Interdisciplinary Research: Promoting Collaboration Between the Life Sciences and Medicine and the Physical Sciences and Engineering

DETAILS

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Interdisciplinary Research

Promoting Collaboration Between the Life Sciences and Medicine and the Physical Sciences and Engineering

Committee on Promoting Research Collaboration

Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

Division of Health Sciences Policy
Institute of Medicine

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Foreword

This report is the product of a joint activity of the Institute of Medicine's Division of Health Sciences Policy and the Board on Physics and Astronomy of the National Research Council's Commission on Physical Sciences, Mathematics, and Resources. The study arose out of the strong sense in both the division and the board that enormous opportunities were being missed at the interface of the life sciences and medicine and the physical sciences and engineering. One of the reasons was seen as a lack of communication between the different cultures. The cultures of the physical sciences, engineering, biology, and medicine are characterized by different approaches to problem solving, ways to array data, and use of technical language and mathematics. The problem is how to facilitate communication between these different communities and possibly develop an interdisciplinary hybrid that would serve their needs. Concepts and insights gained in one field could be very helpful to researchers in another field, if they were aware of such advances.

A working group was convened to consider, among other things, changes in the educational system—perhaps back at a point before people become differentiated into engineers or doctors—to give students enough in the way of intellectual resources so that, no matter which specialty they choose, they will have some understanding of the culture and language of the other group. This requires tremendous changes in the way institutions are organized. Even within the life sciences it is hard to achieve communication between departments, let alone across broad disciplines and schools. Nonetheless, the opportunities for real advantages are great.

In response to the recommendations of the working group, a committee was formed of individuals who work at these disciplinary interfaces, are concerned about how to make the communications occur, and have ideas about how to facilitate interdisciplinary research programs. The committee identified the general, institutional, educational, financial, and communication factors needed to create an analytical framework for understanding the problems and successes of individuals and groups who conduct interdisciplinary research. At their first meeting, the committee members discussed their own experiences and observations; in two subsequent meetings they heard from a wide range of speakers. From the presentations and discussions, a view of the practitioners emerged. The committee formulated a means of practically reducing barriers to interdisciplinary research collaboration and came up with specific proposals to facilitate communication and exchange.

I am optimistic that the recommendations in this report will encourage the implementation of interdisciplinary programs. I thank the committee for its work and the National Research Council and the Whitaker Foundation for supporting it.

Samuel O. Thier
President
Institute of Medicine

Preface

In the early 1970s, the Committee on Science Policy for Medicine and Health of the Institute of Medicine (IOM) became interested in interdisciplinary research collaboration between the life sciences and medicine and the physical sciences (which for the purpose of this report include mathematics and computer science) and engineering. Later the topic was maintained on a list of priorities for the IOM Board on Health Sciences Policy. In the early 1980s, Enriqueta Bond, executive director of the IOM and then director of the Board on Health Sciences Policy, and Donald C. Shapero, staff director of the National Research Council's Board on Physics and Astronomy, proposed a study of the factors that facilitate or inhibit interdisciplinary interactions between the physical sciences and medicine. To plan such a study they arranged a program initiation meeting on interdisciplinary collaboration.

The Working Group on Interdisciplinary Collaboration met at the National Academy of Sciences building in Washington, D.C., on July 8, 1983, and was chaired by Robert W. Mann, Whitaker Professor of Biomedical Engineering, Massachusetts Institute of Technology. Other participants at the meeting included physicists, engineers, physicians, and behavioral scientists (the roster is given in Appendix A). The meeting led to a formal proposal for a joint IOM-National Research Council study entitled "Promoting Research Collaboration: Physical-Engineering Sciences and Biological-Clinical Sciences." This proposal recommended that an examination of interdisciplinary research between the physical sciences and engineering, on the one hand, and the biological and medical sciences, on the other, be accorded high priority. The proposal also recommended the formation of a joint IOM-National Research Council study committee to produce a report that would "address (a) the rationale for, and benefits of, interdisciplinary research, (b) factors that promote successful interdisciplinary collaboration among physical scientists/engineers and life scientists, clinical researchers, and (c) policy strategies for promoting interdisciplinary research."

Another impetus for the formation of the Committee on Promoting Research Collaboration was a meeting in the early 1980s between George Keyworth, III, science advisor to the President, and Herbert Friedman, then chairman of the Commission on Physical Sciences, Mathematics, and Resources of the National Research Council, who both recognized the national importance of fruitful interactions between the physical sciences and medicine and the need to facilitate these connections.

The recommendations of the Working Group on Interdisciplinary Collaboration were presented to the presidents of the National Academy of Sciences (NAS), the National Academy of Engineering (NAE), and the IOM, who decided at a meeting on November 20, 1986, to provide financial support for the formation and activities of such a committee. The Whitaker Foundation provided additional support for the study.

To guide the work of the Committee on Promoting Research Collaboration, S. James Adelstein, Professor of Radiology and Dean for Academic Programs, Harvard Medical School, and George B. Benedek, Alfred H. Caspary Professor of Physics and Biological Physics, Massachusetts Institute of Technology, were appointed in June 1987 to serve as co-chairs. A group was constituted of distinguished physical scientists, engineers, biologists, and physicians. The Committee on Promoting Research Collaboration first met at the National Academy of Sciences building on September 21, 1987. At this meeting the basic plan for guiding committee work was formulated as a distillation of the individual scientific experiences presented by the various committee members in their pursuit of interdisciplinary research.

At its second meeting, held on May 25-26, 1988, the committee heard presentations from representatives of the National Institutes of Health and the National Science Foundation on the response of federal funding agencies to interdisciplinary research proposals (see Appendix B, summary agenda). The committee also received reports on interdisciplinary university training and research programs, the role of research centers such as those in the national laboratories and in universities, and the role of U.S. industries and the industrial-academic interface in facilitating interdisciplinary interactions.

The third meeting of the committee was held on December 15-16, 1988 (see Appendix C), and was conducted as a workshop with short lectures by invited speakers, followed by commentary and further development of the themes by discussants. The topics at this workshop were the development of federal policy, the academic-industrial interface, the role of private foundations, and the role of university and teaching hospital structures in facilitating interdisciplinary research. The committee also heard specific case histories of successful biomedical engineering and device development programs and of the successful utilization of mathematical and physical principles in biology and medicine.

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Executive Summary

Scientific and technological developments in diagnostic instrumentation, medical devices, rational drug design, and synthetic and genetically engineered biological materials, combined with the intellectual tools of quantitative and computer-assisted mathematical analysis, have ushered in a revolution in our ability to understand biological systems and to detect and treat disease. Consideration of the factors that produced these advances shows that a flow of knowledge, inventions, and gifted individuals across conventional academic and industrial boundaries is essential for success, yet such interchange has often been painfully slow.

It is clear that the progress seen so far is but the leading edge of a far greater change that could have profound effects not only on the practice of clinical medicine and surgery and on disease prevention and health, but also on the strength of our industrial economy in areas such as pharmaceuticals, biotechnology, and medical devices. In addition it is apparent that the fulfillment of major national responsibilities such as environmental protection and food and drug regulation requires people trained in, and knowledge bases for, interdisciplinary science and technology.

Thus in the early 1980s a working group was created to study the national importance of fruitful interactions between the physical sciences and medicine and the means by which collaborative research between these disciplines could be facilitated. On the working group's recommendation, the Division of Health Sciences Policy of the Institute of Medicine and the Board on Physics and Astronomy of the National Research Council's Commission on Physical Sciences, Mathematics, and Resources convened a committee of distinguished scientists with the charge to "address (a) the rationale for, and benefits of, interdisciplinary research, (b) factors that promote successful interdisciplinary collaboration among physical scientists/engineers and life scientists, clinical researchers, and (c) policy strategies for promoting interdisciplinary research."

The committee acknowledged the growing awareness in science policy circles of the need to create mechanisms within universities, government, and industry to facilitate a flow of knowledge and researchers across the interfaces of the physical sciences (which for the purpose of this report include mathematics and computer science) and engineering, on the one hand, and the life sciences and medicine, on the other. The committee also noted the perceived urgency of this need, as reflected in a number of carefully considered and well-documented recent reports (see Chapter 1) that have endorsed actions to reduce or remove obstacles to fruitful collaborative research across traditional disciplines.

The committee used hearings, interviews, and workshops to draw on the collective experience of committee members and invited participants, representing many years of personal activities in interdisciplinary research. In addition, the committee evaluated responses to its selective national survey of interdisciplinary research programs in biophysics and bioengineering.

FINDINGS

The committee recognized two different motivations for collaborative research: (1) the desire to increase understanding of natural phenomena and (2) the need to provide practical benefits. The relative extent to which these two motivations stimulate collaborators depends on the nature of the research. In the successful promotion of research collaboration, the following critical elements were identified: administrative and institutional support, availability of adequate funding, open communication and collegiality, overlapping educational experience, availability of collaborators, and opportunities for practical application and technology transfer. The committee examined successful programs to learn the mechanisms of their success and discovered that key factors included a strong leader or champion and lack of egocentrism on the part of collaborators.

Ideally, interdisciplinary research involves the active cooperation of scientists with diverse but relevant backgrounds who contribute their individual talents and expertise to addressing complex problems of mutual interest. Specifically, the quantitative, analytical approaches of physical scientists and engineers can contribute greatly to both basic and clinical research on living systems. Conversely, the career opportunities of physical scientists and engineers are extended and enriched when they include the life sciences and medicine in their scope (for example, biomedical engineers and radiological and medical physicists). Indeed, the motivation to produce knowledge that directly benefits human health and well-being often stimulates creative interactions between researchers in the physical sciences and engineering and in the life sciences and medicine. Many individual and organizational factors can facilitate such cross-cultural communication and collaboration.

Members of research and development teams can derive both professional rewards and personal satisfaction from collaborative work on problems of biology and medicine. However, individuals must benefit in tangible and significant ways if their cooperation is to remain active and enthusiastic. Each participant should be treated as an equal partner in an enterprise, and all contributions need to be fully recognized. Collaborative research flourishes in academic environments with a free flow of communication and active interdepartmental programs that are recognized and encouraged by faculty peers and institutional administrators. In addition, successful collaboration requires some extra effort from individual researchers, who often must adapt to unfamiliar scientific cultures and overcome impediments imposed by specialized scientific language and jargon as well as by differences in academic traditions, budgetary priorities, sources of funding, and approaches to research among the relevant disciplines.

RECOMMENDATIONS

Universities and Teaching Hospitals

The committee identified two important requirements for universities and affiliated teaching hospitals as sites for interdisciplinary collaborative research: (1) adequate administrative support and (2) effective organization of the faculty.

Administrative support can be financial, especially for short-term exploratory collaborations that may hold the promise of achieving external funding and prompt technology transfer. Administration policy should also promote interactions among ordinarily discrete organizations within universities and hospitals. The appointment of a high-ranking academic administrator with interdisciplinary collaborative research experience to champion these interactions is recommended.

Faculty organization to conduct collaborative research can take several forms. One incorporates interdisciplinary research into relevant preexisting department(s), in part by creating categorical appointments in cross-disciplinary fields. Another gathers faculty into one department representing the relevant cross-disciplinary expertise. Alternatively, integration may be achieved by setting up organized research units with titles (e.g., "center") that distinguish them from traditional departments. The committee strongly recommends that when an organized research unit is established to foster interdisciplinary collaboration, it should carry an institutional commitment of space, money, and positions.

Academic-Industrial Relations

The creation of effective mechanisms for the flow of knowledge and inventions between the academic community and industry is becoming an important factor in funding for university research and in improving the competitiveness of U.S. businesses in biotechnology, medical devices, and pharmaceuticals. Thus, academic-industrial interaction has become a significant stimulus for interdisciplinary research.

The importance of several issues in collaborative interactions between academic institutions (universities and teaching hospitals) and industry should be emphasized, including preservation of academic initiatives and educational missions, mutual understanding regarding publication of research findings and results of collaboration with other scientific colleagues, proper balance between consulting and/or entrepreneurial activity and academic responsibilities, establishment of policies and procedures to avoid conflicts of interest, and clarification of patent and licensing policies that apply to the ownership of intellectual property.

To facilitate collaborative research and technology transfer between academic institutions and industry, the committee recommends identification of facilitators and the establishment of (1) academic-industrial liaison programs whose activities are regularly reviewed by high-level academic administrators and (2) technology licensing offices that secure patent protection and facilitate industrial licensing of these patents in accordance with clearly established guidelines.

Federal Funding Agencies

The National Science Foundation

The committee noted considerable sensitivity and concern at the National Science Foundation (NSF) about the importance of interdisciplinary collaborative research for the progress of U.S. science and technology. Several new interdisciplinary initiatives have been started, for example, the NSF science and technology research centers, which are potential sites for the promotion of interdisciplinary research in selected fields. The committee recommends a parallel initiative to encourage joint proposals between life scientists and physical scientists and to establish procedures for judging the scientific merit of such proposals. In addition, the committee recommends that mechanisms be established for funding such proposals and that a decision-making process involving directorate-level management be instituted to seek qualified reviewers and to appraise reviews. Furthermore, funds need to be allocated for (1) cross-disciplinary postdoctoral appointments[1] and (2) special cross-directorate sabbatical leave programs aimed at established researchers who wish to become educated in a new discipline.

The National Institutes of Health

The utilization of engineering and physical sciences expertise at many different levels is necessary for the National Institutes of Health (NIH) to accomplish its mandate to improve the nation's health. Nonetheless, it appears difficult for physical scientists to obtain NIH support partly because the organization of the NIH into study sections and institutes, often devoted to specific diseases and organs, does not naturally encourage interdisciplinary proposals directed toward a broad-based, integrated understanding of living phenomena. Study sections are inherently conservative and are unlikely to be enthusiastic about proposals that do not fit neatly into the current structure. The Human Genome Project is one exception that has explicitly solicited interdisciplinary proposals and established special study sections for their evaluation.

The committee recommends that (1) the NIH create two new study sections or joint operational units of existing sections, one of which would specialize in proposals for instrumentation and materials development and the other in proposals for the applications of analytic methods in the physical sciences to the life sciences and medicine, and (2) that the NIH consider a new budget category—either by adding to an existing institute or by establishing a new entity—that would stimulate interactions between life scientists and physical scientists.[2]

The committee recommends that the NSF and the NIH jointly establish a working group of high-level administrators from the two agencies with a charge to recommend mechanisms for interagency cooperation that will diminish existing barriers to collaboration between their scientific constituencies.

The Department of Energy and Its National Laboratories

The committee recognizes the special niche occupied by the national laboratories in providing unique facilities to some biomedical research scientists and their colleagues in the physical sciences. Moreover, much of the goal-oriented research of the Department of Energy (DOE) is conducive to the formation of interdisciplinary research teams. In view of the increasing importance of advanced radiation sources and computational facilities for progress in structural and molecular biology, the committee urges the DOE to remain sensitive to its continuing role in advancing the life and medical sciences. Furthermore, the committee recommends that the DOE regularize its support for graduate students and postdoctoral fellows seeking interdisciplinary experience. The committee also supports initiatives to transfer technology from DOE facilities to the private sector.

Private Foundations

Because of their flexibility, private foundations are uniquely able to foster interdisciplinary research by supporting individuals in new, untried ventures with the goal of defining and unifying such ventures for subsequent development under a more institutionalized format. Private foundation support can particularly benefit the first independent efforts of young collaborating researchers. It can also stimulate emerging areas of interdisciplinary research by funding research fellowships and awards for graduate students and for junior faculty. Foundations also can encourage both junior and senior faculty to enter into interdisciplinary research by providing sabbatical leave awards and establishing endowments and academic chairs.

The committee recommends that private foundations support centers at selected academic institutions. The committee suggests that foundations work closely with academic institutions so that the initial investment is leveraged to encourage the further development of such centers. Private foundations can also support interdisciplinary research by helping to construct physical facilities, a contribution especially important in view of the current decline of federal building programs. The committee recommends that foundations with modest resources contribute funds for interdisciplinary study groups, workshops, summer schools, and seminars that will help to encourage collaboration and interdisciplinary research. Finally, the committee recommends that private foundations take the opportunity afforded by these mechanisms to encourage, define, and unify interdisciplinary research programs.

NOTES

1. In October 1989 the NSF announced the establishment of a new $4 million Research Training Grant Award to stimulate interdisciplinary research in ten U.S. universities.

2. In September 1989 the NIH, through the National Institute of General Medical Sciences, announced the Lawton Chiles Fellowships program, a $2.8 million cross-disciplinary training program for applications of the physical sciences and engineering to biotechnology.

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Rationale for the Report

Scientific and technological developments in diagnostic instrumentation, medical devices, rational drug design, and synthetic and genetically engineered biological materials, combined with the intellectual tools of quantitative and computer-assisted mathematical analysis, have ushered in a revolution in our ability to understand biological systems and to detect and treat disease. Consideration of the factors that produced these advances shows that a flow of knowledge, inventions, and gifted individuals across conventional academic and industrial boundaries is essential for success, yet such interchange has often been painfully slow.

It is clear that the progress seen so far is only the leading edge of a far greater change that could have profound effects not only on the practice of clinical medicine and surgery and on disease prevention and health, but also on the strength of our industrial economy in areas such as pharmaceuticals, biotechnology, and medical devices. In addition it is apparent that the fulfillment of major national responsibilities such as environmental protection and food and drug regulation requires people trained in, and knowledge bases for, interdisciplinary science and technology.

Diagnostic imaging is a paradigm of what may be accomplished when the physical sciences, engineering, and medicine interact. The means of imaging used—x-rays, photons from artificial radionuclides, piezoelectrically produced ultrasound, and microwaves—were discovered and created by physicists. The detectors—sodium iodide and other crystals, phototubes, transducer arrays, and tuned resonance coils—are products of experimental physics. The instrumentation relies on components of modern electronic circuitry; image reconstruction relies on algorithm development, mathematical analysis, and computational mathematics. Following Wilhelm Roentgen's first report (to a medical society) of his discovery of x-rays, the development of diagnostic imaging has been characterized by communication between physical scientists and physicians and by the rapid transfer of the technology to the industrial sector, for the benefit of the sick and suffering as well as the world economy.

CONTEMPORARY REPORTS BEARING ON THE WORK OF THIS COMMITTEE

The committee acknowledged the growing awareness in science policy circles of the need to create within universities, government, and industry mechanisms to facilitate a flow of knowledge and researchers across the interfaces of the physical sciences and engineering, on the one

TABLE 1.1 Examples of Interdisciplinary Advances Resulting from the Collaboration of Life and Medical Scientists with Physical Scientists and Engineers

Scientific Area	Interdisciplinary Advance
Imaging in clinical medicine and surgery	Computer-assisted tomography using x-rays
	Nuclear magnetic resonance imaging
	Positron emission tomography
	Ultrasonic imaging
	Fiber-optic endoscopy
	Mammography
	Magnetoencephalography
Quantitative clinical diagnosis	Radioimmunoassay
	Enzyme-linked immunoassay (ELISA)
	Latex-based optical immunoassay
	Automatic analyzers for blood chemistry
	Vector electrocardiography
Physiological sensors and systems physiology	Cardiovascular flow dynamics
	Tribology (study of friction and lubrication) of synovial joints
	Musculoskeletal modeling
	Electrophysiology of the heart
	Neural networks
	Feedback and control of ventilation
	Fiber-optic temperature and radiation dose sensors
Medical and surgical devices and methods	Cardiac pacemakers
	Defibrillators
	Laser surgery
	High-voltage and particle radiotherapy
	Transluminal angioplasty
	Renal dialysis
	Lithotripsy
	Heart-lung machines
Synthetic biomaterials and artificial organs	Artificial heart valves and blood vessels
	Intraocular lenses
	Neural prostheses
	Polymers for controlled drug delivery
	Hip joints
	Dental materials
	Synthetic and artificial skin

TABLE 1.1 *Continued*

Scientific Area	Interdisciplinary Advance
Imaging of biological structures and biomaterials	Electron, x-ray, and tunneling microscopy Computerized x-ray crystallography Neutron and synchrotron radiation scattering Radionuclide labeling Chromophore-bound monoclonal antibodies
Quantitative characterization of structure and metabolic products of biological molecules	Gel chromatography and electrophoresis Ultracentrifugation Quasi-elastic light scattering Raman, fluorescent, and infrared spectroscopy High-resolution nuclear magnetic resonance Mass spectrometry
Quantitative analyses of biological processes	Bacterial motility and chemotaxis Mathematics of DNA unfolding Molecular basis of photosynthesis Photodetection in the retina Molecular basis of cataract disease Theory of control of enzyme activity
Pharmacology and biotechnology	Computer-assisted rational drug design Biocatalysis Bioreactor design Separation technology Electrodialysis Affinity column chromatography Bioprocess control and instrumentation Flow cytometry
Molecular biology	Computer databases of nucleotide and amino acid sequences Algorithms for detecting sequence similarities and constructing phylogenetic relationships

hand, and the life sciences and medicine, on the other. The urgency of this need is reflected in the relatively recent appearance of a number of carefully considered and well-documented reports bearing on this problem.[1-8]

These reports identify successful examples of interdisciplinary research and point to promising directions for future advances. They also recognize and spell out the substantial institutional and personal obstacles within universities, funding agencies, professional societies, and the academic profession itself that inhibit fruitful interactions across traditional disciplines. Finally, they make recommendations designed to reduce or remove these obstacles.

In view of the resistance that exists within those very institutions whose participation is needed, the committee presents a compilation of successful advances made as a result of the flow of knowledge, invention, and individuals across the boundaries that separate the physical sciences and engineering from the life sciences and medicine (Table 1.1). Computer and information sciences can be credited with a multidisciplinary role in many of these. The listing of examples in Table 1.1, albeit incomplete, demonstrates quite clearly that activity at the interfaces studied by this committee is of crucial importance to advances in the life sciences and the practice of medicine as well as to the strength of our industrial base in both medical technology and biotechnology.

NOTES

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Factors That Facilitate and Impede Collaborative Research

The potential for collaborative research is particularly great between the traditionally quantitative sciences (chemistry, physics, engineering, and mathematics) and the traditionally descriptive ones (biology, physiology, and medicine). Chemistry has a natural connection to the life sciences and medicine through the flourishing discipline of biochemistry. Physics has an entree into the biological and physiological research communities through the application of common and comprehensible physical principles and measurements that contribute to our functional understanding of living matter. Engineering enters through the development of instrumentation and methods for measurement in biology and medicine. Also, mathematical and computational techniques (and therefore computer science) are increasingly important for interpreting observations through a wide range of scales, for example, from understanding the topology and geometry of the molecules of living matter to imaging skeletal systems, tissues, and organs using the techniques of three-dimensional image reconstruction.

But at every level there are barriers to collaboration, barriers that impede understanding of the nature of living matter and inhibit the means to provide practical benefits. The traditional scientific disciplines are conservative and form separate communities. Universities reflect and encourage this separation by organizing teaching and research through these traditional disciplines.[1] Philosopher of science Thomas Kuhn has argued that a discipline, once established, acquires an organizational structure that exerts political influence to maintain itself.[2] The funding agencies naturally organize themselves along disciplinary and program lines, and, depending on the agency, this organizational structure may discourage new initiatives.

Beyond these institutional impediments, substantive intellectual obstacles also hinder the analytic understanding of biological systems, which have developed through an evolutionary process and represent, to a large extent, frozen accidents of history. A biological system works, and we may seek to understand or assist its function using principles obtained from physics, chemistry, or mathematics, but we cannot expect that such a system will be logically simple or that its structure can be deduced from a general law of nature. Understanding the actions of real biological systems within an analytical framework requires sufficient quantitative data bearing on the underlying molecular and cellular mechanisms. Often only some of the needed data are available for biological systems. Indeed, one of the useful features of an analytical theory is its ability to suggest relevant experiments, which together with evolving theory can lead to a fuller understanding of the modes of action of these "frozen accidents."

Clearly one must also recognize the obstacles created by the cultural imperatives of each of the traditional scientific disciplines. Each of these disciplines emphasizes different elements in the spectrum of cognitive skills.[3] For example, the physical sciences and engineering focus on analysis, whereas the life and health sciences communities stress observation and evaluation.

To realize the potential of collaborative research, bridges must be built between the traditional disciplines at all educational levels, bridges that preserve the demands of intellectual rigor and clarity yet also value the contributions of diverse cognitive skills. The committee presents the following expressions of the need to establish connections between disciplines:

> [Engineering-Medicine] Future medical technology will increasingly require more fundamental understanding at the organ, cell, and subcellular levels, and it will be based on collaborative biological and physical science research. . . Such non-parochial research is not likely to be done anywhere but in a university setting, but even here traditional department organisation frequently impedes the essential collaboration among persons skilled in their respective realms.
>
> Even more disturbing to this observer is the accelerating trend toward biological research focusing heavily, if not exclusively, at the molecular level. Physics has traditionally taken a reductionist view of science, and biologists are following that pathway—admittedly with great success. Left vacant, however, are vast research areas of interest and promise at the subcellular, cellular, and organ levels where neither biologists nor physicists and engineers alone are well equipped to frame and address important questions.[4] [Life scientists have been criticized for not integrating molecular biology into systems biology. One reflection of this is diminished support for clinical investigations.[5] The interface between molecular/cellular and systems biology promises to be highly productive, and more physicians and biologists need to take on this challenge.]

> [Biology-Physics] The magnificent complexity of life that we study as biology reflects ultimately the underlying principles of physics. The goal of biological physics is understanding of this physical basis of biology along all the complex pathways from atomic and nuclear physics, quantum mechanics and statistical physics, through the biopolymers (proteins and genes) and supramolecular structures to individual cells, and finally to the behavior of organisms. Biological physics comprises both applications of physics and fundamental problems in physics at the interface between physics and biology.
>
> Biophysics serves mankind through its part in all applied biological sciences and through medical physics. (Medical physics is . . . [considered] as an application of physics, whereas biological physics is [considered] as an interscience interface because the present scientific trends and orientations of these two related fields are quite different.) Today's biophysics anticipates tomorrow's medical physics with a trend from large-scale diagnostic imaging to probes of cellular and molecular-scale processes.[6]

Revealed in these assertions are two different motivations for collaborative research: (1) to increase understanding of natural phenomena and (2) to provide practical benefits. Depending on the kind of problem addressed, the two motivations may be present in differing degrees in scientific and engineering research. Reynolds[7] has defined three kinds of multidisciplinary problems, which, in terms of intellectual motivation, might be paraphrased as follows:

1. Problems of the first kind: Philosophical questions that constitute the foundations of traditional disciplines and are motivated by a quest for understanding nature. The application of analytical physical science to understand a fundamental biological phenomenon, such as the determination of the three-dimensional structure of DNA using crystallographic methods, is an example.

2. Problems of the second kind: Applied problems that are more practical than philosophical but that often involve concepts from more than one traditional discipline. An example might be the development of instruments directed toward specific biological and medical problems.

3. Problems of the third kind: Tasks or services often distinctively multidisciplinary in content and leading to the delivery of a product or technique. The production and surgical use of an artificial joint made of a new biosynthetic material is an example.

There often are no sharp boundaries between these kinds of problems. Fostering effective collaborative research requires first delineating the intellectual questions that can be answered, then developing motivations among potential collaborators, and finally reaching mutual agreement on the kind(s) of problem(s) to be undertaken.

Symptomatic of the critical practical barriers to promoting collaborative research is the decision-making process for funding research. Intellectual, administrative, and institutional gaps between traditional disciplines are mirrored in the composition of peer review groups that determine funding. This is most evident in the organization of current federal funding systems. For example, H. E. Morgan raises the question of the definition of a peer in cross-disciplinary research. He asks, "Is a peer a person knowledgeable primarily in the technical aspects of the approach that is to be applied, or is both technical expertise and a broad knowledge of the field encompassed by the hypothesis and questions to be addressed also a requirement for designation as a peer?"[8] Citing studies of peer review of interdisciplinary research, he concludes that ". . . cross-disciplinary (research proposals) involving application of new basic technologies to physiological problems suffer from malfunction of the dual-review system and the lack of expansion of the expertise of established Study Sections to new and important research areas. These problems must be solved to allow physiologists seeking the molecular mechanisms of physiological events to receive support for their research."[8]

CRITICAL ELEMENTS IN PROMOTING RESEARCH COLLABORATION

The committee, through its hearings, survey, interviews, and workshop, identified certain critical elements needed to promote interdisciplinary research. These included the following:

- administrative and institutional support;
- availability of adequate funding;
- open communication and collegiality;
- overlapping educational experience;
- availability of collaborators; and
- opportunities for practical application and technology transfer.

Each of these elements is worthy of some elaboration.

Administrative and Institutional Support

The role of institutions in supporting collaborative research endeavors cannot be overestimated. Some research facilities, such as the national laboratories supported by the Department of Energy, have collaborative research built into their missions. Others need to make specific commitments if they wish to see interdisciplinary activities pursued. Chapter 3 describes mechanisms for university and teaching hospital support of such endeavors.

Institutional support is required at several levels. If meaningful collaboration is to be established, it certainly must be encouraged in university and hospital departments and divisions. A member of this committee reported that he furtively attended physiology lectures, because excursions outside his parent field were considered to be of little intellectual value. One invited speaker, a leading academic administrator from the physical sciences, told this committee that few, if any, current physics departments would recruit anyone in medical or biological physics, these areas being far from the mainstream of current physics interest. Clearly, such thinking is a barrier to junior faculty members, who might find academic advancement difficult, and a discouragement to senior members, who might face the ridicule of colleagues.

Administrators of universities and medical schools also need to give their approval to interdisciplinary research efforts. Indeed, encouragement needs to be built into the fabric of national science policy as expressed by the Congress, the executive departments, the agencies, and advisory groups.

Availability of Adequate Funding

The committee found from the survey that it sent to biophysics and biomedical engineering departments that nearly all of the respondents stressed the importance of making funds available for the express purpose of promoting interdisciplinary collaborative research.

Home institutions can provide seed funding to bring investigators together to explore problems of mutual concern, to develop research proposals when programs are partially formulated, and, most importantly, to furnish enough funding for start-up studies so that their feasibility can be sufficiently demonstrated to attract outside or other long-term support.

Although relatively sparse, some funds for interdisciplinary research are made available by private agencies, for example, the Whitaker Foundation, which has a grant-in-aid program that supports young investigators working at the interface between engineering and the life sciences, including medicine. This type of funding is particularly crucial for those making a first foray into interdisciplinary research.

The majority of funding comes from federal agencies and is particularly important and of special concern. The National Science Foundation provides the principal support for mathematics, physical sciences, biology, and engineering research. The Public Health Service supports life sciences and medical research. These two diverse missions produce impediments to interdisciplinary collaborative research. Even within the agencies, the place for cross-disciplinary applications is problematic. Some special efforts are being made to address this issue,[9] but the response falls quite short of the need. One general exception is found in some DOE-sponsored programs in which both intramural and extramural funds are used to support collaborative research programs. Unfortunately, this research is restricted to the mission of the DOE.

The industrial sector is less reluctant to sponsor interdisciplinary research, especially if it is likely to lead to product development. With industrially sponsored research increasing in universities, as it seems to be, it might be expected that some funding will flow easily to collaborative projects.

Open Communication and Collegiality

The importance of a common language in furthering collaborative research is often stressed. Cultural differences between scientific research communities can be profound and can extend to the niceties of dress, mannerisms, and even the way data are displayed. (One workshop participant reminded his audience that physical scientists use overhead transparencies, whereas life scientists use 35-mm color slides.) But the greatest difference may lie in the use of specialized language, which divides would-be collaborators. A determined effort to employ a general vocabulary is important to the promotion of interdisciplinary research. Such a vocabulary has several advantages: it deemphasizes disciplinary identification; it reaches to a common understanding, reducing the need to translate technical jargon; and it is less apt to embody the tacit assumptions often contained in disciplinary language that might well be challenged in interdisciplinary investigations.

Of some importance is the absence of appropriate forums and publications to transmit the results of interdisciplinary collaborative research. Some scientific societies are more natural homes for this type of exchange than others—for example, the Biophysical Society, the Radiation Research Society, the Biomedical Engineering Society, the American Association for the Advancement of Science, and Sigma Xi—and their meetings and journals welcome interdisciplinary efforts. On the other hand, some journal editors and referees are unwilling or unable to pass judgment on interdisciplinary papers.

The committee especially emphasizes the importance of interdisciplinary gatherings for initiating collaborative research. These can be formal or informal. Within academic institutions, interdepartmental gatherings can bring together scientists who might not interact under usual circumstances. An ad hoc seminar series can be organized that addresses an area of common interest among investigators from different disciplines. Such seminars can lead to the creation of a program agenda for research or to individual collaborative research projects. They are likely to be most effective if organized by the participants themselves but can also be put together effectively by an institutional administrator so long as the participating faculty have a genuine interest.

At the national level, summer workshops and colloquia can be used effectively to encourage interdisciplinary collaboration. The public agencies (NSF, NIH, DOE, the National Aeronautics and Space Administration, and the Department of Defense, for example) should expand their efforts to organize meetings along interdisciplinary lines, since such gatherings are an efficient means of generating investigator-initiated collaborative research projects. Sometimes interdisciplinary courses (e.g., NATO-sponsored workshops) can serve the same purpose.

Overlapping Educational Experience

Because much interdisciplinary collaboration depends on a common language and on collegiality, education for transdisciplinary activities could facilitate the process.[10] Graduate programs in biophysics tend to attract those who concentrated in physics and mathematics as undergraduates and who then wish to apply these disciplines to biological problems. Graduate programs in biomedical engineering attract students with engineering degrees, but the situation in this area is more complicated because there are undergraduate programs in biomedical engineering as well and there are also graduate students pursuing biomedical problems in traditional engineering departments. These educational programs can provide graduates who are capable of working across the boundaries of disciplines and who are trained in a pattern of thinking that adapts readily to interdisciplinary collaboration.

Those trained solely in the parent disciplines should have opportunities for formal or informal education in other fields. It has been argued that the undergraduate science experience should be more general and less specialized in the natural and life sciences. It might aid the cause of interdisciplinary collaboration if biologists were given more exposure to mathematics, physics, and computational methods than is now required and if physical sciences and engineering students were to obtain at least a rudimentary knowledge of biological systems. Indeed, it would seem appropriate that courses in biological physics in a physics department should receive the same course credit recognition as, for example, plasma physics or general relativity theory. The committee is aware of some attempts to encourage interdisciplinary studies, for example, the course in pathobiology for nonmedical scientists sponsored by the Josiah Macy, Jr., Foundation. However, based on its meetings and workshops, and its own collective experience, the committee has received the impression that, except for interdisciplinary degree programs, the opportunities for education in scientific disciplines outside of the parent one are meager. The committee believes that collaborative, interdisciplinary research could be promoted if educational institutions, including teaching hospitals, were to provide educational offerings for those scientists who would like to do interdisciplinary research. These offerings could be topical and should be taught at an advanced level.

Availability of Collaborators

The essence of collaborative research is that it takes at least two to tango. Finding and matching appropriate research collaborators—a major issue—can come about in several ways:

- One person or group has a scientific problem that requires expertise in another discipline, and collaborators are solicited from that discipline.
- A scientific gathering brings together collaborators who discover that they have a mutual interest and then generate a cooperative research program.
- A program manager or agency decides that an idea's time has come and actively seeks the resources to attract collaborators.
- An entity is formed to promote interdisciplinary research collaboration and searches for projects, resources, and participating scientists. Research ideas are often generated by bringing ad hoc groups together to discuss specific topics.
- An individual acts as a matchmaker or broker.

Whether "top-down" or "bottom-up" methods of initiating collaboration are more effective is not known. The committee suspects that in universities, collaboration tends to be the result of self-generated meetings of faculty members. In the national laboratories and industry-sponsored collaborations, more initiation may come from the directorate and management. Whatever their origin, and whether accidental or planned, initiating events are essential to collaborative research, and those who are proponents of its importance see the need to encourage them.

Opportunities for Practical Application and Technology Transfer

The desire to see practical benefits result from scientific research, whether for altruistic or pecuniary reasons, is a powerful force for promoting collaborative endeavors. Indeed, goal-oriented research often requires interdisciplinary teams for success.

Devices for diagnosis and treatment, instruments for analysis, and new classes of chemicals, cells, and even animals are required for contemporary research in the life sciences. Each of these is made possible to some degree by collaborative research. The desire to transfer ideas from the bench to the clinic and bedside as rapidly as possible has increased the fractional share of industry-supported research in the life sciences and medicine. As hospitals, universities, and research centers learn to utilize this new source of income, they should take the opportunity to use these resources to promote collaborative activities, while protecting the scientific initiative of the investigators.

FACILITATING FACTORS

Ideally, interdisciplinary research involves the active cooperation of scientists with diverse but relevant backgrounds who contribute their individual talents and expertise to address complex problems of mutual interest. Specifically, the quantitative, analytical approaches of physical scientists and engineers can add greatly to both basic and clinical research on health and disease in living systems. In addition, the career opportunities of physical scientists and engineers are extended and enriched when they include biologic and medical topics in their program of studies, ranging from basic courses to the study of biomedical engineering and radiological and medical physics. Physical scientists and engineers can also find challenging research areas in biology and medicine, for example, the topological modeling and chaotic behavior of fibrillation in the heart and advances in nuclear magnetic resonance imaging for clinical use.

Researchers can derive both professional rewards and personal satisfaction from successful involvement in collaborative research and development. However, individuals must benefit in tangible and significant ways if their cooperation is to remain active and enthusiastic. Each participant should be treated as an equal partner in an enterprise, and all contributions need to be fully recognized. Collaborative research can flourish in academic environments where a free flow of communication and active interdepartmental programs are encouraged by faculty, students, and institutional administrators. In addition, successful collaboration requires some extra effort from individual participants, who often must adapt to different cultures and overcome impediments imposed by specialized scientific languages and jargon as well as by gross differences in academic traditions, budgetary priorities, sources of funding, and approaches to research among the various relevant disciplines. Some of these factors are detailed below:

1. *Identification and support of overlapping goals without distortion of internal programs.* In many institutions, individual scientists are often engaged separately in tasks that have common goals, but they conduct their activities in parallel largely because of institutional structures. Establishing simple mechanisms to introduce such individuals to each other and to encourage exploration of common interests, while preserving the progress and stability of separate programs, often is enough to initiate collaborative activities.

2. *Presence of non-overlapping expertise and a spirit of cooperation.* Collaborating scientists with differing areas of expertise can capitalize on their collective diversity if each cooperates to reach common goals. It is emphasized that such collaboration must be based on mutual interdependence, must be intellectually stimulating to each participant, and must involve an optimal use and equitable recognition of participants' expertise.

3. *Physical proximity of potential collaborators.* Researchers who wish to collaborate can be encouraged by the establishment of a separate space or facility that enables interaction among potential collaborators and that is identifiably distinct from conventional spaces or facilities with which individual scientists are directly associated. A separate facility has the advantage of providing a neutral space within which individuals may seek common interests, while preserving the structures and functions of the respective existing facilities. Even when not co-located, robust communications—for example, shared access to computer facilities, networks, and data sets—are especially important for interdisciplinary collaboration.

4. *Perceived mutual need.* Collaborators must each perceive a need for collaboration. This perception may depend largely on the achievements made possible by working together. Thus an initial collaborative effort that is deemed successful by all participants will enhance the perception of mutual need and thereby encourage subsequent collaboration.

5. *Strong one-on-one relationships.* Successful collaborations derive from individual scientists working effectively with each other. A critical prerequisite for this is mutual respect and trust among the collaborators, as well as trust expressed by the institution. It is interesting to note that a number of interdisciplinary collaborations exist between scientists who were friends early in their educational development. Because mutual acquaintance, respect, and trust may not occur spontaneously, facilitators may be needed. If the reasons for facilitation are valid, the rest should follow naturally.

6. *Identifiable early success.* The early achievement of identifiable success will stimulate interest and acceptance within the conventional framework of the institution, which will, in turn, foster further and additional collaboration.

7. *Altruistic facilitator.* One of the most significant factors in promoting research collaboration is the identification of an individual, preferably an institutional administrator or respected senior member, who assumes the role of facilitator to champion potential collaborations. Three

principal characteristics distinguish an effective facilitator: (a) the capacity and the vision to recognize potentially fruitful prospective collaborations, (b) the ability to enjoy fostering and witnessing the evolution of a collaboration, and (c) a proven track record in generating enthusiasm in the participants and in creating the cohesion and inspiration necessary for a successful team. The facilitator, by definition, embodies and emulates the overall sense of mission common to the collaborating scientists themselves.

IMPEDING FACTORS

Some of the factors that impede collaborative research occur at the institutional level. Institutions should recognize that interdisciplinary researchers need extra time to develop a common language, to work with investigators in another discipline on a regular basis, and to maintain their own credentials in a primary discipline.

1. *Perception of exploitation of one collaborator by another.* Perhaps the most heinous impediment to collaboration is the perception that not all parties in the collaboration contribute and benefit equally—that one party gets less credit or gains less, intellectually and otherwise, than does another party. The institution can play a part in circumventing this problem by clearly stating policies, conducting reviews, and maintaining channels for communication.
2. *Administrative negativism.* The need to preserve institutional stability often dictates a conservative response to innovation and change. This is particularly the case if a collaborative venture requires significant financial investments by an academic institution or the commitment of substantial space. A university may resist the creation of interfaculty and interdepartmental organizations, which perturb existing lines of authority and responsibility. If universities are not organized to accept industrial research sponsorship, they may be denied this route to interdisciplinary collaboration.
3. *Fear of the unconventional.* A third impediment is that the security and stability of academic institutions rest on conventional programs and disciplines, in which only gradual changes are acceptable. Institutional resistance to unconventional collaborative activities can be viewed as a collective fear that such collaborations will lead to changes in institutional structure and function that are beyond the control of individuals whose professional identities depend on existing structure and function.

NOTES

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2. Sigma Xi. 1988. Removing the Boundaries: Perspectives on Cross-Disciplinary Research. Final Report on an Inquiry into Cross-Disciplinary Science. New Haven, Conn.: Sigma Xi, p. ii.

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4. Mann, Robert W. 1988. As cited in New Medical Devices: Invention, Development, and Use. Washington, D.C.: National Academy Press, p. v.

5. Committee for the Study of Resources for Clinical Investigation. 1988. Resources for Clinical Investigation. Division of Health Sciences Policy, Institute of Medicine. Washington, D.C.: National Academy Press.

6. National Research Council. 1986. Physics Through the 1990s, volumes entitled Scientific Interfaces and Technological Applications, and Overview. Physics Survey Committee, Board on Physics and Astronomy, Commission on Physical Sciences, Mathematics, and Resources. Washington, D.C.: National Academy Press.

7. Sigma Xi. 1988. Removing the Boundaries: Perspectives on Cross-Disciplinary Research, p. 22.

8. Morgan, H. E. 1988. Open Letter to NIH—Review of Cross-Disciplinary Research. The Physiologist 31(April):17-20.

9. In September 1988, the NIH announced the establishment of a new predoctoral and postdoctoral training program exclusively in biotechnology with an "emphasis on engineering, mathematical and physical research methods, and approaches to the analysis of biological processes." The program was initiated in response to growth of the biotechnology industry. Moreover, the NIH has solicited proposals for interdisciplinary research to develop new technologies for the Human Genome Project. A training center will also be supported in this program.

10. The boundaries between physics, mathematics, and engineering (to say nothing of their various internal branches) also have separate language and cultural differences. To some, these are epistemological artifacts easily solved by the general scientific education often provided to undergraduates in these fields. The inclusion of biology with these more quantitative sciences has been problematic, but with the advent of molecular biology one can expect nature's links to become more apparent. Medicine, on the other hand, includes aspects of the physical, life, and social sciences, their application to the understanding of human diseases, and the full range of empirical knowledge and behavior that make it a learned profession.

3

Conclusions and Recommendations on Policy Strategies for Promoting Interdisciplinary Collaboration in Research

In formulating policy strategies to encourage the promotion of interdisciplinary research collaboration, the committee considered the following factors:

- the particular roles that the organization of the faculty and the administration of universities and teaching hospitals play in facilitating and impeding such collaborations;
- the place of industry in promoting interdisciplinary research within universities and teaching hospitals;
- the great importance of the federal agencies in providing the bulk of funding for scientific research in this country; and
- the special role that private foundations might play in the promotion of interdisciplinary research.

Although these factors are independent, the conclusions and recommendations on policy strategies are all directed toward advancing the following goals:

- promoting the conscious awareness of the synergy to be achieved by exchanges among professionals in the physical and life sciences;
- forging new links between disciplines through educational programs and institutions and through professional activities;
- encouraging career incentives in interdisciplinary research and education;
- ensuring that the most productive and beneficial areas of interdisciplinary research are well supported; and
- identifying factors that create hospitable and productive environments for interdisciplinary research collaboration.

UNIVERSITY AND TEACHING HOSPITAL STRUCTURES THAT FACILITATE AND IMPEDE INTERDISCIPLINARY COLLABORATION IN RESEARCH

Among the principal sites for the development and fulfillment of interdisciplinary collaborative research (between physical scientists and engineers, on the one hand, and life scientists and clinical investigators, on the other) are universities and affiliated teaching hospitals. The structures of both lend themselves to cooperative endeavors and, conversely, can be impediments to their realization. Two aspects of these institutions need to be taken into account. The first is the administrative apparatus; the second is the organization of the faculty. The committee believes that each can be modified to provide opportunities for collaborative interaction.

Administrative Support

A significant factor in the success of collaborative interdisciplinary research is effective administrative support. There are several means of providing assistance. The first is supplying money. Particularly in the early phases of collaboration, relatively small amounts of money can be instrumental in bringing collaborators together and in initiating research projects. Especially useful are funds for pilot projects to prove the feasibility of larger research proposals and for graduate students and postdoctoral fellows who will cross disciplinary lines. Because interdisciplinary research often produces material for prompt technology transfer, some institutions have funded initiatives based on such promise. The committee believes that such programs as the Stanford Institute for Biologic and Clinical Investigation and the Harvard Medical School-affiliated Medical Science Partners should be scrutinized as potential models.

A second important function of university and hospital administrations is promoting interactions among the faculties of medical school and hospital departments, engineering departments, and natural sciences departments. Providing forums for intellectual exchange can be highly productive. Summer workshops and courses (with concomitant salary support when needed) as well as in-term seminars, retreats, colloquia, and informal small group exchanges can also be used effectively to encourage cross-disciplinary communication.

A third and extremely important element is the presence of an academic administrator who has interdisciplinary collaborative research as part of his or her portfolio. Someone needs to awaken mornings thinking about how to promote this activity. The administrator's rank should be high enough to catch faculty and administrative attention, but not so high as to be diluted by other demands. The activity could belong to a vice president for research, an associate provost, or an academic dean. It is important, however, that the oversight not be parochial. The administrators's role should be part matchmaker, part catalyst, part facilitator, part protector, and part ombudsman.

Organization of the Faculty

Virtually all interdisciplinary research programs begin with teams of investigators with diverse backgrounds who collaborate informally at first. Interdisciplinary research by definition transcends the usual boundaries of traditional departments. To promote interdisciplinary research effectively, institutions can either incorporate relevant research into a traditional department or create special interdisciplinary departments (for example, in biomedical engineering or biophysics). Neither approach is without challenges, as discussed below.

Incorporating new areas of research into a preexisting department requires faculty (ideally senior members) prepared to pioneer, in part through collaboration external to the department, potentially promising ventures. Sponsoring interdisciplinary research within an established department guarantees that departmental resources, including faculty, laboratories, and graduate students, will be brought to bear on interdisciplinary research. It also legitimizes that research as part of an acceptable intellectual effort, for example, the study of blood flow as applied fluid mechanics in a mechanical engineering department.

It is possible that a single department member can possess and provide the needed interdisciplinary knowledge. There are notable examples of such individuals, and more may be anticipated as M.D.-Ph.D. graduates with degrees in the engineering, physical, and computer sciences become commonplace. Indeed the committee encourages support for such individuals. Much could be accomplished if research departments of physics, chemistry, mathematics, and engineering had among their members individuals with interdisciplinary interests that included biology and medicine. Likewise, biology and medical school departments should be encouraged to create categorical appointments in biophysics, biomathematics, bioengineering, medical physics, medical engineering, and so on. Faculty members could fulfill their teaching obligations by developing courses in their own disciplinary fields, by team teaching in interdisciplinary educational programs, or by teaching in the parent discipline. Such positions need to be institutionalized either as tenured appointments or as long-term commitments (10 to 15 years) not subject to the vagaries of departmental taste and leadership. Such appointments might also be strengthened by a joint or cross-appointment in another department.

The alternative is to integrate into one newly established department faculty members who are skilled in the relevant cross-disciplines. Care must be taken to restrict the range of the department's research so there is significant overlap in interest among all members; otherwise, there may be too little interaction and constructive criticism. This limiting of scope may conflict with the establishment of a broad-based undergraduate or graduate curriculum, given the breadth of knowledge that can be encompassed by the disciplines of biomedical engineering or biophysics, for example. This dilemma can be resolved by the use of a number of devices, such as extradepartmental courses.

A specially created department with its component powers of appointment, teaching programs, space, a budget, and start-up funds is certainly the strongest means of organizing faculty to advance interdisciplinary research. The ease and wisdom of establishing such departments depend in part on the nature of a university or teaching hospital and the resources available. Some institutions are less likely to nurture nontraditional departments. Others have found them to be an effective vehicle for interdisciplinary research and education. If an academic institution elects to set up a new department, it is important that it be fully committed to providing sufficient faculty to round out the teaching and research programs and sufficient resources to initiate activities and maintain them above and beyond the level made possible by faculty-generated support.

The quandary posed by the choice between traditional versus integrative departmental structures to support collaborative research is often resolved in the university setting by organizing research units titled "center," "division," or "laboratory." Such units may have a physical locus of activity or be without walls; and they may have full appointing status (annual or complete) or none; they may have institutional funding or not; they may have an associated educational program (including degree offerings) or no requirements in teaching. They may differ from departments only in their degree of permanency or, at the opposite extreme, may exist as instruments for collaborative research based only on faculty interest, soft money resources, and a title bestowed by the university or teaching hospital. But the more they incorporate the structure and powers of established departments, the more stable and attractive such research units will be. Without some form of committed institutional support, such units tend to be transient, underproductive, and unattractive. Therefore, the committee strongly recommends that when an organized research unit is established to foster interdisciplinary collaborative research, it should carry an institutional commitment of space, money, and positions. The success and effectiveness of all such structures depend, however, on the enthusiasm (self- or facilitator-generated) of faculty from several disciplines who can participate eagerly in the enterprise and can bring to it their time, effort, and the encouragement of their disciplinary colleagues.

THE ROLE OF ACADEMIC-INDUSTRIAL INTERACTIONS IN FACILITATING INTERDISCIPLINARY COLLABORATION IN RESEARCH

The creation of effective mechanisms for the flow of knowledge and invention between academic institutions and industry is becoming an increasingly important factor in funding for university research and in improving the competitiveness of U.S. businesses in the areas of biotechnology, medical devices, and pharmaceuticals. The flow across this interface has been driven by revolutionary advances in molecular biology and molecular genetics; the application of engineering approaches, methodologies, and principles to problems in pathophysiology; and a deeper understanding of the role of macromolecular structure for rational drug design.

Despite their clear cultural divergences and their differing missions, both the academic community and the industrial community are now engaged in numerous experimental arrangements designed to be mutually beneficial. An illuminating review of the history and the present status of such arrangements is given in *New Alliances and Partnerships in American Science and Engineering*, published in 1986.[1]

Academic-industrial arrangements for conducting research can be of many different types and scales, with differing ground rules. Examples of very large biological or biomedical joint ventures are (1) the Hoechst-Massachusetts General Hospital Department of Molecular Biology; (2) the Cornell University Biotechnology Program, with the support of Eastman Kodak, General Foods, and Union Carbide; (3) the Squibb Center for Biomedical Research at Massachusetts General Hospital; (4) Washington University Medical School-Monsanto Biomedical Research Program; (5) the Stanford Institute for Biological and Clinical Investigation; and (6) the Duke University-du Pont collaborative research agreement. These joint institutes are perhaps the most visible of several means for accomplishing technology transfer. Other mechanisms include industrial support of selected individual research projects, venture capital start-up financing for entrepreneurial faculty members, industrial liaison programs, and the well-established mechanism of consulting by university faculty members.

Generally, academic-industrial arrangements provide industry with windows on new advances and exclusive licenses or patents for new technology, but other arrangements also generate an environment for interdisciplinary research collaboration. Such collaborations can provide companies with problem-solving capabilities in specific scientific disciplines and can benefit academic institutions by making available research funding for both innovative young scientists and established researchers. Collaboration with industry can also broaden the research perspectives of university faculty. Moreover, the industrial pathway is the principal means whereby scientific and technical advances developed in academia can result in products actually used on a broad scale in the diagnosis and treatment of disease.

Although academic-industrial collaboration is likely to remain a relatively small factor in the overall academic research budget, it can play a crucial role in facilitating technology transfer across the boundaries between the physical sciences and engineering, on the one hand, and the life sciences and medicine, on the other. To achieve technology transfer, mechanisms that influence the necessary exchange must be identified and provided.

In addition, academic institutions and industry must address the following six issues in a mutually satisfactory manner:

1. preservation of academic initiatives and educational missions in cooperative ventures with commercial concerns;
2. freedom to publish research findings;
3. freedom to collaborate with scientific colleagues;
4. appropriate limits on consulting and entrepreneurial activity;

5. establishment of policies and procedures to avoid real or perceived conflicts of interest; and

6. establishment of policies that clarify patenting, licensing, and the ownership of intellectual property.

These fundamental issues can be identified and resolved in a variety of ways.[1,2] The precise solutions adopted depend in large measure on the history and experience of the institutions involved. Policies on conflict of interest are being reviewed by the Congress, the National Institutes of Health, state governments, and academic institutions. Professional organizations such as the Association of American Medical Colleges are developing policy guidelines. Federal legislation, such as the 1980 Stevenson-Wydler Act and the 1986 Federal Technology Transfer Act, affects many aspects of collaborative research.[3] For example, the latter legislation includes guidelines that allow government scientists to collaborate with industry in research and development agreements.

Mechanisms to Facilitate Interaction Across the Academic-Industrial Interface

Academic-Industrial Liaison Programs

The research capabilities of the modern university provide a powerful source of specialized knowledge that can be used to help solve a broad variety of industrial problems. Many industries are unable to finance the research required for product improvement and innovation, and even those with research and development staffs may benefit from the stimulation of novel advances made outside the corporation. Furthermore, industrial managers alone may not be able to identify and search out specific scientists or engineers capable of clarifying and solving industrial problems. Clearly industry can benefit greatly if mechanisms are established whereby interested corporations can tap the problem-solving capabilities of universities and gain access to information on newly emerging technologies.

One way to promote academic-industrial collaboration is to establish an industrial liaison office. In many instances university and teaching hospital staff have acted as facilitators between faculty members and putative industrial partners. Industrial liaison offices can be supported by annual contributions from industrial subscribers and should make their services generally available at prices affordable by small firms. In this era of competitiveness, a special effort should be made to accommodate U.S. corporations. Subscribers to the services of such an industrial liaison office could benefit from participation in frequent academic-industrial symposia that explore relevant technical and scientific developments and from interaction, through the offices of an industrial liaison officer, with selected faculty members who can potentially help solve specific problems in the corporation. Such initial contacts, if mutually beneficial, can lead to larger joint activities such as industrially sponsored faculty research programs, or even industrially sponsored research centers or organized research units.

Technology Licensing Offices

Vital to the flow of technology between academia and industry are policies and facilities for the patenting and eventual licensing of new technology. Establishing policies for patenting and/or copyrighting intellectual property and for equitably dividing patenting costs and royalties between a faculty (or staff) inventor and an academic institution is the first step in the technology transfer process. Following this, a technology licensing office can play a vital role in identifying potential industrial licensees for a new technology and in helping to negotiate terms for development of the technology between the inventor and the interested potential corporate licensee. Subsequently, the technology licensing office can monitor the achievement of promised milestones in the licensing agreement and can act to rescind licenses should this be necessary. Finally, the technology licensing office can play a central role in facilitating technology transfer by assisting in corporate start-ups financed by venture capital. Such an office can serve as the intermediary between the academic institution, the academic scientist-inventor, and potential venture capital partners so as to secure satisfactory terms for each participant in the technology transfer process. In addition to licensing offices, other instruments in universities and teaching hospitals can serve this function, including faculty committees that can help to facilitate technology transfer by soliciting and reviewing proposals from other faculty members.

It is of vital importance to universities that technology licensing offices, industrial liaison programs, and affected faculty act strictly in accordance with clearly established policy guidelines. These guidelines must be formulated so as to satisfactorily take into account the six issues enumerated above.

Because technology transfer across the academic-industrial interface is becoming an increasingly important factor in maintaining this country's industrial competitiveness and in financing the biomedical sector of our academic research, it is essential that a broader segment of the academic community put into place programs and policies that facilitate interchange while safeguarding against conflict of interest. Several U.S. universities have acquired experience in these matters and have established the needed policies and procedures.[1,3] Their experience can serve as a useful guide to other institutions that seek to enhance their research funding base as well as to contribute to the economic vitality of the geographic regions they serve.

FEDERAL FUNDING AGENCIES

Since the bulk of research support for the sciences in this country comes from the federal government, the position of the federal agencies vis-a-vis interdisciplinary research is of the greatest importance. In examining the postures of these agencies, the committee realized that both attitudes and structures needed to be scrutinized, and it has tried to address both in this report. Although the recommendations are confined to the NSF, the NIH, and the DOE, the committee recognizes that other agencies (e.g., NASA, DOD) have significant life sciences programs and a role, both realized and potential, in promoting interdisciplinary research collaborations.

The National Science Foundation

The committee found considerable sensitivity and concern at the NSF to the issues raised in this report. Erich Bloch, the director of the NSF, has repeatedly emphasized the importance of collaborative research by scientists and engineers from different disciplines for the progress of American science and technology. In the past few years, the NSF has initiated several new, large-scale efforts in this direction, for example, the new program for Small Grants for Exploratory Research, the Science and Technology Research Centers, the Engineering Research Centers, the Materials Science and Engineering Research Centers, the Tissue Engineering Initiative of the Division of Emerging Engineering Technologies, and an activity in the chemistry of life processes that crosses five NSF divisions.[4]

An internal NSF report on the handling of interdisciplinary proposals—the "Report of the Task Group on Interdisciplinary Research," chaired by Maryanna Henkart[5]—was presented in July

1987. This report and the committee's interviews with NSF personnel made it clear that the NSF is aware of the problems faced by proposals for interdisciplinary research. In particular, the difficulty of finding suitable reviewers for such proposals was widely recognized. A reviewer from one related field who evaluates a proposal for interdisciplinary research will seldom grade it "excellent" if he or she is not familiar enough with the other field(s) involved to judge the merits of the whole proposal. Thus first-rate proposals can be adversely affected by tepid support from both sides and by a lack of reviewers who can judge the whole picture. Furthermore, the funding of such proposals typically depends on the initiative and cooperation of individual program officers, not only across division lines but also across directorate lines, in competition with proposals that are clearly classifiable in a particular program. The committee is reassured to find that NSF program officers have latitude in making scientific judgments and that good faith efforts are made to ensure that interdisciplinary research proposals receive fair treatment. Nevertheless, the committee recommends that the NSF encourage joint proposals between biological and physical scientists and that it put in place review procedures to appropriately judge the scientific merit of such proposals.

The committee notes that many NSF program officers rotate and cannot be expected to establish in two short years good working relationships with program officers in other divisions or directorates. Their chief priorities must be the continuity of the main lines of research within their programs and the development of working relationships with other program officers within their divisions. Furthermore, as long as no special funds are earmarked for collaborations, program officers may have strong personal inclinations to turn down such research in favor of main line research in their own fields. Indeed, they may be strongly pressured to do so by their scientific peers. The committee believes that collaborations between physical scientists and life scientists are so important and have so much scientific potential that their success should not be left to fortuitous relationships between program officers who must choose between interdisciplinary proposals and proposals in their own field of training. The committee therefore recommends that certain funds from the Biological, Behavioral, and Social Sciences (BBS) Directorate, the Mathematics and Physical Sciences Directorate, and the Engineering Directorate be commingled for funding proposals involving collaborations between life scientists and physical scientists or engineers. To oversee the expenditure of such monies, the committee recommends that a high-level working group be set up, consisting, for example, of the associate division directors in the three directorates, to recommend suitable reviewers for the proposals and to act as a decision-making body after the reviews come in. In this way, greater expertise will be available in the choice of referees, and a broader scientific view will be ensured in the selection process. A further benefit of this arrangement would be that divisions would be likely to encourage collaborative proposals as a means of competing for funding.

The NSF has always been concerned with training. The committee recommends that training funds be used to encourage research collaborations between life scientists and physical scientists or engineers. Specifically, support should be made available for postdoctoral fellows who want to work with NSF-supported scientists in fields other than the fellows' own scientific specialties. (For example, a mathematics Ph.D. who works on the ordinary differential equations involved in metabolic control could be given a fellowship to do postdoctoral work with a bench biologist working on metabolic regulation, or a cell biology Ph.D. could do postdoctoral research with a physicist whose specialty is membrane transport.) Such postdoctoral appointments would, at a minimum, partially counter the increasing trend toward a high degree of specialization and could lead to much productive collaborative work in the next generation. The committee also recommends that a special cross-directorate sabbatical leave program be instituted to provide support, over a specific period of time, for established researchers who wish to become educated in a new discipline. Such leaves would increase the breadth of some first-rate American scientists and quickly lead to increased research collaborations.

The National Institutes of Health

As part of its mandate to improve the nation's health, the NIH supports a wide variety of clinical and basic biological studies. Earlier in this report, it was demonstrated that the physical sciences (including engineering, mathematics, and computer science, for the sake of generality) have made significant contributions to the life sciences and medicine and that their potential contributions could be even larger in the future.

Several activities indicate the NIH's awareness of the vital contributions that the physical sciences and mathematics can make to biomedical research. Some of these are listed below:

1. The various institutes employ substantial numbers of mathematicians and physical scientists in their intramural laboratories and are major training centers for scientists seeking to become involved in interdisciplinary research either at the postdoctoral level or as sabbatical visitors. For example, the National Cancer Institute has a laboratory for mathematical biology that among other things runs a supercomputer center dedicated to the development and testing of computational tools for biomedical research. The Biomedical Engineering and Instrumentation Branch of the NIH's Division of Research Services also provides intramural services.
2. The NIH is grappling with problems of fostering interdisciplinary research as well as providing various specialized services in a number of contexts: (a) The Division of Research Resources (DRR) supports a number of centers that develop and provide specialized resources to biomedical scientists. Included are computational centers and special biophysical facilities (e.g., the National Center for Flow Cytometry at Los Alamos). (b) The recently established National Center for Biotechnology Information within the National Library of Medicine is charged with conducting and supporting research on providing molecular biology databases to biomedical researchers. (c) The Human Genome Project has specifically solicited interdisciplinary proposals both for developing advanced sequencing and mapping technology and for computational methods to organize and analyze the resulting data and distribute it to molecular biology laboratories. The Human Genome Project has also proposed a training program to support 200 predoctoral and postdoctoral students, with considerable emphasis on interdisciplinary training.

Much more needs to be done. Many large university medical research groups include associates who are physical scientists. These physical scientists do not generally hold regular academic-track positions but are supported on a year-to-year basis by the grants of several clinical or life sciences investigators. The committee sees nothing wrong with this but notes that eminent physical scientists with or without tenured positions in their own departments can generally be induced to contribute their expertise to health problems only if they are accorded equal status as investigators. It is natural for the best physical scientists interested in health problems to act as principal investigators (PIs) or co-PIs, i.e., as equal partners in collaborative research. Unfortunately, the committee concluded from its interviews that it can be difficult for individual physical scientists, even distinguished ones, to obtain NIH support for collaborative research. Consequently, a great potential in the physical sciences may be lost to the life sciences.

Because few interdisciplinary research proposals from physical scientists are funded, few are submitted. The lack of success in the review process of even those few may be an unintended consequence of the organizational structure of the NIH and of its study section system. With the exception of the National Institute of General Medical Sciences (NIGMS), the NIH is organized, for the most part, into institutes devoted to disease- or organ-specific research. This may make sense programmatically, but it means that physical scientists do not have a natural point of entry to collaborate with life scientists. Physical scientists bring expertise that can and should be used across a wide variety of programs. For example, a physicist might work on cardiac blood flow for several years, then turn to applications of scattering theory in medical imaging, and then work on the problems of neural networks. However, to obtain funding a researcher must usually have a substantial track record and be well known in the specialty of the study section considering the researcher's proposal; hence proposals for interdisciplinary research are often turned down. The NIGMS was established partly to support researchers with general expertise cutting across the domains of several institutes; but the committee was unable to obtain information on the distribution of the specialties of collaborating investigators in NIGMS-supported grants. Nevertheless, the impression is that the overall number of interdisciplinary participants is small.

A second structural feature that works against the success of collaborative proposals with physical scientists as PIs or co-PIs is the NIH study section system. Priority scores determined by study section vote largely determine which programmatically acceptable proposals will be funded. The study sections are inherently conservative since their members are principally established researchers in the same or related disciplines.[6] This committee heard testimony about proposals sent to study sections in which few or none of the members could judge the physical science aspect of the proposal. Even if a study section solicits an outside opinion from a physical scientist and even if the outside review is enthusiastic, the study section is unlikely to give high priority to a proposal that its members cannot completely understand, as opposed to those that are more familiar.

None of this means that the organization of the NIH into institutes or its use of study sections to review proposals is inappropriate. But the system seems not to have greatly encouraged the application of the physical sciences and engineering to the life sciences and medicine. To provide such encouragement, the committee makes two recommendations:

1. In the short term, the NIH should create two new study sections or joint operational units of existing sections. The first would specialize in proposals for instrumentation and materials development. The second would specialize in proposals for applications of analytic methods in the physical sciences to the life sciences and medicine.
2. In the long term, the NIH should consider a corresponding new budget category either by adding to an existing institute or by establishing a new entity. This course of action should lead to measures to stimulate the interest of life scientists in the methods of the physical sciences and the interest of physical scientists in the solution of pressing health problems. (In this context, there is already a proposal supported by a number of scientific societies to establish a National Health Technology Institute.)

Cooperation Between the NSF and the NIH

The committee noted a fundamental difference in the missions of the NSF and the NIH that affects the support of interdisciplinary research. Generally speaking, physical scientists, mathematicians, engineers, and computer scientists are supported by the NSF; medical scientists and most life scientists are supported by the NIH. The facilitation of collaboration between individual researchers in these two groups is one of the major goals of this report. For valid historical and financial reasons, the NSF does not support "medical" research. For the reasons cited in the previous section, the NIH has generally not supported fundamental work outside of the life sciences, especially if the proposing scientists are outside of medical centers or departments of life sciences. Yet, this committee believes it is in just such collaborations that the greatest potential for scientific progress lies. What should be done? It is the committee's opinion that this problem can be solved, in part, by direct ongoing cooperation between the NSF and the NIH. For such cooperation to be successful, it must be initiated and maintained at a high level in the two agencies. The committee therefore recommends that the NSF and the NIH jointly establish a working group of high-level administrators from the two agencies whose charge is to make recommendations for the purpose of establishing, institutionalizing, and financing such cooperation.

The Department of Energy and Its National Laboratories

The Office of Health and Environmental Research of the DOE is charged with conducting research and development to assess the effects of radiation and the products and by-products of energy production on human health. The DOE also maintains at its national laboratories a number of unique national facilities, including nuclear reactors, pulsed neutron and other particle sources, synchrotron light sources, and supercomputers, that are available to and used by biomedical research scientists and their colleagues in the physical sciences.

Much of the goal-oriented research of the DOE is conducive to interdisciplinary research. Moreover, because the life scientists at the national laboratories are surrounded by large numbers of physical scientists, engineers, and computer scientists, it is relatively easy for them to find collaborators in these fields. For these reasons, the DOE—and before it the Atomic Energy Commission and the Energy Research and Development Administration—has been very active in developing resources and technologies, through the efforts of physical scientists and engineers at its national laboratories, that have been of importance to biomedical research.

The national laboratories represent powerful and in some respects unique resources for the conduct of interdisciplinary research directed toward specific goals. In view of the increasing importance of biotechnology and the associated requirements for advanced radiation sources and computational facilities for progress in structural and molecular biology, the role of the DOE will remain important. Although the life sciences represent only a small fraction of the DOE's budget, the committee urges the DOE to remain sensitive to its unique role as a facilitator of collaborative research.

As acknowledged centers for interdisciplinary research, the national laboratories provide examples and training for students and established scientists seeking collaborative arrangements. In particular, the laboratories offer research training for graduate students, sometimes on dissertation topics and in cooperation with degree-granting universities, have active postdoctoral programs, and often welcome sabbatical visitors seeking to gain new perspectives or to change directions (e.g., by providing awards such as the Hollaender fellowships, which fund work in the life, biomedical, and environmental sciences, and other related scientific disciplines). The committee approves of the national laboratories' programs and recommends that the DOE regularize its support for graduate students and postdoctoral fellows seeking interdisciplinary experience and officially broadcast these activities.

In the past, there has been little or no motivation for the national laboratories or their scientists and engineers to transfer technology to the private sector. Partly in response to congressional concerns, the DOE and its laboratories have become more active in involving private companies in research programs and in providing for licensing and commercial use of inventions. The factors involved in encouraging cooperation at the academic-industrial interface apply here, and the national laboratories have responded by establishing industrial liaison programs and technology licensing offices. The committee endorses these initiatives.

THE ROLE OF PRIVATE FOUNDATIONS

Interdisciplinary collaborations reach beyond and often redefine the directions of existing institutional goals. Such enterprises involve risks and may deviate from the established policies of risk-averse institutions. In many respects, then, personal or private support may be best suited for the venturesome collaborations of new, interdisciplinary efforts. Private foundations can thus serve a unique role in fostering interdisciplinary research by providing support for individuals working in new, untried ventures and for the definition and unification of such ventures for subsequent development under a more institutionalized format.

Historically, the vision of private foundations and individual benefactors has provided new paths for joint scientific activity, for example, the Whitaker Foundation's biomedical engineering grants program and the Howard Hughes Medical Institute's Research Programs in Structural Biology. One example of such joint activity, colorfully portrayed by C. H. Holbrow, is seen in the history of the California Institute of Technology's W. K. Kellogg Laboratory, which was originally founded in 1931 as a center for radiation therapy and shortly thereafter shifted from a medical focus to become a renowned laboratory for nuclear physics research.[7] Conversely, the Cyclotron Laboratory at Harvard University was initially funded at the end of World War II by numerous private endowments for individual faculty to conduct basic research in nuclear physics and was sustained for nearly two decades by private foundations and thereafter by armed services funding. Today, this facility has become a leading medical facility for proton beam radiotherapy.

Supporting Collaborative Efforts of Individual Researchers

How can private foundations maximize their impact? In contrast to federal and profit-motivated institutions, private foundations can support new research on risky topics and underfunded subjects of inquiry. If basically conservative federal support is viewed in one extreme as peer-sanctioned reimbursement for collaborations already established, ideas already formulated, and work partially completed, then private foundation support may be viewed in the other extreme as a willingness to actively encourage new programs initiated by individuals working together. The committee thus endorses the principal strategy for private foundations suggested in a report from the Pew Charitable Trusts[8]—that of supporting the first independent efforts of young collaborating researchers and of making initial investments in emerging areas of interdisciplinary research.

A clear and important strategy with high visibility and impact—one that exists only on a small scale and is not emphasized by federal agencies—is fellowship support for new graduate students. The federally funded fellowship programs that exist are in targeted areas and tend to be focused along disciplinary lines. Setting up programs to train students in interdisciplinary efforts would fill a void in current funding mechanisms and provide an opportunity to train new scientists from the beginning with an interdisciplinary perspective.

A second way to support collaborative research is to fund the work of young faculty and of established investigators in new, untried programs. Federal programs exist that are intended, on the one hand, to help establish the research efforts of new investigators and, on the other, to enable established investigators to use leaves of absence to redirect their research interests. But these programs tend to be structured along disciplinary lines. A new assistant professor must quickly establish himself or herself as a convincing independent investigator—one who is capable of securing independent research support. To secure funding for interdisciplinary research is difficult enough for investigators who have already established themselves in one research field; for young investigators it is formidable. Furthermore, promising preliminary results are a prerequisite to securing institutionalized funding. Fellowship programs for junior faculty and sabbatical leaves for senior faculty who are shifting into new areas can provide the interim support needed to obtain the promising results that are, in turn, required to secure further funding. These programs could thus serve as leveraging vehicles for efforts that venture off in new directions of interdisciplinary research.

The committee thus recommends that private foundations support individuals engaged in interdisciplinary research by providing (1) research fellowships and awards for graduate students and junior faculty and (2) sabbatical leave awards, endowments, and academic chairs for junior and senior faculty alike.

Providing for the Definition and Unification of Collaborative Research

More controversial than programs to support individual researchers are programs directed toward supporting centers at selected academic institutions. The committee recognizes that for the latter programs, substantial sums of money are required that may be directed to only a few universities. Given limitations in total resources, it is important that such funding not become institutionalized at the outset. A center might, for example, be established at a university with seed money, which would provide the resources necessary for recruiting collaborating individuals. The sponsoring foundation could then work intimately with the university to encourage the development of center activities, determining subsequently whether or not the center would be institutionalized or dissolved depending on its ability to attract other support. Such approaches to furnishing start-up money for collaborative centers offer creative possibilities for bringing together investigators in different disciplines and, if successful, can provide new structures for interdisciplinary research. The committee recommends that private foundations support centers at selected academic institutions. The committee suggests that foundations work closely with academic institutions so that the initial investment is leveraged to encourage the further development of such centers.

A less controversial way for foundations to target funding to selected universities—and one that can achieve great impact—is to build laboratory facilities, an important need throughout the country that universities are having difficulty financing. Institutional or federal funds are unlikely to support new buildings for collaborative efforts.

The committee recommends that private foundations with even modest resources consider support of interdisciplinary study groups and conferences, as well as workshops, summer schools, and seminars. These interdisciplinary programs are useful vehicles that can bring together people in different disciplines and foster their interactions. Such programs are only occasionally funded through federal agencies.

The committee recommends that private foundations take the opportunity afforded by these mechanisms to encourage, define, and unify interdisciplinary research programs. Such programs can fill an important role in nurturing and stimulating new faculty in these efforts and in fostering research collaborations. The leveraging potential in such programs is great. Foundations can provide the impetus for new ventures that, once they show promise, should become self-sustaining and eligible for more conventional support. Private foundations would thereby play a unique and critical role as catalysts for new interdisciplinary research.

NOTES

1. Academy Industry Program. 1986. New Alliances and Partnerships in American Science and Engineering. Government-University-Industry Research Roundtable. Washington, D.C.: National Academy Press.

2. Committee on Policies for Allocating Health Sciences Research Funds. 1990. Division of Health Sciences Policy, Institute of Medicine. Washington, D.C.: National Academy Press, in press.

3. Hanna, Kathi E. 1989. Collaborative Research in Biomedicine: Resolving Conflicts. Committee on Government-Industry Collaboration in Biomedical Research and Education, Institute of Medicine. Washington, D.C.: National Academy Press.

4. In October 1989 the NSF's BBS Directorate announced the establishment of a new $4 million Research Training Grant Award to stimulate interdisciplinary research in ten U.S. universities.

5. Henkart, Maryanna P. (chair). July 1987. Report of the Task Group on Interdisciplinary Research. Internal report. Directorate for Biological, Behavioral and Social Sciences, National Science Foundation, Washington, D.C.

6. There are some notable exceptions, for example, the Diagnostic Radiology Study Section, whose members include chemists, physicists, and engineers as well as clinical radiologists and radiation biologists.

7. Holbrow, C. H. 1981. The Giant Cancer Tube and the Kellogg Radiation Laboratory. Physics Today 34(7)(July):42-49.

8. Boniface, Z. E., and R. W. Rimel. 1987. U.S. Funding for Biomedical Research. Philadelphia: The Pew Charitable Trusts.

APPENDIXES

Appendix A

Roster of the Working Group on Interdisciplinary Collaboration

Robert W. Mann, Massachusetts Institute of Technology, *Chair*
Richard J. Cohen, Harvard University-Massachusetts Institute of Technology Division of Health Sciences and Technology
Attallah Kappas, The Rockefeller University Hospital
Donald Lyman, University of Utah
James B. Reswick, U.S. Department of Education
David M. Robinson, National Institutes of Health
Robert Straus, University of Kentucky College of Medicine

Institute of Medicine

Enriqueta Bond, Director, Division of Health Sciences Policy
Barbara Filner, Associate Director, Division of Health Sciences Policy
Jane Takeuchi, Staff Officer

National Research Council, Commission on Physical Sciences, Mathematics, and Resources

Donald C. Shapero, Director, Board on Physics and Astronomy

National Research Council, Commission on Life Sciences, Board on Toxicology and Environmental Health Hazards

James Frazier, Senior Staff Officer

Appendix B

Agenda for the Second Committee Meeting

Federal Agencies and Foundations: National Institutes of Health

- John Watson, chief, Devices and Technology Branch of the Heart, Lung, and Blood Institute
- David Fleming, chairman, Biomedical Research Technology Review Committee, Division of Research Resources, and adjunct professor of biomedical engineering, Department of Pediatrics, Cleveland Metropolitan General Hospital
- Marvin Cassman, director, Biophysics and Physiological Sciences Program, National Institute of General Medical Sciences, NIH

Discussant: Mischa Friedman, chief, Referral and Review Branch, E Division Research Grants, NIH

Federal Agencies and Foundations: National Science Foundation

- Duane Bruley, program director, Biochemical and Biomass Engineering Program
- John Wooley, division director, Division of Instrumentation and Resources, Directorate for Biological, Behavioral and Social Sciences
- Andre Manitius, deputy director, Division of Mathematical and Physical Sciences
- Maryanna P. Henkart, program director, Cellular Physiology Program, Division of Cellular Biosciences, Directorate for Biological, Behavioral and Social Sciences, and former chair, NSF Task Group on Inter-Disciplinary Research

Interdisciplinary Research and Training Programs (discussed in three subgroups)

Subgroup on Educational and Training Programs
(Chair: R. Mann; members: S. J. Adelstein, J. Barton, P. Lauterbur, R. Rushmer)

- M.D.-Ph.D. Programs: S. James Adelstein, former training director, Medical Scientist Training Program at Harvard Medical School

- National Institute of General Medical Sciences: Bert Shapiro, deputy program director, Cellular and Molecular Basis of Disease Program
- Biomedical Engineering Programs: Robert Rushmer, former director, Center for Bioengineering, University of Washington
- Biophysics Program: Watt Webb, professor and director, Applied Engineering Physics, Cornell University

Subgroup on Research Centers
(Chair: G. Benedek; members: S. Krimm, M. Reed, C. Stevens)

- Argonne National Laboratory: Harvey Drucker, assistant laboratory director, Energy, Environmental, and Biological Research
- Biotechnology Center, Massachusetts Institute of Technology: Dan Wang, professor of chemical engineering and director, Biotechnology Processing Engineering Center
- Department of Energy: Murray Shulman, deputy director, Office of Health and Environmental Research, Office of Energy Research, Washington, D.C.

Subgroup on Industry and Industry-University Interface
(Chair: K. Melmon; members: J. Bawden, J. Davie, D. Sabiston)

- Eli Lilly: Al Potvin, director, Medical Instrument Systems
- Baxter Health Care Corporation: Sumner Barenberg, biomaterials development manager
- Searle: Joseph Davie, senior vice president, Searle Research and Development

Appendix C

Agenda for the Committee Workshop

Federal Policy

Invited speakers: Frank Young, Food and Drug Administration, and Donald S. Frederickson, National Institutes of Health
Moderator: Jacqueline K. Barton, Columbia University
Rapporteur: S. James Adelstein, Harvard Medical School

The Industrial-Academic Interface

Invited speaker: Edgar Haber, Squibb Institute for Medical Research
Moderator: Thomas F. Hornbein, University of Washington
Rapporteur: George Benedek, Massachusetts Institute of Technology

The Role of Private Foundations

Invited speaker: Miles Gibbons, Jr., Whitaker Foundation
Moderator: Robert W. Mann, Massachusetts Institute of Technology
Rapporteur: Jacqueline K. Barton

Engineering and Device Development in Biology and Medicine

Invited speakers: Richard Johns, Johns Hopkins University, and Ioannis Yannas, Massachusetts Institute of Technology
Moderator: Paul Lauterbur, University of Illinois
Rapporteur: Thomas F. Hornbein

Mathematics and the Physical Sciences in Medicine and Biology

Invited speakers: Howard C. Berg, Harvard University, and Paul Silverman, Lawrence Berkeley Laboratory
Moderator: Samuel Krimm, University of Michigan
Rapporteur: Michael C. Reed, Duke University

University and Hospital Structures that Facilitate or Impede Interdisciplinary Research Collaboration

Invited speakers: Sheldon S. King, Stanford University Hospital, and David Saxon, MIT Corporation
Moderator: S. James Adelstein
Rapporteur: Robert W. Mann