplinary understanding of science and the intellectual challenges that must be overcome to develop that understanding. These challenges are addressed in the next section.

ENDNOTES


4. This mode of teaching evolved as a method for teaching all students in the mid-19th century in the teaching research laboratory of Justus von Liebig at Giessen and in the teaching research seminar of Franz Neumann at Königsberg. Both Liebig and Neumann, through trial and error, discovered that the most effective pedagogy for teaching chemistry and physics was to teach them as they were practiced. Olesko, K. (1989). Environments and strategies for science learning: A historical perspective. Paper presented at the National Forum for School Science '87: Science and Student Learning, Arlington, VA, sponsored by the American Association for the Advancement of Science.


7. This program is not contained in the Appendix. For more information see Note 6.


9. See Note 1.


11. Ibid.

13. This program is different from the program with the same name that appears in the Appendix. For more information about this example, see Brown, P. (1982). West Virginia University: Science for citizen action. The Forum for Liberal Education, V(1), 7–8.


15. Woodhull-McNeal, op. cit.

The essence of a liberal education arises from the synthesis of the various domains of knowledge.

Programmatic Approaches to Liberal Education in Science
The goal of understanding science as a liberal art will be achieved only when science is integrated into programs of liberal studies. The development of coherent programs—those in which all the disciplines are integrated—necessitates the collaboration of faculty members from the humanities, the natural and social sciences, engineering, and the fine and practical arts. The success of institutions' efforts to design cohesive programs is contingent on faculty members who are knowledgeable about curricular issues and who possess the skills required for course development. For their part, institutions must provide opportunities for faculty to develop the necessary knowledge and skills and they must reward faculty members who engage in educational development activities.

This chapter discusses the curricular and administrative aspects of creating coherent programs and describes programmatic approaches that have proven successful.

**CURRICULAR MATTERS**

The first steps toward realizing coherent coordinated programs are to arrive at faculty consensus on institutional goals for science in liberal education and to develop a data base containing information about the existing program's effectiveness in reaching the institution's goals. Examination of this information in light of institutional objectives will show which aspects of the existing program are effective and what changes—additions, deletions, or modifications—are necessary in current courses and programs.

**Consensus on Goals**

Coherent programs are contingent on faculty consensus on institutional goals for education in the liberal arts. A useful mechanism for stimulating faculty debate is to compare institutional goals with those of other institutions and with those set forth in reports such as this one. The targets for scientific understanding characteristic of liberally educated people given in *Aspects of Scientific Understanding* are a standard against which faculty members can judge their institution's goals.

Among the issues that are likely to arise in setting institutionwide goals for science in liberal education are the relative emphases in undergraduate programs on liberal studies and on the major, the subjects that should be included in liberal studies, and whether natural science majors should be excused from liberal studies in the natural sciences. Recommendations to guide faculty consideration of each of these issues are made in the next chapter.
Faculty debates on goals inevitably touch on whether or not the extant program is achieving institutional objectives. This question can be answered using data obtained from assessments of the program. Data for program assessment are available from many sources. Opinion surveys of students, parents, and graduates furnish information about how well the institution is serving the expectations of individuals in each of these groups. Do students believe that they are making adequate progress toward their personal aspirations and the institution's goals for their education? Do parents believe that the institution is meeting their expectations for their children's education? Are graduates satisfied that the institution prepared them adequately for graduate and professional education, the workplace, participation in civic affairs, and an intellectually satisfying and examined life? Students' transcripts provide quantitative answers to several questions. What science courses are the institutions' students taking? Are they taking more than the minimum science requirements? Are their programs of study coherent?

Professional and scholarly societies are another source of data. These organizations set standards for undergraduate education in their fields and some certify the quality of undergraduate programs. Indicators of the quality of undergraduate programs are the success of an institution's graduates in gaining admission to graduate programs and professional schools, in obtaining desirable employment, and in their attainments on a professional level.

Written examinations given either by the institution or by external agencies are another source of data. In some institutions, departments give written comprehensive examinations that contain both objective and integrative questions. Many institutions require seniors to write and defend a thesis. The quality of the written document and the adequacy of the defense are strong indicators of the effectiveness of the institution's overall program.

The most objective indicators of program quality are the standardized examinations used to certify graduates for practice or for admission to graduate and professional programs (such as the Graduate Record Examination, the Medical College Admission Test, the Law School Admission Test, and the Graduate Management Admission Test). Standardized examinations provide both qualitative and quantitative data. However, they emphasize specialized rather than integrated knowledge and give information only about the extent and accuracy of students' factual knowledge of specific disciplines and their ability to apply that information to academic exercises. They furnish little information about students' understanding of a subject in its broader contexts because questions dealing with the liberal arts' application of their knowledge are virtually absent from the examinations. Al-
though good performance on examinations of this kind is an important objective of undergraduate education, they measure only a narrow part of the capabilities that this report argues are necessary for successful graduate study, professional practice, and personal decision-making.

It is difficult to obtain objective data with which to assess students’ understanding of science in its broader contexts or to measure the contributions of liberal education to either professional success or a satisfying life. Consequently, judgments about the quality of programs are made on the basis of indicators of other values. Faculty members need to recognize the relevance of a liberal education to students’ broader understanding of science and to their postgraduate lives. Faculty members also must make efforts to obtain this information by redesigning their examinations and by convincing external agencies to redesign theirs.

The essence of a liberal education arises from the synthesis of the various domains of knowledge. While most institutions require students to take courses in disciplines outside their area of concentration in order to produce well-rounded individuals, rarely are opportunities available for students to explore the intellectual relationships of their major disciplines to other disciplines or to contemporary life. The unifying themes proposed earlier in this report are examples of “threads” for elaborating relationships among the disciplines. However, students cannot be expected to make these connections on their own. Only through coordinated efforts can faculty help students see and understand the connections.

Intellectual integration can be accomplished through a variety of pedagogical strategies. It can be achieved within a single course or across several courses. Within a course, the professor can add topics from other disciplines to the usual content. For instance, a science professor might add materials from the philosophy of science, history of science, and sociology of science and technology to the standard science curriculum. However, this method of integration may concern those faculty members who do not believe that they are prepared adequately to teach topics outside their areas of expertise. Team teaching is one way to address this concern. A team might be composed of a historian, philosopher, sociologist, and an engineer who teach a natural science discipline in its historical, philosophical, social, and technological contexts. A math-

* For examples of programs and courses that are team-taught, see Appendix A: The Technology Cluster (Syracuse University); Appendix D: The Century of Genius (University of San Diego), Medical Technology and Critical Decisions (Wellesley College), Science, Poetry, and the Imagination (Macon College).
ematician on the team might address the intellectual elements of the natural sciences and mathematics, perhaps considering the historical interrelations of developments in these two disciplines.

Intellectual integration also can be achieved across courses by treating a sequence of courses as a single intellectual entity. Different faculty members would teach the individual courses, but undertake joint planning to ensure that the content is integrated and that the development of intellectual skills proceeds sequentially.\(^b\)

Alternatively, a block of courses can be integrated through a capstone course.\(^c\) Capstone courses provide opportunities for students to integrate the knowledge of several disciplines acquired in separate courses. In some institutions, the capstone course consists of writing and defending a major integrative paper—a senior thesis.

Establishing coherent programs requires the cooperation of faculties across the disciplines. This can be a challenging task. It also requires institutionwide consensus on goals and willingness on the part of faculty members to make the full effort necessary to plan and implement multidisciplinary teaching. It further requires that faculty outside the natural sciences become knowledgeable about the relationships between their disciplines and science and that they highlight these relationships in their courses. However, unless faculties develop cooperative strategies (task forces, curriculum committees, and faculty development seminars), on a campuswide basis, to develop and implement coherent programs of study, the kind of liberal education in the sciences envisioned in this report will not be possible.

---

**Core Curriculum**

**Brooklyn College**

Brooklyn College has realized program coherence by introducing students to the diversity of scientific knowledge and skills through the required science component in its liberal arts core, *Science in Modern Life I* (chemistry and physics) and *Science in Modern Life II* (biology and geology).\(^2\) The requirement that all students study all four sciences allows for a variety of approaches appropriate to each discipline (e.g., problem oriented, historical, topical). Each disciplinary module, taught by a specialist in the discipline, includes laboratory work and complies with the college’s writing-across-the-core mandate. The vertically designed core curriculum allows the science courses in the second tier to take advantage of the intellec-

---

\(^b\) For examples of programs and courses that coordinate several faculties, see Appendix A: Science in Modern Life (Brooklyn College); Appendix C: Foundations of Science (Hunter College), The Theory and Practice of Science (Columbia University); Appendix D: Science and Technology in the Modern World (Kean College of New Jersey), Ways of Knowing (Macalester College).

\(^c\) For examples of programs with capstone courses or senior projects, see Appendix A: The Liberal Arts/Mathematics-Based Alternative Core (Case Western Reserve University); Appendix B: History, Philosophy, and Social Studies of Science and Medicine (The University of Chicago), Liberal Arts and Science Program (Utah State University).
tual context and skills developed in the first-tier courses (e.g., Classical Origins of Western Culture, The Shaping of the Modern World, and Introduction to Mathematical Reasoning and Computer Programming). This intellectual integration takes place in faculty development seminars. The programmatic approach also allows faculty teaching core courses in the humanities, social sciences, and fine arts to integrate an understanding of the impact of science and technology on their discipline in an attempt to spread the scientific perspective across the core curriculum.

Faculty initiatives must have administrative support to flourish. Administrative support comes in the form of opportunities for faculty to develop new knowledge and skills and through the broadening of the conventional academic reward system to include contributions to the improvement of the institution's educational programs.

Redefining institutional goals, conducting program assessments, and designing coherent programs and courses are activities that require knowledge and skills that most faculty members have not acquired. Thus, a comprehensive faculty development program is essential for achieving the programmatic approaches recommended herein. Faculty development activities provide faculty members with opportunities to master the new expertise necessary to engage in curricular analysis and reform. The possibility of working with colleagues from other disciplines is particularly important when the approach to undergraduate programs and courses is multidisciplinary.

Institutions that have implemented formal or informal faculty development programs report numerous positive results for both students and faculty. Two, major, positive consequences for faculty are the increased, intellectual, campus-wide interaction among faculty members and a new respect for each other's disciplines. Many report that they find the serious and animated discussions of substantive texts, integrative teaching techniques, and common purpose to be both a revitalizing and a rewarding antidote to their customary isolation. All testify that the new perspectives they take from

---

4 For examples of institutions that have implemented faculty development seminars, see Appendix A: Science in Modern Life (Brooklyn College), Scientific and Technological Literacy (Iona College); Appendix D: Science and Technology in the Modern World (Kean College of New Jersey).
the seminars have influenced their teaching and their research.

The importance of faculty development to achieving coherent programs cannot be overemphasized. However, if, in addition to providing opportunities to develop curricular expertise, the academic reward structure is not altered drastically, the goals of liberal education in the sciences will not be achieved.³

Core Faculty Development Seminars
Brooklyn College

Since the inception of its core curriculum in 1981, Brooklyn College has been holding annual Core Faculty Development Seminars. The primary objectives of the summer seminars are: to develop coherence among the college’s 10 core courses by providing a mechanism for faculty from different disciplines to become acquainted with each other and with each other’s courses through working together toward the common goals of the liberal arts program; to develop and share pedagogical strategies to meet the core’s objectives; and to unleash the power of accomplished specialists to speak to the general concerns of their disciplines in a coherent, liberal arts context. As the core curriculum matured, the seminars incorporated their remaining objectives: to reappraise the core curriculum’s goals and structure, to assess the success of each course, and to increase articulation between the core curriculum, departmental majors, and other academic programs.

During every spring semester, a seminar planning committee of rotating faculty who are released from one course meets once a week to identify areas, problems, or issues to be discussed, to design the detailed agenda for the summer program, and to select participants from the pool of applicants. With an average of 60 faculty, remunerated for participation in the intensive three- or four-day sessions, a total of 450 faculty have contributed to these development seminars to date. While all the courses are subjected to scrutiny, the science modules (physics, chemistry, biology, and geology) have received the greatest attention during the past eight summers. In searching for vertical integration and horizontal cross-fertilization of the core curriculum, workshops on the relationship of the science component to other areas provide valuable multidisciplinary perspectives and reciprocal benefits. With regard to laboratory experience, engagement by non-scientific faculty in laboratory classes laid to rest any doubt about the need for hands-on, goal-oriented laboratory components. The results of the seminars, small-group workshops, and plenary sessions are published in proceedings which form the faculty’s agenda for the subsequent academic year. Other regular faculty development activities include workshops for the college’s writing-across-the-core mandate, sample classes for colleagues in other core curriculum areas, study groups, and a core conversation series.

Science and Technology Fellows Program
Iona College

Iona College’s Science and Technology Fellows Program emerged out of the faculty’s efforts to develop its Scientific and Tech-
nological Literacy core. The purpose of the fellows program is to infuse science and technology across the curriculum, help faculty from outside the natural sciences understand the Scientific and Technological Literacy component, and involve nonscience faculty in the development of scientific and technological literacy components for their own courses. Six to nine nonscience faculty participate annually in the fellows program. The fellows, who are nominated by a dean, are selected on the basis of their active involvement in curricular affairs. They are released from other duties in order to participate in this program. The fellows program is directed by a member of the Scientific and Technological Literacy faculty. During the fall semester, the fellows attend biweekly seminars, which include book-length reading assignments designed to help them update their scientific and technological knowledge. During the spring semester, the fellows each develop a course component that includes science, technology, and social content for a course they are currently teaching or plan to teach.

Reward Structure

Academic status, the currency of academe, is awarded primarily on the basis of scholarly attainment and research. At many institutions, effectiveness in teaching and other contributions to education are weighted insufficiently in promotion and tenure decisions. Faculty members who devote time to planning programs and excellence in teaching not only are committing time to activities that are undervalued by their institution and their colleagues, but also they take precious time away from scholarly activities and research that are valued, thus distancing themselves from academe's rewards.

Institutions of higher education and professional societies share responsibility for the reward structure. Leaders in these organizations should recognize the value of contributions to education, to academic institutions, the academic disciplines, and the professions and they should reward accordingly individuals who make such contributions. More specifically, education in the sciences plays a significant part in the advancement of science. Academic scientists must recognize this fact by making contributions to education in the sciences a criterion for professional advancement.

Attention to science education cannot and should not be left to the established senior scientist who, having been recognized for scientific accomplishments, turns his or her attention to education in the sciences. Nor can the responsibility be left solely to a few, young, faculty members acting out of personal commitment. The enthusiasm of a scientist at the beginning of his or her career is as stimulating to students as the seasoned perspectives of the mature scientist. The participation of each in program development and research must be encouraged by educational institutions and professional societies alike.
Scientific knowledge and the structure and needs of society are changing constantly. As a result, programs and courses appropriate for today's students are doomed to obsolescence. Therefore, institutions must monitor their objectives and programs periodically for changes in knowledge and in the needs of society and alter them accordingly. Institutions should have standing committees composed of administrators, members of the science and nonscience faculties, science and nonscience students, parents, teachers, representatives from local and state governments, as well as representatives from business and industry. The committee should be charged with assessing continually the congruence among the institution's objectives, the needs of the larger society, and the needs of undergraduates in that society.

ENDNOTES

1. An example of a professional society that certifies programs is the American Chemical Society.


3. The importance of faculty development programs has been recognized by many institutions of higher education. During the developmental stages of new programs, faculty development endeavors at a number of institutions have been supported by private foundations.
All students have the right to the empowerment that understanding science as a liberal art provides.

LIBERAL EDUCATION IN SCIENCE FOR SPECIAL GROUPS
Although this report advocates a liberal education in science for all students, the undergraduate science education of four groups is of such national significance that it demands special attention. The groups of special concern are:

- future science teachers;
- the underrepresented in science—namely, women, blacks, and Hispanics;
- the disabled; and
- science and engineering majors.

These groups demand special attention for two reasons:

- the right of all students to the empowerment that understanding science as a liberal art provides; and
- the nation's projected need for scientists, engineers, technicians, and science teachers.

Science teachers have a major influence on the scientific literacy of the nation and on the nation's supply of scientists and technically trained workers. For fully half of our population, school science is the last formal exposure to science. For this segment of the population, the school science experience in grades K through 12 determines in large part their lifetime levels of scientific understanding and attitudes toward science. Even for those whose education continues beyond high school, the quality of their school science experience influences their level of adult scientific literacy and career choices.

School science is the beginning of the science education pipeline—the path of youth from elementary school science through high school and college science to professional preparation in the sciences and related technical fields. Students who complete high school with a sense that they are capable of learning science and have derived personal benefit from knowing science are likely to continue studying science. They become scientifically literate adults and may choose careers in science or science-related fields.

Teachers who are knowledgeable and enthusiastic about their subjects make learning relevant and exciting. Also, they are more successful in engaging students in learning science and in giving them confidence in their ability to learn it. For these reasons, the undergraduate education of those who intend to teach science is a critical element in achieving adequate levels of scientific understanding for all citizens as well as for preparing and encouraging school students to continue their science studies at the college level and to enter science and science-related careers.
All undergraduates who intend to become teachers, regardless of the grades or subjects they will teach, should develop the basic understanding of science as a liberal art that is advocated in this report. Such an education will provide future teachers of all subjects with the fundamental understanding of the natural sciences that will enable them to undertake multidisciplinary teaching and to make science an integral part of the school curriculum.

Those who plan to specialize in science teaching at the elementary, middle, or senior high school levels must develop a knowledge of the natural sciences that is broader and deeper than the basic level of understanding proposed for all undergraduates. The Study Group’s recommendation for education in the natural sciences for school science specialists is based on the expectation that in the future all teachers will be liberally educated and that science specialists will major in a natural science. This expectation is consistent with the efforts to restructure teacher education programs that are under way already in many institutions that educate teachers.

The science requirements for science specialists recommended by the Study Group are based on a consideration of the intellectual competencies that should be possessed by liberally educated science teachers. The recommendations are unconstrained by current state certification requirements or typical staffing patterns in the nation’s schools. Basing recommendations on an image of the liberally educated science teacher is justified for several reasons. One is that state certification requirements and standards for teacher education are in a period of intense reexamination and rapid change. Another is that relying on school staffing patterns is unwise because they are driven more by economic and administrative concerns than by educational principles. As practiced currently, teachers often are required to teach outside their fields of specialization, a practice contrary to the basic premises of this report.

The subject matter knowledge required for competent teaching, as well as the complex interactions of teachers’ disciplinary knowledge with their pedagogical skills, is a topic of considerable debate among teacher educators, education policy formulators, and state certification agencies. The results of these debates will have implications for the subject matter preparation of teachers. What is clear at the moment is that the national sentiment is in the direction of strong subject matter preparation integrated with the liberal arts for teachers at all grade levels, a view consonant with the recommendations in this report.

All students planning to teach science should develop the profound scientific understanding that comes from majoring in the natural science they intend to teach. An issue yet to be resolved is the breadth of knowledge of the natural sciences needed to teach science. Should students specializing in a natural science be required to develop competence in related sciences? If so, in how many? In which disciplines should the competence be developed and to what depth? Should the depth
of preparation in the other sciences be the same as in the discipline in which students specialize? These issues still need resolution for those preparing to be junior or senior high school science teachers.

The undergraduate preparation of the elementary school teacher who will teach science raises a number of similar issues. Is a teacher who has majored in a discipline other than a natural science and who has the level of preparation in the natural sciences recommended in this report for all undergraduates adequately prepared to teach science in elementary school? Should individuals intending to become elementary school teachers be required to take at least one advanced course or sequence in each of the natural sciences—biology, chemistry, physics, and earth sciences? If this requirement is too stringent, which discipline or disciplines are most essential? Several options for the undergraduate preparation in science of elementary school teachers need to be assessed before these issues can be decided. One option is to require the comprehensive study of a single natural science—a three- or four-course sequence—and then a general science course in the fifth year whose purpose is purely professional training.

Another option is to frame the issue of the scientific knowledge required by all elementary school teachers in terms of a specified level of scientific literacy. For example, *Science for All Americans* is a statement by the scientific community about what all 18-year-olds should know about science, technology, and mathematics. If a person has the scientific knowledge and competencies described in *Science for All Americans* in addition to specialized professional training in teaching science to elementary school children, is that person adequately prepared to teach elementary school science?

The most radical option is to leave the teaching of elementary science to science specialists who have the same undergraduate training and the same competencies in the sciences as high school science teachers, but who also possess specialized professional expertise in the teaching of science to elementary school students.

In the short term, the Study Group’s recommendation for all science teachers is that their study of the natural sciences—whatever the actual requirements—be an integral part of a program in liberal studies.

The numbers of women, blacks, and Hispanics who major in the natural sciences and pursue science and science-related careers are much lower than their representation in the general population. Increasing their participation in science
must be a national imperative as the United States faces a future in which, according to demographic projections, the demand for people trained in the natural sciences will increase.

The number of jobs requiring specialized education in science is increasing, while the number of young people of college age is decreasing. At the same time, the proportion of individuals of college age coming from populations traditionally underrepresented in science is growing. Unless more young women and minorities choose to concentrate—or take more advanced courses—in the natural sciences, jobs calling for specialized preparation in the sciences may go unfilled. In addition, not only will these individuals be denied many potentially satisfying and fulfilling science or science-related career opportunities, but also they will be inadequately prepared to participate in civic affairs.

One area in which the shortage of scientifically trained personnel is particularly acute is science teaching. The shortage is expected to worsen in the next 10 to 15 years when many teachers will reach retirement age. Soon, the proportion of blacks and Hispanics in the total teacher population will be as low as 5%. Consequently, few students will learn science from minority teachers, a situation that will reinforce a student’s perception that science is primarily the purview of white males. The social implications of the limited participation in the sciences of women and minorities and the economic and other implications of impending shortages of science specialists for the practice of science argue for special attention at the undergraduate level to underrepresented groups.

The causes of the insufficient participation of women and minorities in science are receiving increased attention, as are methods for changing the situation. It is known that, by the time they reach college, many students from underrepresented groups are alienated from science already. Therefore, college-level, liberal education science courses are the last chance to capture their interest in science and to encourage them to take more advanced courses in science. There is every indication that the methods for teaching science espoused in this report are particularly effective for engaging the underrepresented in science.

In addition to teaching science as a liberal art, science faculties must take cognizance of social and cultural factors that hinder the underrepresented from entering the study of science and from making progress in science and must mitigate these factors. The underrepresented can be assisted further by strengthening academic support services. These support services include tutoring, group study sessions, and activities to build science, mathematics, and writing skills. Such services should be provided by people who are sensitive to the different stresses that female and minority students encounter. Particular efforts should be made to provide students from underrepresented populations with opportunities to participate in research and applied learning experiences.
THE DISABLED

Access to and opportunities in the natural sciences are particular concerns for disabled students.\textsuperscript{11} However, as currently designed, many laboratory and field experiences are not accessible to disabled students. Faculty members must recognize the needs of disabled students in their courses and take the initiative to work with them to overcome the obstacles that prevent them from participating fully.

Often, the degree of disability determines the amount of special assistance disabled students need. In all cases, orientation sessions should be made available to disabled students to acquaint them with course requirements and with the laboratory. Some general strategies that can make science courses and science laboratories more accessible to the disabled are:

- distributing course syllabi, assignments, and other course material far enough in advance to allow disabled students to acquire texts or tapes or to make other preparations;
- allowing students with learning or motor disabilities extra time to complete laboratory assignments;
- considering the special needs of disabled students when assigning laboratory partners or providing disabled students with specially trained laboratory assistants;
- adjusting the height of laboratory stations for students who use wheelchairs; and
- providing tactile versions of charts, graphs, and models for visually impaired students.\textsuperscript{12}

SCIENCE AND ENGINEERING MAJORS

Integration of the study of the natural sciences with a program in liberal studies is a necessary component of the education of undergraduates majoring in the natural sciences and engineering.\textsuperscript{13} The knowledge and skills necessary to address the social and ethical issues confronting the practicing scientist or engineer can only be developed in a program of integrated studies. Technical skills and knowledge alone are inadequate for the responsible practice of science or engineering.

Training in analysis, independent thinking, and awareness of the social, political, economic, and ethical contexts of science must not be relegated to a special segment of science in the curriculum, taught by faculty members who are not scientists or engineers. Instead, the ability to see science and technology in context must be conveyed and assessed in science and engineering courses themselves. Even for engineers,
science courses taught as building blocks for engineering skills should be augmented with components that achieve the goals of teaching science as a liberal art.

The recommendation to add multidisciplinary studies to the already overburdened curriculum of natural science and engineering majors surely will generate expressions of concern from faculty responsible for their education. One reservation may be that students will be inadequately prepared in their discipline for admission to graduate or professional schools or to perform competently in the workplace. But, for all the reasons presented earlier in this report, the Study Group's position is that the benefits of the broader understanding far outweigh those of extremely detailed knowledge. Furthermore, there is evidence that a natural science major in the tradition of liberal studies encourages graduate study in the natural sciences.  

ENDNOTES


3. Research on the relationship between teachers' subject matter knowledge and pedagogical skills is being conducted by the Teacher Assessment Project at Stanford University. The project is directed by Dr. Lee S. Shulman, with funds from the Carnegie Corporation of New York. Project 30, another activity supported by the Carnegie Corporation of New York, is a three-year project, which commenced in 1988, designed to foster a reform of the way in which prospective teachers are educated. Thirty-two, four-year institutions, each with a five-member team composed of faculty drawn from the arts and sciences and administrators, are addressing such issues as the teacher's subject-matter understanding, entailing the teacher as a professional, pedagogical content knowledge, minority participation in teaching, and, international and multicultural perspectives. Nine of the institutions are focusing specifically on science and mathematics. The project is directed by Dr. Daniel Fallon, Dean, College of Liberal Arts, Texas A&M University and Dr. Frank Murray, Dean, College of Education, University of Delaware.


5. Blacks represent 12% of the population; they constitute 9% of college freshmen; and they receive 2.6% of the bachelor's degrees and 2% of the doctoral degrees awarded in science and engineering. The modest level of participation in higher education in the sciences and engineering by both blacks and Hispanics is exacerbated by high attrition rates. Only about 50% of Hispanics and one third of blacks complete their degrees. By contrast, women represent 52% of the population, but receive only 38% of the science and engineering bachelor's degrees, which are predominantly in the social and life sciences. (Office of Technology Assessment. [1988]. Educating scientists and engineers: Grade school to grad school. Washington, DC: U.S. Government Printing Office.)


11. For information on higher education resources for students with disabilities, contact HEATH Resource Center (Higher Education and Adult Training for People with Handicaps), One Dupont Circle, Suite 800, Washington, DC 20036, 1-800-544-3284 (T/TDD) or 202/939-9320. For information on services in post secondary institutions across the country for disabled students, contact Association on Handicapped Student Service Programs in Postsecondary Education (AHSSPPE), P. O. Box 21192, Columbus, OH 43221, 614/488-4972 (T/TDD).


14. The leading liberal arts colleges rank at or near the top of all American institutions of higher education—including multiversities and major centers of research—in the baccalaureate training of students who go on to earn doctorates in the sciences. Their success is due significantly to the frequent and close contact between students and faculty, close interaction with mentors, extensive research experience at the undergraduate level, and the opportunity to publish research findings. Davis-Van Atta, D., Carrier, S. C., & Frankfort, F. (1985). *Educating America's scientists: The role of research colleges.* Report for the Conference on the Future of Science at Liberal Arts Colleges held at Oberlin College. Oberlin, OH: Office of the Provost, Oberlin College.
The costs of implementing a new era in science education will be high. The costs of continuing to educate undergraduates inadequately in the sciences will be even higher.

Afterword
The proposition that the natural sciences be taught in the tradition of the liberal arts may be met with skepticism and objections. Certainly, considerable resources are necessary for the development and implementation of new or restructured programs. Some will argue that the resources needed will be difficult to find in institutions of higher education already facing budgetary constraints; that the undergraduate curriculum is overburdened already; and that the pedagogical innovations in the teaching of the natural sciences will be too time-consuming. The proposal to add new content—the history, philosophy, and sociology of science and technology—to the study of the natural sciences raises concerns about reducing the coverage of science content and about valuable time being diverted from the basic science curriculum. Teacher educators will ask where the time for professional studies in education is to be found. Granted, the costs of implementing a new era in science education will be high. However, the costs of continuing to educate undergraduates inadequately in the sciences will be even higher.

To dispel doubts about the viability of the proposals recommended, the appendix lists courses and programs whose goals, liberal arts perspective, multidisciplinary content, and pedagogical techniques are similar to those espoused in this report. These and other programs and courses available at institutions of higher education across the nation can serve as both tests and working models for the feasibility of integrating the sciences and the liberal arts and of enacting the recommendations herein.
The Appendixes
INTRODUCTION TO THE APPENDIXES

Appendixes A through D (A: Programs Involving the Core Curriculum, B: Programs Constituting a Major, C: Full-Year Courses and Course Sequences, and D: One-Semester Courses) contain profiles of existing programs and courses that achieve some of the substantive recommendations of this report. The purposes of the appendixes are twofold:

- to provide examples to illustrate further the points made in the report and
- to give references and contacts for future program and course development.

The programs and courses included were selected from descriptions that were sent, solicited and unsolicited, to AAAS project staff or Study Group members. In some instances, the programs and courses were brought to the Study Group’s attention by articles in newsletters or journals. In all cases, the program director or individual instructor was sent a questionnaire asking for specific information about the program or course. The main criterion for inclusion was that the program or course exemplify an aspect of one or both of the report’s two major principles:

- Science is one of the liberal arts and should be taught as such.
- Science should be taught as it is practiced at its best.

The program and course descriptions are grouped into four appendixes according to their overriding structure. Appendix A, Programs Involving the Core Curriculum, highlights course sequences in science that are required of the majority of an institution’s students. Appendix B, Programs Constituting a Major, is a compilation of some innovative, baccalaureate degree programs whose purpose is to produce graduates who have both a liberal arts viewpoint and an in-depth understanding of science and the scientific enterprise. Many of the programs in Appendixes A and B strive to achieve the intellectual integration and program coherence called for in the report. Appendix C, Full-Year Courses and Course Sequences, presents profiles of full-year courses and course sequences that provide a comprehensive study of science in a liberal arts context and employ the pedagogical techniques described in the report. Finally, Appendix D, One-Semester Courses, lists individual courses that teach science as a liberal art and/or represent one or more of the recommendations concerning pedagogy.

All the profiles follow the same basic structure. Each one starts with the aims, purposes, goals, and objectives of the program or course(s). An outline of the structure of the program or course(s) is given, followed by a general discussion of its content. Pedagogical techniques and laboratory and experiential activities are described, with greater attention given to nontraditional modes of instruction. Each profile also contains a description of the method of assessment. Finally, such basic information as the intended audience, enrollment, program or course prerequisites, year instituted, require-
ments satisfied, and the name(s), address(es), and telephone number(s) of the contact person(s) is given.

Many more descriptions were reviewed than could be included. Inclusion does not necessarily signify the Study Group's endorsement of a program or course. Rather, it represents agreement that aspects of the program or course serve as good examples of their recommendations. Similarly, exclusion is not a reflection on the quality of a program or a course, but rather on how well it exemplifies the recommendations that the Study Group would like colleges and universities to implement.

Special thanks go to Study Group member A. Truman Schwartz and Study Group associate Lynn Ewart for developing the questionnaire, working with program directors and course instructors, and selecting and compiling the programs and courses profiled.
All the programs described in Appendix A either constitute an institution’s core science requirement for all of its students or are voluntary alternatives to the institution’s core science requirement. The core programs are unique in that they provide a common experience in science for the majority of students. The individual courses within the core sequences (most are sequences of two courses or four modules) represent a coherent program of study in the sciences that goes beyond the traditional survey because they place science in its historical and/or contemporary societal context and emphasize the development of science-related, intellectual skills. Several of the core programs also strive for intellectual integration with the nonscience core courses in their institutions.
The Integrated Liberal Studies Program (ILS) is a voluntary interdisciplinary program that integrates the humanities, social sciences, and natural sciences. The objective is to produce responsible citizens conversant with the social, political, scientific, and cultural history of their society and with the latest developments in human knowledge. In the sciences, the specific goals are scientific literacy—the understanding of science as a process, the connections between science, technology, and economics, and the philosophical implications of science.

The program consists of 14 three-credit one-semester courses. Students who take seven or more ILS courses earn a certificate. Four of the courses are in the natural sciences. Participants in the four science courses meet for two 1-hour lectures and one 1-hour discussion each week.

The science courses include:

- **Science, Technology, and Philosophy I**, which discusses views of nature in ancient philosophy; Ptolemaic cosmology; ancient and medieval medicine; science and mathematics in Islamic civilization; the Copernican and Tychonian systems; and Galileo, Descartes, and Newton.
- **Science, Technology, and Philosophy II**, which reviews the Newtonian system; the energy concept; science and technology in the industrial revolution; Darwin’s theory of evolution; the professionalization of scientific research; and the rise of the theory of relativity.
- **Contemporary Physical Sciences**, which examines special and general relativity; modern cosmology; the quantum theory; causality and chance; semiconductors and superconductors; nuclear physics; nuclear energy; technology; and the arms race.

Lectures are conducted in a conventional style, although the discussion sections are led using the Socratic method and emphasize student participation.

There are extensive demonstrations in **Science, Technology, and Philosophy II** and in **Contemporary Physical Sciences**. Audiovisual materials are used in **Contemporary Life Sciences**, which has a “walk-in” laboratory (there is no set class hour, but an assistant is on duty several hours each day). The laboratory resembles a “hands-on museum” and features exhibits that students handle and about which they answer questions. Other courses involve visits to on-campus museums and research laboratories. Additional field trips may be organized in the future.

Evaluation is primarily through examinations, with an emphasis on essay questions which require critical evaluation rather than a summary of facts. All courses require term papers. Also, participation in discussion is taken into account. Some mathematical proficiency is required in **Contemporary Physical Sciences**.

**Audience:** Science, Technology, and Philosophy I and II are targeted for freshmen and sophomores; Contemporary Physical Sciences and Contemporary Life Sciences for sophomores and juniors. Nearly all students are humanities and social science majors fulfilling a natural science breadth requirement.

**Enrollment:** About 20% of the 33,000 undergraduates take at least one ILS course. About 1% take seven or more. About 70 students per year take all four science courses, while most students take two or three.

- **Science, Technology, and Philosophy I**: 440 students per year (2 lectures; 19 discussion sections).
- **Science, Technology, and Philosophy II**: 420 students per year (2 lectures; 18 sections).
- **Contemporary Physical Sciences**: 80 students per year (1 lecture; 4 sections).
- **Contemporary Life Sciences**: 120 students per year (1 lecture; 5 sections).

**Prerequisites:** Science, Technology, and Philosophy II is a prerequisite for **Contemporary Physical Sciences**.

**Year instituted:** Science, Technology, and Philosophy I and II and Contemporary Life Sciences were introduced in 1981; Contemporary Physical Sciences in 1982.

**Requirements satisfied:** Completion of all four science courses satisfies the university’s science requirement for the bachelor of arts degree in the College of Letters and Science as well as for certain professional programs (business, journalism, etc.).

**For further information, contact:**

- **Science, Technology, and Philosophy I**
  - David Lindberg  (608) 262-3971
  - Department of the History of Science

- **Science, Technology, and Philosophy II**
  - Daniel Siegel  (608) 262-1434
  - Department of the History of Science

- **Contemporary Physical Sciences**
  - Robert March  (608) 262-2278
  - Department of Physics

- **Contemporary Life Sciences**
  - Tim Allen  (608) 262-2692
  - Department of Botany

  - Walter Plaut  (608) 262-2579
  - Department of Zoology

University of Wisconsin
Madison, WI 53706
INTRODUCTION TO THE NATURAL SCIENCES
Lehman College

Introduction to the Natural Sciences is a two-semester core science course for liberal arts students. It is designed to introduce the basic concepts, major scientific figures, and the most significant methods, results, experiments, and literature related to the history of science from antiquity to the present.

The course traces the history of science from antiquity to the 1700s during the first semester and from the Enlightenment to the present during the second. Participants meet for 2 hours once a week. The first hour is devoted to lecture and the second to a Socratic discussion of the material students were assigned in preparation for the class.

The course progresses chronologically, beginning with a general discussion of what distinguishes science from other endeavors and other forms of knowledge. Students read both primary and secondary source materials covering a broad spectrum of literature—scientific, historical, and philosophical—related to the great figures of science from antiquity to the present. In the first semester, topics include Plato versus Aristotle, Galen versus Harvey, and Copernicus, Kepler, Galileo, and Newton; the last 2 weeks cover the confrontation between science and religion in the 17th century.

The second semester begins with a discussion of the chemical revolution and the work of Priestley and Lavoisier. Three weeks are spent reviewing 19th-century theories of evolution, especially those of Darwin and Wallace. Freud occupies two weeks; the question of whether psychoanalysis is "scientific" is addressed, with special attention paid to the issue of what constitutes a "scientific theory" in any branch of science. Two weeks are devoted to Planck, Bohr, and Einstein and the philosophical foundations of modern science, the role of mathematical models, instrumentalism, and the interaction of experiment and prediction in confirming or falsifying scientific theories. Another 2 weeks are allotted to Watson and Crick and the race to discover the structure of DNA, with emphasis given to the role of Rosalind Franklin. A social critique of the organization of modern science, how it is pursued individually and by large teams working cooperatively or competitively, is made in this unit. In the final week of the course, issues of ethical judgment and the extent to which scientists are and should be responsible for the extra-scientific consequences of the research they perform are reviewed.

In addition to lectures and laboratory work, the course involves discussion sessions, guided by faculty, where material is read jointly and debated in a question-and-answer, Socratic format intended to help students appreciate the difficult ways in which means and methods, social and psychological factors, and physical and metaphysical assumptions place limitations on any theory of knowledge, scientific or otherwise. Essays keyed to specific issues raised in lectures, reading, and discussion sessions guide students in their thinking about the nature of science and its historical development. For example, students might be asked to state why they thought that the scientific revolution in chemistry was "postponed" and what significant prerequisites were needed before chemistry could undergo the transformation it did in the 18th century.

Laboratory work includes three assignments whose purpose is to acquaint students with many of the perils and surprises that accompany scientific investigation. The first laboratory session reviews Galileo's classic pendulum experiments and raises questions about data, measurement, accuracy, and the mathematical interpretation of results. The second is a chemistry laboratory in which students recreate the classic experiments for generating oxygen and hydrogen and then compare the two gases for similarities and differences. The third session is assigned to biology. Students examine a number of biological specimens, some requiring the use of a microscope, and then develop their own taxonomies based upon whatever criteria they deem most appropriate. Although the experiments are simple, students come away with a concrete sense of how human error, imperfections in equipment and data, and the crucial factor of experimental design are all interrelated.

About once a month, a short essay is assigned on a topic ranging from a comparison of the scientific assumptions and methodologies of Plato and Aristotle to an analysis of the very different approaches used by Priestley and Lavoisier for their chemical studies in the 18th century. Final examinations are take-home essays meant to provide students with ample time and opportunity to evaluate diverse aspects of the course and to interrelate the many figures and examples they have studied during the semester.

Audience: Undergraduates in a general core curriculum for science at the City University of New York (CUNY) and graduate students in a master's degree in liberal arts program at New York University (NYU) and CUNY. The course at Lehman College is currently limited to undergraduate students in the adult degree program.

Enrollment: A maximum of 30 at CUNY (enrollment is limited to keep classes relatively small); a maximum of 50 is projected at NYU.

Prerequisites: None.

Year Instituted: 1985–86 at CUNY; 1989 at NYU.

Requirements satisfied: The science core is required of all candidates for the bachelor of arts degree or the master

For further information, contact: Joseph W. Dauben (212) 960-8289
Department of History
Lehman College
City University of New York
Bronx, NY 10468
Learning Science Through Inquiry is the Division I science requirement for the School of Natural Science at Hampshire College. Its primary goal, both for students who intend to concentrate in the sciences and for those whose primary interests lie elsewhere, is to cultivate the analytical skills necessary to engage in the ongoing enterprise of science.

Students progress toward the bachelor of arts degree by completing three levels (divisions) of study. They must accomplish their distribution requirement in science through an inquiry-based project. This focused engagement in the process of science is called Division I.

Courses are offered on a variety of topics in the physical sciences, human and animal biology, and environmental science. Course offerings range from Quantum Mechanics for the Myriad to Health Issues for Minority Communities to Aquatic Biology. Each course is problem-centered and combines extensive laboratory work and/or field projects with library experience and critical reading of primary literature.

In this program, science is characterized as a way of approaching the natural world through a process of questioning, posing hypotheses, and developing and evaluating experiments to test those hypotheses. Starting in introductory courses, students learn that science does not consist primarily of gathering "facts" or determining absolute truths and that the principal task of each new generation of scientists is to modify (and, in some cases, to overthrow) the "truths" handed down to them.

The required, inquiry-based projects may be laboratory, field, or library studies. Two ingredients are essential for successful projects. First, the research must be genuine; the outcome of the investigation, however small, should not be "known" by the professor. Second, the students and their teachers work together in developing, addressing, and analyzing the questions and the data.

Some projects are accomplished within the context of a course. For example, in one environmental geochemistry course, students conducted an intensive study of the influence of bedrock chemistry on stream pH and alkalinity in a small watershed. The laboratory component of this course differed from many similar courses in that the focus of the question evolved during the course, building on the class's initial findings. Each student carried out a different part of the investigation and wrote a research paper based on the entire data set.

Other students develop projects on their own, with skills (reading and writing research papers, developing hypotheses, and logical thinking) that they practiced in a Division I course. Although these independent investigations are extraordinarily diverse, the purpose of each is the same: students become scientists who ask focused questions, use nature and other resources in attempts to find answers, and develop their results in research papers and oral defenses.

Students work through several drafts of their research papers with faculty members. In a final meeting with faculty, students respond to questions about the arguments and evidence presented in the paper. Faculty write a one-page evaluation based on the quality of the paper and the discussions held throughout the process. This evaluation becomes part of the student's official college transcript.

**Audience:** Required of all students.

**Enrollment:** 15–25 students per professor per course. Approximately 300 students per year complete the Division I requirement in science.

**Prerequisites:** None.

**Year instituted:** 1970.

**Requirements satisfied:** These courses satisfy the core distribution requirement in science.

**For further information, contact:** Merie S. Bruno
Department of Biology
Charlene D'Avanzo
Department of Ecology
John Reid
Department of Geology
School of Natural Science
Hampshire College
Amherst, MA 01002
(413) 549-4600
The Lambda program at Case Western Reserve University is a voluntary alternative to the university's standard core program. Lambda is premised on the belief that mathematics and logic constitute the common language, method of thought, and integrative process underlying the revolutions in the physical sciences, social sciences, information and computer sciences, and other technological fields. The aims of the Lambda program are to provide the background necessary for effective participation in a modern, democratic, rapidly changing society as well as to furnish the insights and values normally associated with a traditional education in the humanities.

The Lambda core curriculum is a 56-credit-hour, structured program consisting of a sequence of required courses and other sequences within which there is a choice of courses. Eight distinctive, bachelor of arts degree programs are based on the Lambda core. Currently, there are programs in anthropology, economics, history, philosophy, political science, psychology, sociology, and computer science. Programs in management and artificial intelligence are under consideration.

All students must take a four-course sequence in mathematics which includes continuous mathematics, discrete mathematics, probability, and mathematical modeling. The continuous mathematics courses emphasize concepts and basic understanding, as opposed to methods of solving specific types of problems. The discrete mathematics course is rigorous and conceptual, with a more general coverage than the discrete mathematics course designed solely for computer science. The mathematical modeling course stresses the application of mathematical methods to problems in the social and natural sciences. All participants in the Lambda core must take a two-semester sequence in natural philosophy. This course provides a unified inquiry into natural science and into philosophical issues of values and knowledge.

To meet the natural science requirement, students choose between two 1-year sequences in a natural science. The first sequence, Physics and the Cosmos, presents concepts of modern physics. The other sequence consists of two courses, The Earth and Planets and Geologic Cycles. Both sequences cover basic scientific principles and expose students to methods of scientific inquiry applied to particular problems. The students take a 1-year sequence in a social science where the courses contain significant quantitative material and emphasize analytical skills. Students also must take a two-course sequence in history and culture and a two-course sequence in literature and the arts. Additional Lambda core requirements include acquiring skills in English, composition, and computing.

Except for the senior thesis, the courses in the Lambda program are taught in the traditional, one-semester format. Computer use is highlighted, but there are no minimum computer requirements within individual courses.

Each student participating in a Lambda program completes a senior project (senior thesis) on a topic of his or her choice which uses the mathematical sophistication developed during the core program. For example, a student majoring in philosophy might do a project on artificial intelligence. A student majoring in political science might do a project on computer analysis of voting patterns.

**Audience:** Undergraduates majoring in the liberal arts.

**Enrollment:** The program is too new to determine the number of majors. However, enrollment in Lambda courses averages 33 students per semester.

**Prerequisites:** None.

**Year instituted:** Fall 1988.

**Requirements satisfied:**

**For further information, contact:** John C. Angus (216) 368-4133
Department of Chemical Engineering
A. W. Smith Building
Case Western Reserve University
Cleveland, OH 44106
SCIENCE IN MODERN LIFE I AND II
Brooklyn College

Science in Modern Life is the natural sciences component of a mandated, 10-course, core curriculum which all students share in common. The science requirement is viewed by the college as a unitary experience designed to provide students with an understanding of science as a mode of thought and a way in which knowledge of nature is acquired. Integration is facilitated by division of the core into two tiers in which a course in mathematical reasoning and computer programming precedes the science component of the second tier where greater sophistication is assumed.

Science in Modern Life consists of four half-semester modules—Chemistry and Physics I and Biology and Geology II. The absence of choice among the four sciences conforms to the common-experience philosophy underlying the core curriculum, promotes integration of scientific and technological perspectives across all the core courses, and seeks to prepare students for the responsible exercise of judgment about the relationship of science to public policy.

All of the modules, taught by faculty with expertise in the respective disciplines, introduce students to the roles of observation and inference in the scientific method, the intellectual excitement of hands-on experience, and the tentative nature of scientific truth in problem-solving. Through exploring the subject matter of the four separate fields, students become familiar with the basic concepts and methods of the physical and natural sciences, the evolution of scientific discoveries, and their implications for modern life.

Space and time are the theme of the physics module. Attention is paid to the origins of the concepts, from the observations and inferences of the classical Greeks to the most recent theories in contemporary physics. Two thirds of the chemistry module focus on basic principles; the remaining third is devoted to selected topics (biochemistry, environmental chemistry, energy, etc.). The biology module consists of selected fundamental principles and processes (the diversity of life, cells, genetics, energy, evolution, ecosystems, etc.). The geology module concentrates on the recognition of plate tectonics as a scientifically verified phenomenon, its immediate impact on the modern human environment, and its effect on the evolution of life.

All four modules require laboratory work. The physics laboratories, which focus on the single theme of “measurement,” are taught by the faculty member responsible for the lecture, thus facilitating greater integration between laboratory and lecture experiences. In the chemistry laboratories, students perform four experiments, observe the nature of the physical and chemical properties of matter, and learn the importance of analysis and identification of chemical materials and the structure of molecules all by using molecular models. Some of the biology sections probe each laboratory topic in two sessions: first, as regular laboratory experience; then, the same topic is examined through computer simulations, thus providing additional cases for analysis and a more thorough understanding of the laboratory experiments. The geology laboratories are designed to give students an experience that mimics that of professional earth scientists. Students learn to decipher geological history by observing features in rocks, both in the classroom and on field trips. The logical bases for identifying and classifying rocks are demonstrated.

Students are evaluated by their performance on hour-long tests and final examinations as well as by laboratory reports and quizzes. Laboratory reports are used toward fulfilling the writing-across-the-core requirement. Examinations vary by discipline, combining short essays and problem questions with definitions, identifications, and multiple-choice and fill-in questions.

Audience: All students. (Exemption from an individual module is granted to students completing a full semester of more advanced course work in that discipline.)

Enrollment: 60 students per section; 20 per laboratory section; 110 sections per year.

Prerequisites: The core curriculum is divided into two tiers of five courses each, with completion of the first tier serving as a prerequisite for entry into the second. Science in Modern Life I and II are in the second tier.

Year instituted: 1981.

Requirements satisfied: The science courses are part of a 10-course, common and integrated, core curriculum program which must be completed by every student for the baccalaureate degree.

For further information, contact:
PETER BRANCAZIO, (718) 780-5418
Department of Physics
David Seidemann, (718) 780-5416
Department of Geology
Brooklyn College
City University of New York
Bedford Avenue & Avenue H
Brooklyn, NY 11210
The Scientific and Technological Literacy (STL) program is a multifaceted and interdisciplinary effort. It is designed to impart the analytical skills and knowledge of scientific methods needed by educated and concerned citizens to meet today’s scientific and technological challenges.

Two semesters are necessary to complete this STL sequence. Each course is one semester in length and is subdivided into two modules of equal length. Each module has a somewhat different focus within the overall theme of the sequence; generally, every module is taught by a different professor. Thus, a student completing two semesters usually is exposed to four different viewpoints on science and technology, with a problem-oriented theme providing the integrating factor.

The four themes and their associated courses are:

- **Commercial Systems Theme**
  - Modules I and II: Matter, Energy, Life, and Systems
  - Module III: Systems
  - Module IV: Futurcasting Methods and Assessment

- **Environment Theme**
  - Module II: Uses and Abuses of Resources
  - Module III: Controlling Wastes
  - Module IV: Assessing the Environmental Future

- **Health Theme**
  - Module II: Functional Anatomy and Fitness
  - Module III: Mental Health
  - Module IV: Assessing the Health Future

- **Energy Theme**
  - Module II: Renewable Energy Resources
  - Module III: Electricity and Electrical Technology
  - Module IV: Assessing the Energy Future

Students begin an STL sequence by practicing and polishing some basic problem-solving, quantitative, and measurement skills. They are introduced (or reintroduced) to some of the basic principles and theories of science from a systems viewpoint. They continue their studies by delving more deeply into a few problem areas of current import. This approach enables the students to build on their basic backgrounds while pursuing such technological analyses as risks and benefits, epidemiology, or technology assessment studies. Technology enters the courses more in the form of systematic procedures than in the detailed study of devices. Thus, each sequence deals with an aspect of modeling, analysis of costs, risks and benefits, forecasting, technology assessment, and so forth.

**STL courses** have a hands-on, activities component which regularly makes use of laboratory exercises. Laboratory activities during the first semester emphasize basic measurement techniques, collection of data, analysis, and modeling, using simple, introductory, biological, chemical, and physical experiments. Activities in the second semester highlight analyses of costs, risks, benefits, and assessment techniques. Many activities rely on the use of computer packages such as Lotus 1-2-3 and dBASE III Plus to test models and scenarios that the students investigate and report. The focus is on decision-making and assessment. The form of the laboratory report requirement helps to reinforce the program of writing across the curriculum and increases students’ abilities to use computer application packages. Some field trips are arranged. In addition, guest speakers lecture on scientific and technological issues twice a semester in the Science and Technology Lecture series, which brings Nobel Laureates and outstanding scientists to the campus. The lecture series is an integral part of the program.

Students are evaluated each semester on the basis of four examinations, 12 to 14 five-page reports (fewer reports are required in the second semester), and optional critical analysis of one or two books on a scientific or technological discovery. Many instructors also require critical analysis of lectures given in the Science and Technology Lecture series. Examinations, which may be open book, test reasoning, understanding, and problem-solving skills. Laboratory reports must be produced on a word processor and written in standard English.

**Audience:** All candidates for an undergraduate degree in the School of Arts and Science and the Hagan School of Business, excluding students pursuing a bachelor of science degree in biology, chemistry, computer and information sciences, computer electronic science, ecology, interdisciplinary science, mathematics, physics, and psychology.

**Enrollment:** Approximately 550 students each semester.

**Prerequisites:** STL courses with prerequisites have another STL course(s) as their prerequisite.

**Year instituted:** 1983.

**Requirements satisfied:** This curriculum satisfies the scientific and technological literacy requirement for students in the School of Arts and Science and the Hagan School of Business, excluding students pursuing a bachelor of science degree in biology, chemistry, computer and information sciences, computer electronic science, ecology, interdisciplinary science, mathematics, physics, and psychology.

**For further information, contact:**
- Victor A. Stanonis (914) 633-2236
- Department of Physics
- Iona College
- 715 North Avenue
- New Rochelle, NY 10801
The Technology Cluster is a two-course sequence on technology and its social impacts which may be substituted for two of the four science courses required of most undergraduates as part of their general education requirement. The purposes of the sequence are to enable non-science majors to become literate in technology and aware of the social implications of technology.

The cluster begins with a standard two-course science sequence (selected from a roster of physics, chemistry, biology, and geology courses) with laboratory work, followed by a two-course technology sequence. The year of science—any science—gives students a useful background in scientific vocabulary, calculation skills, notions of theory and verification, familiarity with laboratory techniques, and some understanding of the distinction between empirically testable scientific claims and subjective value judgments.

The two courses comprising The Technology Cluster are Introduction to Technology (given in the fall) and The Social Impact of Technology (given in the spring). Introduction to Technology is a lecture course for large classes which meets three times a week. It is taught jointly by two professors, an electrical engineer and a science journalist, who attend each other’s lectures. The course acquaints non-science students with the general principles of modern engineering and technology, showing how they are related to science and society. Emphasis is placed on communications technology, such as radio and television, as a vehicle for illustrating more general principles, historical controversies, and safety problems common to most technologies. The problem of assessing a new technology in order to anticipate its effects on society is examined.

The Social Impact of Technology is also a lecture course which meets three times weekly and offers opportunities for discussion. It is taught by several professors who, collectively, have social, scientific, and technical expertise. Guest lecturers augment the course. Students’ understanding of the general effects of technology on society is applied to three or four specific technologies which are of current public concern. Examples include nuclear arms, manipulation of human genetics and human reproduction, large-scale accidents, and the prediction and control of natural and man-made hazards such as earthquakes and ozone depletion. Cases are examined in light of both their technical background and the social and political factors that have brought them to public attention. Students study opposing positions in an attempt to disentangle scientific questions from those that must be answered in the political arena. Topics are reconsidered each year to ensure their timeliness.

In Introduction to Technology, students get hands-on experience through laboratory assignments relating to basic electronics. Demonstrations and audiovisual materials are used in The Social Impact of Technology to express concretely some of the abstract concepts of science and technology.

Grades in Introduction to Technology are based on five examinations distributed throughout the semester. Grades in The Social Impact of Technology are based on an examination or discussion paper due after the completion of each topic and on several short quizzes. Examinations provide students with opportunities to write critical responses to current news articles that contain technological arguments.

Audience: Undergraduates pursuing nontechnical majors.
Enrollment: About 100 students a year complete the program.
Prerequisite: One year of undergraduate science—biology, chemistry, geology, or physics.
Year instituted: 1982.
Requirements satisfied: Most undergraduates must take four science courses as part of their general education requirement. Students may replace two science courses with the two courses of The Technology Cluster.
For further information, contact: Marshal H. Segall, Associate Dean of the College of Arts and Sciences
Address: Hall of Languages
City: Syracuse
State: NY
Zip: 13244
Phone: (315) 443-1011
INTRODUCTION

The programs described in Appendix B represent some of the innovative, interdisciplinary, baccalaureate programs that are emerging in American colleges and universities. All the programs require students to develop a solid foundation in one or more sciences through traditional science courses combined with other courses designed to develop a broad understanding of science in relationship to the humanities, social sciences, and technology. The interdisciplinary approach allows students to construct programs of study that are coherent and intellectually well integrated. Several of the programs require capstone courses to ensure intellectual integration.
The Curriculum in Science and Culture is an interdisciplinary program that concentrates on the interactions among science, technology, and society so that students develop a broad understanding of the sciences, the humanities, the social sciences, and technology. The purposes of the program are to help students understand and be able to deal with a technological society different from any that has existed previously and to help them gain a global view of society and an awareness of the wisdom needed to manage it. It is based on the premise that, in order for technology to provide society with benefits greater than its costs, society must learn to use science and technology as instruments to achieve human ends, rather than as ends in themselves.

The curriculum has a science requirement—6 hours in a physical science (chemistry, geoscience, or physics) and 6 hours in the life sciences (biology or psychology); five required courses—Science Writing, Science and Technology in Western Civilization II, Philosophy of Science, Introduction to Science and Government, and Sociology of Science and Technology; a wide range of elective courses from which a student must complete at least two; and two required seminars—variable topic courses which deal with issues at the interface of science and technology on the one hand and society’s social, economic, political, and ethical structures on the other. Topics studied include medical ethics, alternative technology, and technological risk assessment.

Class formats vary with the size of the class, but most of them emphasize discussion. Some classes are lecture-style and some courses highlight independent studies. A few have involved empirical research.

Most frequently, activities outside the classroom have been developed by students and advisors in pursuit of data for research papers. These activities have included interviews with faculty members in science, engineering, pharmacology; data collection; visits to industrial plants; and interviews with city, county, and state officials in such areas as environmental protection, health, and occupational health and safety.

Students are evaluated on the basis of typical university examinations, with emphasis placed on essay questions. Greater stress than normal is placed upon the quality of term projects, whether library or empirical investigations.

**Audience:** All undergraduates.

**Enrollment:** 5 majors per year.

**Prerequisites:** None.

**Year instituted:** 1969.

**Requirements Satisfied:** This program is a major in the School of Humanities, Social Sciences, and Education.

**For further information, contact:**
Leon Trachtman
Department of Communication
Purdue University
West Lafayette, IN 47907

(317) 494-3335 or (317) 494-3429
The bachelor of arts program in the History, Philosophy, and Social Studies of Science and Medicine (HIPSS) makes possible the study of a wide range of social, historical, and conceptual issues relating to science. The goal of the program is to teach students to make reasoned interpretations and evaluations of science and science policy. Students in the program must do sufficient work in one or more sciences to acquire a sound foundation for studying the nature of science. After attaining this basic familiarity, they are expected to gain an understanding of how science arose and how the content of scientific thought has changed and is changing continually, both because of its own internal dynamics and because of its interaction with the larger society in which it is embedded.

The curriculum of the program contains five principal elements: (1) the foundation: the foundation consists of any common core biology sequence, a common core sequence in the physical sciences, a mathematics sequence, and the sequence surveying the growth of science in Western civilization (each sequence extends over three quarters); (2) advanced science: students are expected to take three courses in science or mathematics beyond the introductory level; (3) areas of concentration: each student in the program determines a particular major area of concentration in the history, philosophy, ethics, and/or social contexts of science and medicine; in consultation with the program director and student advisor, the student selects five courses to constitute the area of concentration; (4) tutorials: each student takes two tutorial courses; and (5) bachelor’s thesis and senior seminar: each student completes the program with a bachelor’s thesis; during the senior year, students also enroll in a designated, one-quarter seminar that deals with general aspects of the history, philosophy, and social studies of science.

Students in the program have opportunities to engage in collaborative research in science departments during their years as a HIPSS major. In their senior year, they undertake a research project—with a faculty supervisor—in the history, philosophy, or sociology of science. This becomes the basis of their bachelor’s thesis. Theses are read and evaluated by faculty supervisors and the director of the program. Students also must defend their thesis orally.

**Audience:** Undergraduates who will major in the program.

**Enrollment:** 25 majors.

**Prerequisites:** Certain science courses and a high grade point average are needed for admission to the program.

**Year instituted:** 1981.

**Requirements Satisfied:** The HIPSS program is a regular major in the college.

**For further information, contact:** Robert J. Richards, Director (312) 702-8348

History, Philosophy, and Social Studies of Science and Medicine
Social Science Research Building 205
The University of Chicago
Chicago, IL 60637
The Liberal Arts and Science Program is a coherent curriculum that links the sciences and liberal arts in order to increase students’ educational experiences and commitments to lifelong learning. The curriculum is designed to prepare students to contribute meaningfully to a society that is technologically sophisticated, increasingly multicultural, and ethically complex.

The program offers a major, a minor, and an area studies certificate. All students take a minimum of two course clusters, which are interdisciplinary sets of courses grouped around common themes, to help them discover significant insights about the theme from various perspectives. Each cluster contains 15 to 20 courses, from which students must take a core of 2 or 3, plus other electives. Each cluster spans several fields of study—life sciences, physical sciences, humanities, social sciences, and the arts. Each concludes with a capstone course in which students link insights across courses to explore the cluster’s theme.

Three clusters have been developed to date: (1) Science and Society; (2) Beauty: What Pleases and Why; and (3) Civilization. Science and Society deals with problematic aspects of the complex relationship between science and society. It includes courses in the physical, life, and social sciences. These courses provide introductory knowledge of representative scientific areas, an understanding of the strengths and limitations of scientific methods and reasoning, and an awareness of the role of science in important current issues. Courses in the Civilization cluster deal with the historical development of the world’s civilizations, tracing the evolution of political, economic, social, and cultural institutions and models of thought. Courses in the Beauty: What Pleases and Why cluster examine the intellectual, structural, emotional, cultural, and sensory aspects of beauty as it is found in nature and the arts.

Two additional clusters are being developed. The first, Choice in a Limited World, will deal with the limits that physical reality imposes on our increasing use of the planet and with the biological, social, and economic relationships that serve as the basis for making informed choices in using natural resources. The other cluster, 21st Century Mind-Set: Interdependency, will view the world in terms of interrelationships and integration in biology, physics, sociology, history, environment, cultures, politics, literature, and philosophy.

In addition to focusing on specific learning skills, the program emphasizes course work to meet specific objectives of critical thinking and communication, an understanding of numerical data, comprehension of the methods and systems of the natural sciences, a consciousness of history, familiarity with the social sciences, an awareness of multicultural contexts, and an appreciation of the fine arts.

The curriculum involves students directly in self-expression, primary research, and field and laboratory studies. Capstone activities help students to discover meaningful relationships among their courses.

The program presently relies on the university’s teaching evaluation procedures. Techniques specific to its goals are under development.

**Audience:** All undergraduates.

**Enrollment:** Approximately 175 students per year in orientation classes; more in clusters, minor, and major tracks.

**Prerequisites:** None.

**Year instituted:** Fall 1987.

**Requirements satisfied:** The university’s general education requirements. Certificate, minor, and/or major requirements also may be satisfied.

**For further information, contact:** Ann Leffler, Director  (801) 750-1243
Liberal Arts and Science Program
College of Science
SER 101
Utah State University
Logan, UT 84344-4400
The objective of the Science in Society Program is to help students to explore systematically the interrelations between scientific knowledge, society, and the quality of human life. The program strives to give students an understanding of the roles of science and technology in modern industrial society by providing them with the opportunity to specialize in disciplinary and cross-disciplinary science and social science fields while at the same time exploring the uses and impacts of scientific knowledge in solving social problems.

Students are required to complete four colloquia, two advanced seminars, a minimum of two basic science courses, a course involving quantitative skills, one on ethics or political theory, and a senior thesis or essay. The colloquia offered are: Philosophy of Science, an examination of science in social and political contexts, explanation and justification, theory and experiment, cumulative versus revolutionary developments, and a comparison of the natural and social sciences; Sociology of Science and Technology, which considers science as a social institution, a culture, and a process for constructing knowledge; Political Economy, a review of markets, state agencies, labor unions, production organization, labor process, gender, and work; and Public Policy, in which the factors that shape policy and condition the capacity of public officials to address a broad spectrum of societal problems are explored.

The advanced seminars are: Myths and Paradigms; Women, Health, and Technology; Technology and Society; Rationality and Political Criticism; Ocean Policy and the Law of the Sea; The Politics of Work; and Policy Innovation. The general education courses are: The Human Prospect and Ocean Resources.

The size of the colloquia and seminars is limited in order to stimulate substantial discussion. Group projects and presentations are encouraged. Students often arrange experiential activities and field study to supplement the colloquia. Experiential activities are built into some seminars.

All students are required to complete a senior thesis or essay and to pass an oral examination by outside examiners on their ability to connect their thesis or essay research to broader concerns about the interactions of science and technology with their social and political contexts.

**Audience:** 3-year program for sophomores, juniors, and seniors.

**Enrollment:** 53 majors; total enrollment in the courses in 1988–89 was 311.

**Prerequisites:** None, but application to the program includes a personal interview with a faculty member in order to ascertain a student’s interest and preparation for studying science and societal issues.

**Year instituted:** Founded in 1975 and accepted as a regular part of the curriculum in 1980. Grants from the National Science Foundation, the Fund for the Improvement of Post-Secondary Education, and the Andrew W. Mellon Foundation financed the program’s development during the initial 5 years.

**Requirements Satisfied:** The Science in Society Program is a major in the college.

**For further information, contact:** Joseph T. Rouse, Chairperson (203) 347-9411
Science in Society Program
Wesleyan University
Middletown, CT 06457
Appendix C contains examples of full-year courses and course sequences. All are initial courses designed to introduce students to science and the scientific enterprise. The full-year sequence allows for the comprehensive, coherent, and coordinated study of science. Although the majority of the courses were developed for the nonscience major, some can and do serve the needs of the science major.
Chemistry of Our World is a three-quarter program whose purpose is to help students understand the contemporary world through the study of practical everyday substances. It aims to provide students with a working knowledge of the logic and methods of science as they see the development of scientific knowledge from the generation of hypotheses to experimentation to the validation of facts; to increase their knowledge of natural phenomena, physical and biological substances, and change; and to enable them to evaluate scientific problems and decisions. It is intended that students should be able to understand and benefit from the world of nature through knowledge of the underlying principles of chemical processes which they discover for themselves using mathematical and logical analysis.

Chemistry of Our World consists of a sequence of three courses: (1) Living Things (fall quarter); (2) Materials (winter quarter); and (3) Energy and the Environment (spring quarter). In all three courses, the material covered is organized around its applications and its relevance to the development of chemical principles. There are normally nine laboratories of 2 hours each per course.

In Living Things, compounds of carbon, hydrogen, oxygen, and nitrogen are used in developing principles of covalent bonding and structures and reactions of molecules of importance to living things. The characteristics and reactions of biologically important molecules are explained on the basis of their underlying chemical structures and the reactions involved. The technological, regulatory, and social complexities of problems relating to these topics are noted.

In Materials, metallic bonding and the bonding between nonmetals and metals are explored to explain the nature and reactions of familiar materials of industrial importance. The risk versus benefit implications of the use of these materials and technologies for consumers are indicated.

In Energy and the Environment, the study of gas laws is used as the scientific basis for understanding the complicated factors involved in air quality. Similarly, the properties of liquids and the equilibria that are possible in aqueous solutions are the scientific basis for the study of water quality. Principles of thermochemistry are used to calculate the energy derivable from fossil fuels and technological questions of fuel supply and renewability are addressed.

Demonstrations are used where appropriate and an understanding of them is developed by postdemonstration explanations or discussions. Students are shown how observations lead to generalizations; generalizations lead to proposing natural laws; laws are tested; and, finally, theories are proposed to explain laws. Students learn how principles and concepts are applied and extended. For example, from an understanding of bonding in simple hydrocarbons, students are expected to deduce structures for more complicated hydrocarbons.

When topics with social or ethical implications are raised, an effort is made to present both sides of the issues as factually as possible. Discussion and opinions are encouraged. For example, in Energy and the Environment, trade-offs between the effects of environmental pollution on the quality of life versus economics and doing without some products are presented and discussed. Ethical questions, such as nuclear warfare, sharing technology, or industrialized nations using raw materials from less developed countries, may be debated.

Teaching strategies for the laboratory include analysis, conceptualization, and understanding in addition to laboratory skills and procedures. For example, in Living Things, the chemical identification experiment requires that students develop a method of analysis from observations of chemical reactions, instead of merely doing a qualitative analysis scheme. In Materials, the periodicity experiment is coupled with the use of “attribute blocks” to illustrate the logic of classification by similarities and differences, using the minimum number of comparisons and questions. In Energy and the Environment, the heating-values-of-fuels procedure uses simple principles of thermochemistry to reach a conclusion of applied significance.

During each quarter, there are three tests and a final examination. Most tests include an essay or problem-type questions that require comprehension, analysis, and synthesis as well as memory. Evaluation of the laboratory section is based on quizzes, reports, and skills. Laboratory reports are graded for style and grammar as well as for observations.

Audience: Primarily freshmen, nonscience/engineering majors.
Enrollment: 105 per course, with no more than 30 per laboratory.
Prerequisites: None for Living Things; some chemistry, or three units of any high school science for Materials or Energy and the Environment.
Year instituted: Fall 1987.
Requirements Satisfied: The one year of the university’s general education requirement in laboratory science.
For further information, contact: John J. Fortman (513) 873-2188 or 2855
Department of Chemistry
Wright State University
Dayton, OH 45435
FOUNDATIONS OF SCIENCE
Hunter College

 Foundations of Science is a 1-year, introductory science course for nonscience majors. Its fundamental goal is to enable students to leave the course with the background information needed to appreciate "how we know what we know and why we believe what we believe."

The course meets for three 1-hour lecture/discussion periods a week and 3 hours of laboratory work. Lectures are given by participating faculty, representing the departments of anthropology, biology, chemistry, and physics.

The course focuses on a limited number of the broad concepts lying at the foundations of science. The three themes considered are the development of the idea of a heliocentric planetary system, the long process of realizing that matter is fundamentally particulate in nature, and the manner in which it was recognized and accepted that the earth and life on it are not as unchanging as they seem.

While the course is not a history course by definition, it does adopt a modified historical approach. Moreover, it attends to "periscientific" concepts—those issues that are not in the formal mainstream of the subject, but may be more personally or socially important in the eyes of the student. These range from the relationship between astrology and astronomy to the role of belief structures in setting the limits of inquiry (e.g., Greek idealism and divine creation).

Laboratory experience is an important part of Foundations of Science. Great efforts are made to demonstrate the importance of observing and doing in science. A "learning cycle" approach is used in which the student explores, analyzes, and applies knowledge. The discovery mode thus replaces the traditional didactic mode and considerable responsibility for nonintrusive guidance is placed on the laboratory instructor. A special laboratory manual for instructors has been developed for use in the course.

Final grades are based on performance on midterm and final examinations, four or five essays (with revisions) each semester, and laboratory work. One feature of the instructional strategy is the distribution of sets of "Focus Questions" that guide study and promote comprehension of important concepts.

**Audience:** Nonscience majors.

**Enrollment:** Currently: 100 per lecture section; seven laboratory sections per semester. Capacity: 180.

**Prerequisites:** None.

**Year instituted:** 1987, with support from the Andrew W. Mellon Foundation.

**Requirements Satisfied:** These courses partially fulfill distribution requirements in science and mathematics. (The courses also are recommended for students seeking licensure as elementary and middle school teachers.)

**For further information, contact:** Ezra Shahn
(212) 772-5349
Department of Biological Science
Hunter College
City University of New York
New York, NY 10021
The Physical Science Program is a two-semester program for preservice, elementary education majors. The program is designed to enable students to discern manifestations of science in the world around them, to encourage their creative thinking, and to give them opportunities to practice analytical reasoning, apply generalized scientific concepts, and use the skills and processes of science.

The program consists of two 4-credit-hour courses, Physical Science 1 and Physical Science 2. In Physical Science 1, the emphasis is on practicing the reasoning abilities necessary to carry out simple scientific inquiries. Among the major concepts from physical science and astronomy taught in this course are mass, volume, density, solubility, azimuth, celestial sphere, season, phase, tide, and eclipse. Physical Science 2 is a continuation of Physical Science 1, with topics that include electricity, motion, heat, and temperature.

Most of the time in class is spent on laboratory work and solving problems using an activity-based approach. Two laboratory sessions meet for 2 hours a week. There is also one lecture or discussion every week. Major learning is based on hands-on, investigative activities in the laboratory. Exercising reasoning abilities by performing simple experiments and making observations is stressed.

Evaluation consists of a written test every other week, which involves the analysis of experimental situations, and comprehensive final examinations at the end of the semester. In addition, there is weekly evaluation of the skills and concepts acquired in the laboratory.

**Audience:** Elementary education majors only.

**Enrollment:** First semester: 50; second semester: 30.

**Prerequisites:** Introductory Mathematics for Elementary Teachers and its sequel are recommended.

**Year instituted:** 1983.

**Requirements Satisfied:** This course fulfills the science requirement for elementary education majors.

**For further information, contact:** Pauline A. Ayra (304) 293-6137
306 Hodges Hall
West Virginia University
Morgantown, WV 26505
The Theory and Practice of Science is a two-semester sequence that combines mathematics, atomic physics, and molecular biology. Designed for undergraduates majoring in the humanities, the course differs from standard “nonscientist” courses in that it introduces sufficient mathematics so that original scientific papers can be studied.

The sequence attempts to convey to students a sense of what distinguishes science as a form of inquiry by giving them the tools and opportunities to study the processes of science. By using original scientific papers, the course also aims to give students a certain kind of scientific literacy, to lay a foundation for departmental courses, and to implant the sense of competence and autonomy that students need in order to follow the developments of modern science.

Each semester of the course begins with 4 to 5 weeks of mathematics. The purpose of the topics introduced is to impart a sense of what mathematics is for mathematicians and how mathematics is used as a measurement and a modeling tool in the natural sciences.

In the fall, the mathematics section is followed by a unit in physics in which students study the discovery of nuclear fission from primary scientific writings. The sequence begins with an excerpt from Faraday’s Experimental Researches in Electricity and ends with the 1939 paper by Meitner and Frisch that reports the discovery of nuclear fission. In the second semester, the mathematics is followed by a unit in molecular biology in which students investigate the discovery of the structure of DNA. The unit begins with Mendel’s famous “pea plant” paper, “Experiments in Plant Hybridization,” and continues through Watson and Crick’s 1953 paper on the double helical structure of DNA.

There are two lectures and a mandatory, 90-minute, discussion session each week. The discussion sessions are taught by faculty and teaching assistants and there are no more than 10 students in each section. In-class demonstrations elaborate rather than supplement the lectures and discussions. The demonstrations range from Faraday’s electrolysis to the manipulation of a cathode ray tube by a magnetic field to the nuclear fission of uranium to the use of molecular, space-filling models. Constraints on resources currently prevent actual laboratory work by students, although some demonstrations are more like laboratories than others. However, all demonstrations are experiential and hands-on.

Weekly homework consists of problems of various sorts. Problem sets combine mechanical (i.e., standard), science text questions with more open-ended, problem-solving, and short-answer, analytical questions about papers under consideration. The problem sets occasionally include longer essay questions about books being read, such as C. P. Snow’s The Two Cultures, Richard Feynman’s The Character of a Physical Law, and Darwin’s Origin of the Species. The final examination each semester consists of a paper in physics or molecular biology taken from a scientific journal which the students have not seen before. Students are required to read, analyze, and answer questions about the paper as part of the 3-hour examination. In addition, there is one, in-class, mathematics, midterm examination each semester which involves problem-solving exercises.

**Audience:** Undergraduate nonscience majors.

**Enrollment:** 9 to 50 per class; ideally, there are multiple sections of no more than 25.

**Prerequisites:** None.

**Year instituted:** 1981.

**Requirements** This sequence satisfies the two-semester science requirement.

**Satisfied:**

**For further information, contact:** Robert Pollack  
Department Of Biological Sciences  
Fairchild Hall  
Columbia University  
New York, NY 10027
The examples in Appendix D represent innovative courses that effectively integrate science in a liberal arts context and/or teach science as it is practiced. Most of the courses are elective and introduce students to the foundations of science and the scientific enterprise. They all tend to incorporate issues at the interface of science, technology, and society. The courses designed to teach science as it is practiced engage students in activities that replicate the activities of bench scientists; that is, students engage in original research in which the outcome of the activity is not known by either the student or the instructor.
The Century of Genius, developed and taught by a chemist and a philosopher, examines the foundations of the modern scientific revolution, beginning with Copernican astronomy (1543) and culminating in Newtonian mechanics (1687). The course enables students to read original scientific writings, to place scientific achievements in their historical context, and to hone writing skills.

The class meets formally twice a week (2 hours per period). In addition, informal sessions are conducted at the homes of the faculty.

The class investigates why scientific inquiry arose during the Renaissance, why it arose in the West, and why it became a permanent part of modern culture. Issues are explored through study of the major contributors to the scientific movement of the 17th century. Key developments of 17th-century history are reviewed to see what influence they exerted on science (and vice versa). In addition, the class examines why modern science broke away from philosophy, yet remains dependent on it today.

The class is structured essentially as a roundtable discussion of topics, with both faculty and students acting as equal participants. The instructors suggest pertinent passages from the primary source materials (Copernicus, Kepler, Galileo, and Newton); then, a free-wheeling examination of the purpose of the passage in the broader context of the development of science and philosophy ensues. Along with scientific and philosophical constructs, social, artistic, religious, and historical issues are emphasized and their impact is examined.

The experiential components consist of a group project in which the class writes a play about Copernicus in order to give students the opportunity to probe more intimately the life of one of science's early leaders, at least two field trips to view the stars through telescopes, films on Galileo and Newton, and a guest lecture by a local astronomer.

The course requirements include: (1) a journal that logs daily impressions, observations, reactions to class discussions and readings, and records the student's progress in coping with the course materials; (2) a 15-to-20-page term paper on an approved topic; (3) a take-home examination on Kepler; and (4) a group project that requires the class to write a screen play about Copernicus' life and work. Each requirement constitutes 25% of the final grade.

Audience: Open to all students in the honors program and also by the instructors' approval.

Enrollment: 9.

Prerequisites: None.


Requirements Satisfied: General education credit in history or philosophy.

For further information, contact:

Mitchell Malachowski (619) 260-4600, ext. 4421
Department of Physical Science

Dennis Rohatyn (619) 260-4600, ext. 4704 or 4416
Department of Philosophy

University of San Diego
San Diego, CA 92110-2492
Communications Technology presents the interactions of science, technology, and society to general undergraduate students while teaching the basic concepts underlying the technology.

The class meets 3 hours a week for lectures.

The course starts with basic, underlying, scientific concepts. It focuses on electromagnetic fields; the revolutionary thinking involved in spectral decomposition (Fourier and Wiener), which leads to the concepts of resonance, computer speech, and automated speech recognition; digital signals; and information measure (Nyquist and Shannon), which leads to bar codes in supermarket, post office, and manufacturing automation. The transition to probabilistic and digital thinking in engineering is traced to parallel developments in science and in human perception of the world.

The course then turns to audio and sound systems (up to the national digital audiotape controversy) and television systems (is there a role for U.S. firms in high-definition television?). After returning to the basic concept of electromagnetic signals, the course covers possible health effects at length. To conclude, a few specific systems, such as radio, radar, and satellite navigation, and the search for extraterrestrial intelligence, are reviewed in technological assessment terms.

Frequent in-class demonstrations include speech spectra decomposition, Loran navigation, and high-fidelity equipment. Undergraduate teaching assistants and one graduate student work with the instructor in assisting individual students. A text will be published by February 1990 (MIT Press and McGraw-Hill).

Performance is evaluated from four examinations involving brief essays, an individual paper on a specific technology, and a final examination.

**Audience:** The course is elective for all majors; it is designed for advanced liberal arts students.

**Enrollment:** 500.

**Prerequisites:** Upper-division status.

**Year instituted:** 1979.

**Requirements Satisfied:**

The course satisfies the college’s science, technology, and society requirement.

**For further information, contact:**

John G. Truxal  (516) 632-8760
Department of Technology and Society
State University of New York at Stony Brook
Stony Brook, NY 11794
How People Move is an introductory science course that examines human kinesiology. The course is designed to teach students to inquire by doing their own original laboratory investigations.

The class meets twice a week, once for 1½ hours and once for 3 hours. The first 6 weeks of the course build background and skills through reading and discussion of primary scientific papers, short lectures on muscle physiology and other topics, and preliminary group laboratory experiments using the electromyograph to measure muscle activity. The second 6 weeks are devoted to individual or small-group projects, beginning with a written proposal for a project.

From the first day of the course, students are introduced to primary scientific literature in order to educate them to think experimentally and to drop old habits of waiting passively for scientific facts to be given to them. There is no textbook for the same reason. Students read a series of scientific articles on muscle activity and how it is affected by such factors as training. They are taught how to use one laboratory instrument, the electromyograph, which measures muscle activity. Science is taught as a continuing inquiry, with no permanent right answers. Breadth of coverage of human physiology is consciously sacrificed for depth of individual investigations.

The first laboratory experience is structured so that students design very simple experiments and analyze their data statistically before presenting it to the rest of the class. Students are then encouraged to think of ways in which the electromyograph can be used to investigate questions such as muscle fatigue, the effects of warming up, and the use of muscles in different exercises. By focusing on one instrument, students see both the possibilities and the limitations of any one approach. They begin to "act like scientists," striving toward excellence because they cannot compete for the teacher's "right" answer, but rather must report results of independent investigation into questions such as: How do videotapes with different emotional content affect muscle tension? How do different muscle stretches affect muscle tension?

Required work includes short written summaries of scientific papers, a bibliography for the project, and chapters of the final paper. Writing as well as content is important and students are often asked to rewrite their materials. Each student presents a formal oral report at the end of the semester. The final paper is usually on original laboratory investigation (but sometimes it is a library-based paper). Students who carry out their own experiments also must research the related scientific literature and present the investigation in the form of a scientific paper. Evaluation is based on all written work and class participation.

**Audience:** Beginning students; no scientific background is needed.

**Enrollment:** The course is offered once a year, for 20 students.

**Prerequisites:** None.

**Year instituted:** 1977.

**Requirements** If the project is of sufficient quality and is revised, it may satisfy the science requirement.

**Satisfied:**

For further information, contact: Ann P. McNeal, School of Natural Science, Hampshire College, Amherst, MA 01002

(413) 549-4600, ext. 571
Intermediate Technology examines the applications of technology, particularly small-scale approaches, to real-world problems, and evaluates alternative approaches in terms of cost, environmental effects, influence on self-reliance, and social impact. The course seeks to foster an understanding of the interactions of science, technology, and society by focusing on intermediate technology and related issues.

The class meets 3 hours a week for lecture and discussion. The course deals with such topics as water, wind and solar power, human-powered vehicles, and methane digesters, which lead to the teaching of a variety of scientific principles from heat transfer, fluid dynamics, and energy conversion to the chemistry of bioconversion and the basics of electrical circuits. Students are asked to make calculations that include heat loss, mass flow in a stream, the potential energy of a water wheel, and electrical loss. Specific examples of the applications of technology to real-world problems raise such issues as energy use and conservation, fuel consumption, and food production. Students compute the economic, social, and environmental costs of implementing various competing technologies.

Students acquire a better understanding of the issues and of the engineering content and methodology by designing, building, and implementing projects intended to solve specific problems or meet particular needs. The requirements for the projects include: (1) the basic calculations for the project, giving, for example, costs, outputs, and time to construct; (2) a paper describing why the project makes sense—what the approach offers, particularly in terms of life-style; and (3) the project itself, usually something the student has built, and a paper explaining it.

For example, if the project is small-scale gardening, the basic calculations would show the amount of land required, the amount of food produced, the cost and time for preparation and cultivation, the cost of seeds and fertilizer, and so forth. The “life-style” paper would discuss the drawbacks of existing agriculture and the advantages of what the student is proposing. The project would be the plants grown and the plan for the garden.

In addition to the students’ projects, there are field trips to an urban gardening project, an energy-efficient house, and a history of technology museum. A pair of subsistence farmers and a photovoltaic engineer give guest lectures.

The final grade weighs equally class participation and each of the three parts of the project.

**Audience:** This course is elective for all students, but is intended primarily for nonscience students.

**Enrollment:** 50 to 100 per section; one section per year.

**Prerequisites:** None.

**Year instituted:** 1980.

**Requirements** None. Counts toward graduation as any other course.

**Satisfied:**

**For further information, contact:** Division of Engineering
Brown University
Providence, RI 02912

(401) 863-2673
Medical Technology and Critical Decisions addresses the profound effects that the genetic revolution and the general progress of medical science and technology have had on people. More specifically, it looks at new possibilities for human reproduction, treatment of diseases, and the social provision of medical care that have resulted from the advances in medical science and technology. The course aims to provide students with an understanding of the possibilities provided by science and technology and to assist them in applying individual and social values and economics in making responsible decisions related to medical science and technology.

The course has been team-taught by different combinations of faculty; for example, a physicist and a mathematician or an economist and a physician. The class meets for 3 1/2 hours a week during a 13-week semester.

The central feature of this course is its integration of a broad range of subjects and techniques from various academic disciplines. The scientific principles taught span a range encompassing elements of Mendelian genetics, probability and statistics, and the nature of wave motion and sound. Case studies that incorporate these components in a natural way provide effective vehicles for communicating this ambitious range of topics. Medical decision-making problems make particularly good cases because they carry an inherent drama and form a class of experiences that everyone faces in life. A typical case would be to consider whether or not a pregnant woman should undergo amniocentesis.

The course’s two main components are instruction in the technology of the new options and the scientific principles on which they rest, and experience in the decision-making process itself. The latter involves modeling the problem chosen using the methodology of decision analysis, which incorporates the statistical limits of the data available, the probabilities of various outcomes, and the values held by the decision-makers.

Classroom lectures and discussions are supplemented by guest speakers and field trips. Laboratory sessions on probability and sound complement the class periods with hands-on experiments and data-gathering. Students use interactive microcomputer software for decision analysis to simplify the computations in decision modeling problems. They analyze the results of the laboratory and computer sessions in problem sets and in a midterm examination, both of which include questions involving computations as well as their interpretation.

The capstone of the course is a final paper in the form of a complete analysis of an actual, clinical, decision problem taken from the medical literature. Small groups of students are given materials describing the patient’s history, research results relevant to the case, and an outline of the possible choices the physician and/or the patient can make. Students then model the problem, acting as if they were a team of consultants to the attending physicians. Finally, each student analyzes the model, presents her or his analysis, and justifies her or his recommendations of a decision. This is a challenging assignment that integrates the entire semester’s experience in the course.

Audience: This is an elective for all programs of study and all majors, but is intended especially for nonscience majors.

Enrollment: 12 to 30.

Prerequisites: None.

Year instituted: 1983, with support from the Alfred P. Sloan Foundation’s New Liberal Arts Program.

Requirements Satisfied: This course satisfies one unit of the college’s nonlaboratory science distribution requirement.

For further information, contact:
Theodore Ducas (617) 235-0320, ext. 3047
Department of Physics
Alan Shuchat (617) 235-0320, ext. 3111
Department of Mathematics
Wellesley College
Wellesley, MA 02181
Role-Playing Laboratories in Analytical Chemistry are three independent laboratory courses in analytical chemistry whose purpose is to cultivate the interdependence of individual student investigators through role-playing.

Chemical Methods of Analysis: Quality Control (for juniors) and Instrumental Methods of Analysis: Methods Development (for seniors) are one-semester courses, each with 3 hours of lectures and 3 hours of laboratory work a week. The lecture and laboratory components of these two courses are nominally independent (and individually numbered), but, in fact, they are closely integrated. Uses of Computers in the Health-Related Professions (for sophomores) is a 1-month, intensive, interim session designed to develop the computer skills that are needed in the upper-level laboratories.

In the laboratory, students are divided into teams (companies) of four. For every individual experiment, each member of the team has a particular role or responsibility: chemist (procurement and preparation of reagents, standards, and solutions), hardware (assembly and operation of instrumentation), software (creation, linking, and/or operation of any computer software required), and manager (overall organization, implementation, and communication). The manager communicates on behalf of her or his team with upper management (the professor) by electronic mail or in person in a management interview. Roles and responsibilities rotate throughout the semester. Thus students are involved directly in all aspects of the discovery process.

This collaborative approach and the "real-world" problems which are assigned replicate the environment and the work of many analytical laboratories. Analytical methods, development problems, and management dilemma experiments increase the verisimilitude of these courses and contribute to students' interest.

Grades are based on the principle that good management produces good results; good grades follow from good management. Thus, the actual results are not graded. Instead one grade is assigned to the manager (and, by extension, to the entire team) on the basis of how well the objectives of upper management were met. Conventional examinations are given in the lecture component.

**Audience:** Science majors; especially chemistry majors.

**Enrollment:** Uses of Computers in the Health-Related Professions: 16 maximum; 8 optimum. Chemical Methods of Analysis: Quality Control: 48 maximum; 32 optimum. Instrumental Methods of Analysis: Methods Development: 16 maximum; 8 optimum.


**Year instituted:** 1983.

**Requirements satisfied:** These courses are required for the bachelor's degree in chemistry (Chemical Methods of Analysis: Quality Control) and for the American Chemical Society's certified degree in chemistry Instrumental Methods of Analysis: Methods Development.

**For further information, contact:** John P. Walters (507) 663-3429 Department of Chemistry St. Olaf College Northfield, MN 55057
Science and Technology in the Modern World is a sophomore-level, interdisciplinary, core course that looks at the interrelatedness of science, technology, and society. The course’s learning objectives are for students to: (1) understand the separate natures of technology and science and the relationship between them; (2) realize the impact that technological and scientific achievements have on individuals and society on a local, national, and global scale; (3) comprehend scientific and technical articles written for the general public; (4) be able to apply reasoning and quantitative skills to scientific and technological topics; (5) be able to support a viewpoint and know how to take action as a responsible, scientifically and technologically informed citizen; and (6) be acquainted with diverse positions (political, social, economic, religious, moral, etc.) on scientific and technological issues.

The course is taught by a pool of about 10 instructors from various departments as biology, geology, fine arts, chemistry, meteorology, technology, and mathematics. Faculty members meet for an intensive, 4-day training session each spring, sharing teaching materials and strategies.

Although the instructors have a great deal of leeway in how they reach these objectives, they must cover two major topics. One of them must emphasize mathematics and/or the physical sciences, while the other must be related to biology, health, or agriculture. Instructors are allowed to select their own major topics.

All sections deal with the scientific method and experimental design, reading and understanding scientific and technical articles written for the nonscientist, understanding charts and graphs, solving mathematical problems related to the topics under discussion, taking action as a responsible citizen, and the many ways of viewing scientific and technological issues (political, economic, social, religious, etc.).

The format of the course is left to the individual instructor, but, in general, there is a minimum of lecturing. Class discussions, small group discussions, oral presentations, videotapes, movies, and so forth are used by many instructors. Often, individual instructors supplement the course with hands-on experiments, research projects, guest speakers, computer activities, and field trips.

Instructors write and grade their own examinations. However, all participants in the general education core program are deeply involved in “outcomes assessment” to determine whether the students are reaching the objectives of the course. As part of the outcomes assessment process, students in all sections periodically take a “common” examination and are asked to fill out surveys. Data from these common examinations and surveys are used to modify the course in order to help students reach its objectives.

**Audience:** All undergraduates must take either this course or substitute a traditional science course (lecture and laboratory in biology, chemistry, physics, astronomy, geology, and meteorology) as part of their general education requirements. Most nonscience majors prefer to take this course.

**Enrollment:** Each section has a limit of 30 students. Enrollment is about 240 students per semester, with 2 sections in the summer.

**Prerequisites:** Completion of all the following: one college-level science course, one college-level mathematics course, English composition, and completion of all “developmental” coursework.

**Year instituted:** Fall 1985.

**Requirements Satisfied:** One of six required, interdisciplinary, core courses in the general education program.

**For further information, contact:** Judith W. Rosenthal (201) 527-2012

Biological Sciences
Kean College of New Jersey
Union, NJ 07083
Science, Poetry, and the Imagination is a sophomore-level course in which students examine the parallels between the use of imagination in poetry and in science and between the methods of the humanist and the scientist (e.g., a poet explores the unknowns in an emotion; a chemist explores the unknown properties of a new compound) as well as the analogy between the use of metaphors and symbols in understanding poetry and the use of models in understanding atomic structures. The course aims to break down the wall between C. P. Snow's two cultures and to show science students that poetry is not a waste of time and humanities students that science is not detrimental to society, but, rather, that each domain of knowledge is important to Western civilization.

This is a one-quarter course that meets 1 hour a day, 5 days a week, for lectures, discussions, and other pedagogical activities. The poet/instructor and the chemist/instructor alternate weeks after each has given a 1-day introduction to outline the goals, ground rules, and so forth. Panel discussions, in which parallels between the disciplines are emphasized, are scheduled with the poet and the chemist.

The chemist uses lectures, demonstrations, original journal articles (such as E. Rutherford's paper, "The Scattering of Alpha and Beta Particles by Matter and the Structure of the Atom"), movies, and videotapes to press the analogy between metaphor and theory. The parallel between tenor (abstract idea) and vehicle (concrete idea) is developed using equations, for example, $E = hv$. The analogy is further elaborated by describing each image of atomic structure from the late 19th century to the present using data and theory: Crookes tube (J. J. Thompson), scattering (E. Rutherford), H-atom spectrum (N. Bohr), and many-body problem (quantum mechanics).

The poet includes lectures, readings, movies, and videotapes as well as readings and discussions by visiting poets such as Robert Earl Price, Yusef Komonyakka, and William Matthews. The poet may go from "Petrarch to Prufrock" or may deal exclusively with American poets. Readings may be taken from the essays and poems of Miroslav Holub (immunologist/poet) and Robert Pack (poet). Discussions emphasize how mental images become poetry and illustrate the effectiveness of this approach.

The chemist introduces an experimental component to the course in several ways: (1) a Crookes tube is used to illustrate phenomena plausibly explained by the Thompson atom; (2) a Geiger counter is used to acquaint students with properties of alpha, beta, and gamma radiation; (3) a scattering table prepares the class for discussion of the inadequacy of the Thompson atom and the plausibility of the Rutherford atom; (4) line spectra are used to demonstrate Rutherford's unanswered question—"Where are the electrons?"—which is confronted by Bohr; then (5) the consistency of Bohr's theory with Balmer's lines and Rydberg's constant as well as prediction of Pfund lines is developed. Students are taught to write BASIC programs to predict the lines of helium and lithium and to compare them to experimental observations, which leads to the study of the quantum mechanical atom.

The poet typically gives several examinations and assigns papers (with draft consultations); the chemist gives four, 1-hour examinations, algebra-based where appropriate. Each instructor administers a 1-hour, final examination. The poet has students analyze poetry written by humanists about science. The chemist has students react to the caricatured worldview captured in a dialogue between a stereotypical poet, Mr. Spitquill, and a stereotypical scientist, Dr. Crashbeaker. The exercise is designed to probe persisting narrowness of thought, understanding of the role of imagination in both domains of knowledge, and recognition of the importance of science and the humanities in Western civilization.

**Audience:** Sophomores and above.

**Enrollment:** There is no limit on enrollment; registration has varied from 10 to 28. The course is offered once a year.

**Prerequisites:** Freshman English and college algebra.

**Year instituted:** Spring 1985.

**Requirements Satisfied:** This course satisfies distribution (core) requirements in the humanities or the natural sciences.

**For further information, contact:**
David F. Dever
(912) 471-2743
Department of Chemistry
Macon College
Macon, GA 31297
The Sciences is an interarea (biology, chemistry, physics) introduction to science that examines how scientists formulate and address questions about life, matter, and the nature of the universe. The course seeks to involve students in actively considering: (1) elements of critical thinking; (2) the nature of scientific thinking and "doing"; (3) the interrelatedness of the sciences; (4) the utility of science; and (5) sociopolitical implications of science and technology. Emphasis is placed on the methods by which scientists achieve understanding and on the perspectives on the contemporary world that such understanding provides.

Ordinarily, the class meets for three 50-minute lectures and one 50-minute recitation. The course is usually team-taught by a biologist, a physicist, and a chemist, but is sometimes taught by a single faculty member who is experienced with the course.

The course is motivated by asking such questions as: What is the nature of the universe? Students study aspects of the history of astronomy from ancient times through Newton, with attention to methods that were used or introduced. Similarly, in answering basic questions about the nature of matter, students explore changes in the composition of matter, how changes led to the development of Dalton’s atomic theory, and how new technologies led from Dalton’s structureless atoms to the Bohr model. The question: What is life? invites consideration of such topics as metabolism, photosynthesis, respiration, chemical information, and the genetic code.

The focus of the class then turns from an understanding of science to its applications. The relationship between science and technology and the predictive properties of science are explored. The human species is examined in its global environment. A dilemma such as the depletion of rain forests opens up discussion of exponential growth in a limited environment, conservation laws, and the availability of resources.

Laboratory assignments accompany the course and include spectroscopic and microscopic observations, scattering experiments, computer simulations, and classification exercises.

Evaluation is based on three examinations and a comprehensive final examination (examinations include essays), homework, written accounts of laboratory work, and participation in the recitation.

Audience: All students except science and nursing majors.

Enrollment: 15 to 20 per section, with two to six sections. Between 50 and 100 students take the course each semester.

Prerequisites: None.

Year instituted: 1979.

Requirements Satisfied: This course satisfies the science component of central liberal arts requirements.

For further information, contact: Jerold Touger (617) 333-0500, ext. 2221
Science Division
Curry College
Milton, MA 02186
Technical Applications of Light illustrates how fundamental scientific principles, light, and the interaction of light with matter are developed into a series of technologies to address a number of different problems. In addition, the interplay of technology with social, economic, and political forces is an underlying theme of the course as are ethical issues regarding the question of what is an appropriate application of technology.

The class meets for 3 hours once a week. There is an emphasis on discussion.

The course begins with a study of lasers—the principles behind their development and their application in a number of fields, particularly medicine. Through an understanding of the properties of laser light, students are asked to evaluate a number of suggestions regarding areas in which lasers might be useful. Their decisions are based on knowledge of what laser light is and on the broader questions that might arise. For example, a discussion of the use of laser-induced, photochemical reactions in the synthetic chemical industry requires information on the cost of the current synthetic procedures, the cost of laser light, safety issues, and a cost-benefit analysis of the problem.

No formal laboratory work is scheduled although 10 to 15 hours' experimental work is done on an unscheduled basis. In conjunction with their research assignments and class presentations, students have arranged field trips to magnetic resonance imaging laboratories, the telephone company, and a solar panel production facility.

Several problems are assigned, based on the discussions and readings. In addition, each student is responsible for preparing a 15-to-20-page paper and making a 45-minute presentation to the class on his or her individual research project. Topics of students' presentations have included optical fiber technology and communication, magnetic resonance imaging, lasers in the entertainment industry, irradiation of produce, and light-based computers.

Audience: Elective for all students, but intended primarily for nonscience majors.

Enrollment: 20 per section; 1 section per year.

Prerequisites: None.

Year instituted: 1985.

Requirements Satisfied: This course satisfies the nonlaboratory science distribution requirement.

For further information, contact: William F. Coleman (617) 235-0320, ext. 3129

Department of Chemistry
Wellesley College
Wellesley, MA 02181
WAYS OF KNOWING
Macalester College

Ways of Knowing is a multidisciplinary freshman seminar that uses a historical, case-study approach to examine the epistemological basis for science and to compare the claims of science with those of other branches of knowledge.

This one-semester seminar meets 3 or 4 hours a week for lectures and discussion. When multiple sections are offered, one session a week usually is devoted to joint meetings for special presentations (often by on- or off-campus guests), films, or tapes. The teaching staff is drawn from a trained cadre of 11 faculty, representing 11 different disciplines in all divisions of the college.

All students study three intellectual revolutions: the overthrow of the geocentric cosmos, the development of the theory of evolution of species through natural selection, and the creation of a newly perceived physical reality through relativity theory and quantum mechanics. (Additional topics are included at each instructor’s discretion.) Although the revolutions in question had their immediate focus in natural science, they altered human self-concept and human society profoundly. Consequently, this course embeds science in its cultural context. The approach is decidedly interdisciplinary. Textual materials include readings from original scientific works, history, philosophy, theology, religion, and literature. A relevant work of fiction is selected for each case study and, typically, a general work on scientific revolutions is on the reading list.

The revolutionary case studies are presented as conflicts between and among ways of knowing and both their original receptions and their current impacts are considered. Students are challenged with such questions as: How do we know anything? How can we understand and explain ourselves, our fellow human beings, and the world we inhabit?

Special activities include telescopic and other astronomical observations, planetarium presentations, demonstrations of physical and chemical phenomena, and the study of geological and biological specimens. The first year the course was taught, seven distinguished visiting lecturers, among them John A. Wheeler, Martin Kline, David Schram, and Owen Gingerich, participated.

Discussion of readings and issues is an important part of the course and participation in it is considered in assigning grades. Both brief quizzes and essay examinations have been used for evaluation. Writing assignments are made every week and at least four papers, with preliminary drafts and revisions, are required.

Audience: This seminar is restricted to first-semester freshmen. Students with a diversity of interests from all potential majors are encouraged.

Enrollment: Limited to 15 per section; 1 to 6 sections per year.

Prerequisites: None. Counts toward graduation as any other course.

Year instituted: 1981, with support from the National Endowment for the Humanities.

Requirements: None.

Satisfied:

For further information, contact: A. Truman Schwartz (612) 696-6271
Department of Chemistry
Macalester College
St. Paul, MN 55105
Many individuals contributed their time and ideas to the work of the Project on Liberal Education and the Sciences. At every stage of the project, from the development of the grant proposal to the review of the final manuscript, representatives of the science, engineering, education, and other scholarly and professional communities unselfishly shared their knowledge, experience, and opinions with Project staff and Study Group members. Understandably, not all are in complete agreement with the entire report, but all are committed to the Project's goal to strengthen undergraduate education in the natural sciences. Their names are recorded here to acknowledge their contributions and commitment.
The work of the Project on Liberal Education and the Sciences was conducted with the financial and intellectual support of the Carnegie Corporation of New York. The idea for the project originated with Alden Dunham, Program Chair of Carnegie, who guided the development of the proposal and its implementation.

Advisory Board

Alphonse Buccino  
Dean, College of Education  
University of Georgia

Fletcher L. Byrom  
Chairman of the Board (Retired)  
Koppers Co., Inc.

John D. Caplan  
Executive Director (Retired)  
General Motors Research Laboratories

Johnnetta B. Cole  
President  
Spelman College

Stephen Jay Gould  
Alexander Agassiz Professor of Zoology  
Harvard University

Vera C. Rubin  
Department of Terrestrial Magnetism  
Carnegie Institution of Washington

Study Group

Study Group Members

C. Edward Buchwald  
Lloyd McBride Professor of Environmental Studies  
Department of Geology  
Carleton College

Rodger W. Bybee  
Associate Director  
Biological Sciences Curriculum Study

Nancy S. Cole  
Executive Vice President  
Educational Testing Service

Susan E. Cozzens  
Associate Professor  
Department of Science and Technology Studies  
Rensselaer Polytechnic Institute

David Crandall  
President  
The NETWORK, Inc.
Ed Dubinsky
Professor
Department of Mathematics
Department of Education
Purdue University

Barrett Hazeltine
Associate Dean of the College
Division of Engineering
Brown University

Norris S. Hetherington
Research Associate
Office for the History of Science and Technology
University of California, Berkeley

James Isen
Professor
Department of Psychology
Department of Radiation Biology and Biophysics
University of Rochester

Peter Machamer
Chairman and Professor
Department of History and Philosophy of Science
University of Pittsburgh

Diana Mariner
Professor
Department of Biochemistry
Michigan State University

John A. Moore
Professor Emeritus
Department of Biology
University of California, Riverside

John S. Rigden
Director of Physics Programs
American Institute of Physics

John I. Sandson*
Dean Emeritus
School of Medicine
Boston University

A. Truman Schwartz*
DeWitt Wallace Professor of Chemistry
Macalester College

Ethyle R. Wolfe*
Provost Emerita
Professor of Classics (Emerita)
Brooklyn College
City University of New York

Study Group Associates

Lynn Ewart* (B. Hazeltine)
Division of Engineering
Brown University

* Member of the Executive Committee of the Study Group
Bruce Hoffacker (E. Wolfe)
Assistant to the Provost
Brooklyn College
City University of New York

Susan Hojnacki (P. Machamer)
Department of Psychology
University of Pittsburgh

Marianne Miller (N. Hetherington)
Office for the History of Science and Technology
University of California, Berkeley

Patricia Morris (N. Cole)
Chairperson
Science Department
University of Illinois Curriculum Laboratory

Mona Moss (J. Rigden)
Research Assistant
American Institute of Physics

Devilyna L. Nichols (E. Dubinsky)
Department of Mathematics Education
Purdue University

David Patton (S. Cozzens)
Department of Science and Technology Studies
Rensselaer Polytechnic Institute

Peter Reich (J. Sandson)
Assistant to the Dean
School of Medicine
Boston University

Lisa Robinson (D. Marinez)
Assistant Professor
Lyman Briggs School
Michigan State University

Ken Shenkman (J. Ison)
Department of Psychology
University of Rochester

Stephen Shuster (J. Moore)
Department of Biology
University of California, Riverside

Norman Sperling (N. Hetherington)
Instructor
Department of Physics and Astronomy
Sonoma State University

Denice Winegar (A. Schwartz)
Science and Mathematics Teacher
St. Paul (MN) Public Schools

Project Staff

Audrey B. Champagne
Project Director

Barbara E. Lovitts
Project Associate
Betty J. Calinger
Administrative Associate

Gary E. Hammond
Project Secretary

Proposal to the Carnegie Corporation of New York

Franklin F. Flint
Randolph-Macon Woman's College

Kenneth W. Ford
The American Physical Society

Andrew Fraknoi
Astronomical Society of the Pacific

Robert Gowen
Dakota State College

John Layman
University of Maryland

Rita W. Peterson
University of California, Irvine

Jack M. Wilson
American Association of Physics Teachers

Report

James Adams
Stanford University

Richard N. L. Andrews
University of North Carolina at Chapel Hill

Helen H. Bacon
Barnard College

Thomas J. Baerwald
National Council for Geographic Education

Robert M. Berdahl
University of Illinois at Urbana-Champaign

Charles E. Bidwell
University of Chicago

Wayne W. Bishop
California State University at Los Angeles

Rolf K. Blank
Council of Chief State School Officers

Joseph Bordogna
University of Pennsylvania

Eleanor Brantley Schwartz
University of Missouri-Kansas City
Stephen G. Brush
University of Maryland

John D. Caplan
General Motors Research Laboratory

Jack L. Carter
The Colorado College

Larry D. Clark
University of Missouri-Columbia

William F. Coleman
Wellesley College

Raymond Coveney
University of Missouri-Kansas City

Glen A. Crosby
Washington State University

Lois B. DeFleur
University of Missouri-Columbia

Linda R. DeTure
National Association for Research in Science Teaching

Franklin F. Flint
Randolph-Macon Woman's College

William L. Flowers
Virginia Polytechnic Institute

Martin Frank
American Physiological Society

Anthony P. French
Massachusetts Institute of Technology

James D. Gates
National Council of Teachers of Mathematics

Carl J. George
Union College

Samuel Goldberg
Alfred P. Sloan Foundation

Joel E. Gordon
Amherst College

Joe Griffith
National Science Resources Center

Marilyn Haring-Hidore
University of Massachusetts at Amherst

Diana Hayman
College-University Resources Institute

John L. Heilbron
University of California, Berkeley
Ernest M. Henley
University of Washington

Robert B. Herschler
University of California, Riverside

Russell K. Hbbie
University of Minnesota

Roald Hoffman
Cornell University

Wendell G. Holladay
Vanderbilt University

Rachelle Hollander
National Science Foundation

Gerald Holton
Harvard University

David L. Hull
Northwestern University

Paul DeHart Hurd
Stanford University

Julia M. Jacobsen
Association of College and University Offices, Inc.

William A. Jensen
The Ohio State University

Gladys Johnston
Arizona State University

E. C. Keller, Jr.
Foundation for Science and the Handicapped

Judith A. Kelley
University of Lowell

Arthur H. Kibbe
American Pharmaceutical Association

John C. Kotz
State University of New York at Oneonta

Harry Lawton
University of California, Riverside

William H. Leonard
National Association of Biology Teachers

Judith Lisansky
American Anthropological Association

Jerod M. Loeb
American Medical Association

Sheilah Mann
American Political Science Association
William B. Martin
Union College

Stephen B. Maurer
Swarthmore College

Ernan McMullin
University of Notre Dame

Sherman M. Mellinkoff
University of California, Los Angeles

Richard D. Miller
American Association of School Administrators

W. R. Miller
University of Missouri-Columbia

Donald W. Mocker
University of Missouri-Kansas City

Thomas F. Moore
Winthrop College

Allison R. Palmer
Geological Society of America

David W. Pratt
University of Pittsburgh

Anthony Ralston
State University of New York at Buffalo

Samuel M. Rankin, III
Worcester Polytechnic Institute

James Raths
University of Vermont

Robert A. Rescorla
University of Pennsylvania

David R. Reyes-Guerra
Accreditation Board for Engineering and Technology, Inc.

Jerry Robbins
Georgia State University

Alex Roland
Society for the History of Technology

M. L. Rosenthal
New York University

Vera C. Rubin
Carnegie Institution of Washington

Barbara W. Saigo
University of Northern Iowa

Klaus Schultz
University of Massachusetts at Amherst
Ruth Selig  
Smithsonian Institution

Thomas A. Shannon  
National School Board Association

Ruth I. Shirey  
National Council for Geographic Education

Max Skidmore  
University of Missouri-Kansas City

Gerald Skoog  
Texas Tech University

Gerald E. Sroufe  
American Educational Research Association

Rudolf A. Stampfl  
Institute of Electrical and Electronics Engineers, Inc.

Scott D. Thomson  
National Association of Secondary School Principals

Steven S. Tigner  
American Philosophical Association

Sheila Tobias  
University of Arizona

John G. Truxal  
State University of New York at Stony Brook

Irwin M. Wall  
University of California, Riverside

Frank H. Westheimer  
Harvard University

F. Karl Willenbrock  
American Society for Engineering Education

Alfred Wohlpart  
Oak Ridge Associated Universities

---

Acoustical Society of America  
Logan Hargrove

American Anthropological Association  
Melody Curtis  
Judith Lisansky

American Association of Colleges  
Joseph Johnston  
Jane Spaulding

American Association of Colleges for Teacher Education  
David Imig
American Association of Colleges of Pharmacy
Carl Trinca

American Association of Community and Junior Colleges
Carol Cross
Dale Parnell

American Association of Petroleum Geologists
Robert C. Millsbaugh

American Association of Physics Teachers
Jack M. Wilson

American Association of School Administrators
Herman R. Goldberg
Richard D. Miller

American Association of University Professors
Robert Kreiser

American Chemical Society
Sylvia A. Ware

American Dairy Science Association
Donald Barth
L. D. Miller

American Educational Research Association
Laurie Gardueke

American Institute of Biological Sciences
Franklin F. Flint

American Institute of Physics
Lewis Slack

American Medical Association
M. Roy Schwarz

American Meteorological Society
David Houghton

American Nature Study Society
John J. Padalino

American Nuclear Society
Gilbert J. Brown

American Philosophical Association
Steven S. Tigner

American Physical Society
Brian B. Schwartz

American Physiological Society
Martin Frank

American Phytopathological Society
Anne K. Vidaver

American Political Science Association
Sheilah Mann
American Psychological Association
Ira Cohen
Vivian Parker Makosky
Genevieve Whittemore

American Society for Engineering Education
F. Karl Willenbrock

American Society for Microbiology
Helen Bishop
Sharon Zablotney

American Sociological Association
Bettina Huber

American Statistical Association
Sheila Edwards
Jill Stormer

Association for Women in Science
Barbara Filner
Diana M. Tycer

Association of American Geographers
Robert Aangeebrug

Association of College and University Offices, Inc.
Julia M. Jacobsen

Astronomical Society of the Pacific
Andrew Fraknoi

Council of Chief State School Officers
Gordon M. Ambach
Rolf K. Blank

Foundation for Science and the Handicapped
E. C. Keller, Jr.

Geological Society of America
Allison R. Palmer

Institute of Electrical and Electronics Engineers, Inc.
Rudolf A. Stampfl

Mathematical Association of America
Alfred B. Willcox

National Association for Research in Science Teaching
Linda DeTure

National Association of Biology Teachers
William Leonard
Patricia J. McWethy

National Association of Elementary School Principals
Romaine B. Thomas

National Association of Geology Teachers
N. Dane Pickard

National Association of Secondary School Principals
Scott D. Thomson
Advisors and Consultants

AAAS Section Officers and Members

Those who served as Chairs and Secretaries of the AAAS Sections from 1987 through 1990 were a continuous source of advice and criticism. Many Chairs and Secretaries attended the Inaugural Meeting and a Project meeting at the 1988 AAAS Annual Meeting in Boston, MA.

Inaugural Meeting

The Project on Liberal Education and the Sciences made its public debut at a conference attended by over 150 people on 12–13 June 1987. The purpose of the conference was to define and discuss critical issues pertaining to science and liberal education and to garner advice on how to proceed with the project. While all who attended made important contributions and deserve recognition, only the speakers and moderators are listed here.

Joseph Bordogna
University of Pennsylvania
Hamilton Davis  
University of Vermont

Harold Dorn  
Stevens Institute of Technology

Mildred Dresselhaus  
Massachusetts Institute of Technology

Edward Friedman  
Stevens Institute of Technology

Steven L. Goldman  
Lehigh University

James H. Grant  
Wellesley College

John L. Heilbron  
University of California, Berkeley

H. Craig Heller  
Stanford University

E. D. Hirsch, Jr.  
University of Virginia

Art Hobson  
University of Arkansas

Helen M. McCammon  
U.S. Department of Energy

Kathryn Olesko  
Georgetown University

Robert J. Richards  
The University of Chicago

B. William Shragge, MD  
McMaster University

John G. Truxal  
State University of New York at Stony Brook

Sylvia Ware  
American Chemical Society

Edward J. Woodhouse  
Rensselaer Polytechnic Institute

**Ad hoc Consultants and Reviewers**

Glen Aikenhead  
University of Saskatchewan

John C. Angus  
Case Western Reserve University

Ed Barry  
Montana State University
Sylvia Bozeman  
Spelman College

Dineh Davis  
Bentley College

Paul Di Virgilio  
Hofstra University

Russell Y. Garth  
Council of Independent Colleges

Claire Gaudiani  
University of Pennsylvania

Joseph R. Herkert  
Lafayette College

Peter Heywood  
Brown University

Fred Horne  
Oregon State University

Eugene Kemp  
West Virginia University

Walter R. Lynn  
Cornell University

Pamela Mack  
Clemson University

Robert March  
University of Wisconsin

Mike McCormack  
McCormack Associates, Inc.

Robert McGinn  
Stanford University

James J. Murphy  
Iona College

Alan Nagel  
The University of Iowa

John Opie  
New Jersey Institute of Technology

Robert J. Richards  
The University of Chicago

Joseph T. Rouse  
Wesleyan University

Brian B. Schwartz  
American Physical Society

Jerry Stannard  
University of Kansas
Leon Trachtman
Purdue University

Frank Vellaccio
College of the Holy Cross

Marian Visich, Jr.
State University of New York at Stony Brook

Rudi Volli
Pitzer College

Leonard Waks
The Pennsylvania State University

D. M. Warren
Iowa State University

Laurence Wiseman
College of William and Mary

John Wright
American Association of State Colleges and Universities

Robert E. Yager
The University of Iowa

F. James Rutherford
Chief Education Officer and
Director, Project 2061

Shirley M. Malcom
Head, Directorate for Education and
Human Resources Programs

Andrew Ahlgren

Walter Gillespie

Gerald Kulm

Patricia S. Warren

Audrey Pendergast, Editor

Karen Winget, Production Manager

Carol Conway Leigh, Cover Design