Facilitating Interdisciplinary Research
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The Drivers of Interdisciplinary Research

No one can predict the issues that science and society will consider most pressing in the decades to come. But if we look at some high-priority issues of today—such as world hunger, biomedical ethics, sustainable resources, homeland security, and child development and learning—and pressing research questions, such as the evolution of virulence in pathogens and the relationship between biodiversity and ecosystem functions, we can predict that those of the future will be so complex as to require insights from multiple disciplines. What research strategies are needed to address such a future? To what extent will interdisciplinary research (IDR) and interdisciplinary education be among the strategies? Just what is IDR?

DEFINING INTERDISCIPLINARY RESEARCH

No single definition is likely to encompass the diverse range of activities that have been described under the heading of IDR. Reflecting the diversity of modes of interdisciplinary work, several organizational models have evolved (see Table 2-1). For the purpose of this report, the committee has developed the following description as a point of departure:

> Interdisciplinary research (IDR) is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice.

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Research is truly interdisciplinary when it is not just pasting two disciplines together to create one product but rather is an integration and synthesis of ideas and methods. An example is the current exploration of string theory by theoretical physicists and mathematicians, in which the questions posed have brought fundamental new insights both to mathematicians and to physicists.

Convocation Quote

> Interdisciplinary research by definition requires the researchers to learn the other discipline. I like to stress vocabulary, but also methodology; I feel very strongly about it.
>
> Ruzena Bajcsy, director of the Center for Information Technology Research in the Interest of Society, University of California, Berkeley

Other terms used include borrowing and multidisciplinary research.

- *Borrowing* describes the use of one discipline's methods, skills, or theories in a different discipline. A borrowed technique may be assimilated so completely that it is no longer considered foreign, and it may transform practice without being considered interdisciplinary.[1] An example of borrowing is the use of physical-science methods in biologic research, such as electron microscopy, x-ray crystallography, and spectroscopy. Such borrowing may be so extensive that the origin of the technique is obscured.[2]
- For purposes of this discussion, *multidisciplinary research* is taken to mean research that involves more than a single discipline in which each discipline makes a separate contribution. Investigators may share facilities and research approaches while working separately on distinct aspects of a problem.[3] For example, an archaeological program might require the participation of a geologist in a role that is primarily supportive. Multidisciplinary

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[1] Klein, J. T. "A Conceptual Vocabulary of Interdisciplinary Science." *Practising Interdisciplinarity*. Eds. Weingart, P. and Stehr, N. University of Toronto Press, Toronto, 2000. pp. 3-24.

[2] See Holton, G., Chang, H., and Jurkowitz, E. "How a scientific discovery is made: A case history." *American Scientist*, Vol. 84, July-August 1996, pp. 364-75, for specific examples of borrowing.

[3] Friedman, R. S. and Friedman, R. C. "Organized Research Units of Academe Revisited." In *Managing High Technology: An Interdisciplinary Perspective*. Eds., Mar, B. W., Newell, W. T. and Saxberg, B. O. Amsterdam: North Holland-Elsevier, 1985. pp. 75-91.

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STRUCTURE/POLICIES

TABLE 2-1 Interdisciplinary Research Structures

As a direct response to one component of its charge, "Identify and analyze current structural models of interdisciplinary research," the committee collected information on about 100 existing IDR groups and centers. The committee tested the categorization proposed by Epton et al.[a] and found that, although it is largely applicable, there are important additional IDR structural categories and characteristics, including national labs, space allocation, and fluidity of teams.

SMALL ACADEMIC (< 10 persons)
- Bottom-up initiation
- Research is primary; training is byproduct
- Loose management structure
- Many participants have disciplinary research commitments as well

LARGE ACADEMIC
- Bottom-up initiation, top-down incubation and management
- Research and training components
- Management by directors who report directly to vice president for research or equivalent
- Tend to be permanent features: new building, instrumentation
- Some centers "co-hire" faculty, but faculty are affiliated with departments
- Space allocation: mix of permanent and "hotel" facilities

INDUSTRY
- Top-down, product-driven research
- Focused on research, not training
- Structured management
- Discrete timelines and end points
- Fluid movement of researchers between teams

NATIONAL LABORATORIES
- Blend of top-down, mission-driven research and bottom-up initiation
- Research and training components
- Structured management
- Discrete timelines and end points
- Fluid movement of researchers between teams

INTERINDUSTRY, INTERUNIVERSITY, UNIVERSITY-INDUSTRY
- Top-down, societal needs-driven research (can be basic and applied)
- Research and training components
- Part-time directors with advisory boards
- Often initiated with large starting grants (such as National Science Foundation–funded Science and Technology Centers and Engineering Research Centers)
- Except for seed grants, faculty must provide own grant money
- Programs may offer an "immersion" IDR opportunity

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[a] Epton, S. R., Payne, R. L., and Pearson, A. W. (1985) "Contextual Issues in Managing Cross-Disciplinary Research." In *Managing High Technology: An Interdisciplinary Perspective*. Eds. Mar, B. W., Newell, W. T. and Saxberg, B. O. New York: Elsevier. pp. 209-29.

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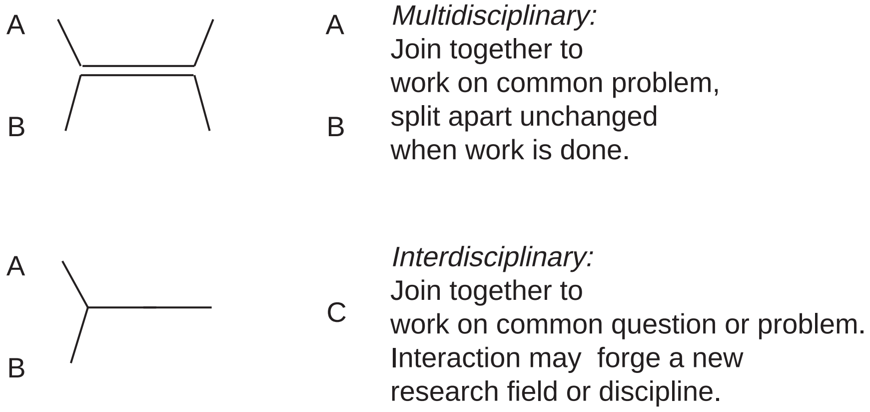

Multidisciplinary:
Join together to
work on common problem,
split apart unchanged
when work is done.

Interdisciplinary:
Join together to
work on common question or problem.
Interaction may forge a new
research field or discipline.

FIGURE 2-1 Difference between multi- and interdisciplinary.
SOURCE: Adapted from L. Tabak, Director, NINDS, NIH. Presentation at Convocation on Facilitating Interdisciplinary Research, Washington, D.C., January 29, 2004.

research often refers to efforts that are additive but not necessarily integrative (see Figure 2-1).[4,5]

IDR can also be described in terms of modes of participation. In one mode an individual investigator masters and integrates several fields. The investigator may conceive a new problem or method or may venture far enough from his or her original discipline to create a new field. For example, Albert Einstein ventured from his field of physics into Riemann geometry to describe his new General Theory of Relativity.

In a second mode, a group of investigators, each with mastery in one field, learn to communicate and collaborate on a single problem.[6] In some cases, such groups may be quite large, as in high-energy physics and genomics research.

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[4] Porter, A. L. and Rossini, F. A. "Multiskill Research," *Knowledge: Creation, Diffusion, Utilization*, Vol. 7, No. 3, March 1986, p. 219.

[5] Klein, J. T. *Interdisciplinarity: History, Theory, and Practice*. Detroit: Wayne State University Press, 1990, p. 56.

[6] In one formulation, this mode is termed consilience: the "jumping together of knowledge" across disciplines "to create a common groundwork of explanation". Wilson, E. O. *Consilience: The Unity of Science*, New York: Alfred A. Knopf, 1998, p. 8.

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Convocation Quote

If you think of disciplines as organs, true interdisciplinarity is something like blood. It flows. It is a liquid. It is not contained. There is no inside and outside.

Alice Gottlieb, professor of medicine and director, Clinical Research Center at the Robert Wood Johnson Medical School

The committee paid special attention to interdisciplinary *education*, viewing it as a central component of IDR. Students are prepared for the complexities of IDR when they are encouraged to understand and pursue multiple disciplines and to address complex problems from the perspective of multiple fields in their undergraduate and graduate studies. Specific suggestions for strengthening interdisciplinary education are presented in Chapters 4, 5, and 9.

CHALLENGES DRIVING INTERDISCIPLINARY RESEARCH

To understand the natural world, scientists are drawn toward the unknown, especially toward the "grand challenges" of research. How did the universe originate? What physical processes control climate? What is the carrying capacity of the biosphere? Such challenges almost always invite journeys across disciplinary frontiers. A scientist may respond to many kinds of motivation, or "drivers," in undertaking interdisciplinary projects. We list four such drivers below, providing examples and exploring why the practice of modern science and engineering requires interdisciplinary work.

The Inherent Complexity of Nature and Society

Human society in its natural setting contends with enormously complex systems that are influenced by myriad forces. It is not possible to study the earth's climate, for example, without considering the oceans, rivers, sea ice, atmospheric constituents, solar radiation, transport processes, land-use, land-cover, and other anthropogenic practices and the feedback mechanisms that link this "system of subsystems" across scales of space and time. A full predictive or even descriptive understanding requires the use of many disciplines (see Box 2-1).

Nature's complexity often leads to surprises that require much thought and experimentation to unravel. An example is the unexpected emergence of the Antarctic ozone hole in the austral springtime, a phenomenon found to be the consequence of complex chemical and dynamic pathways attributable to the use of chlorine- and bromine-bearing compounds in commercial

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EVOLUTION

BOX 2-1 The International Geosphere-Biosphere Program (IGBP)

> The real connections that link the geosphere and biosphere to each other are subtle, complex, and often synergistic; their study transcends the bounds of specialized, scientific disciplines and the scope of limited, national scientific endeavors. For these reasons progress in fundamental areas of ocean-atmosphere interactions, biogeochemical cycles, and solar-terrestrial relationships has come far more slowly than in specialized fields, in spite of the obvious practical importance of such studies. If, however, we could launch a cooperative interdisciplinary program in the earth sciences, on an international scale, we might hope to take a major step toward revealing the physical, chemical, and biological workings of the Sun-Earth system and the mysteries of the origins and survival of life in the biosphere. The concept of an International Geosphere-Biosphere Program (IGBP), as outlined in this report, calls for this sort of bold "holistic" venture in organized research—the study of whole systems of interdisciplinary science in an effort to understand global changes in the terrestrial environment and its living systems.[a]

So begins the preface to a 1983 workshop report that would help to launch the IGBP, which 20 years later is one of the largest interdisciplinary international research efforts ever undertaken. In its origins, the program reflected all the major drivers of IDR. It begins with the *complexity of nature*, the interactions between the land mass, the oceans of air and water, and the life forms of Earth. It finds that much of the most exciting science takes place on the boundaries of both systems and disciplines, such as the biogeochemical flows of the major life-support elements. Encouraging such explorations are powerful *societal needs* to understand how humankind is transforming the earth and the threats and opportunities that such transformation poses. Making possible such ambition are *generative technologies*, particularly computer simulation and modeling, remote sensing from space, and recovering the past from cores of ocean bottom, ice, lakes, and trees.

In scale, the program reflects both big science and local investigation. Some 10,000 scientists in 80 countries and more than 20 disciplines take part in IGBP scientific activities.[b] They include agricultural scientists, archaeologists, atmospheric chemists, and dynamicists, biologists, climatologists, ecologists, economists, environmental historians, geographers, geologists, hydrologists, mathematicians, meteorologists, plant physiologists, political scientists, physical and chemical oceanographers, remote sensing scientists, and sociologists.

The program has transformed the disciplines initially involved. Disciplines that were primarily focused on local and small scales, such as ecology, now address large-scale processes and conduct extensive experiments including in situ carbon enrichment and experimental deforestation. Disciplines that were primarily curiosity-driven such as the many paleosciences, have acquired important societal relevance. Natural and social sciences have come to need and value each other.

continues

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[a] Friedman, H. Preface. *Toward an International Geosphere-Biosphere Program: A Study of Global Change*. Report of a National Research Council Workshop, Woods Hole, MA July 25-29, 1983. Washington: National Academy Press, p. vii.

[b] For these details and insights we are grateful to Will Steffen, Executive Director of the IGBP.

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BOX 2-1 Continued

Disciplines have discovered common interests, such as how to relate wholes to parts, macro processes to micro behavior, and global to local. Indeed, global change science now exhibits many interdisciplinary aspects, with a second generation of scientists transcending their disciplines and schooled in problem-driven common knowledge.

But most important are the major scientific findings. The program has transformed our understanding of both nature and humankind. A recent summary volume[c] finds that:

- The earth is a system that life itself helps to modulate. Biological processes interact with chemical and physical processes to create the planetary environment.
- Human activities are influencing the functioning of the earth system in many important ways.
- The earth is operating in a no-analogue state. The magnitudes and rates of changes occurring simultaneously in the earth system are unprecedented.
- The earth's dynamics are characterized by critical thresholds and abrupt changes.

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[c] Steffen, W., Sanderson, A., Tyson, P., Jäger, J., Matson, P., Moore III, B., Oldfield, F., Richardson, K., Schellnhuber, H-J., Turner II, B. L., Wasson, R. *Global Change and the Earth System: A Planet Under Pressure*. IGBP Global Change Series.New York: Springer-Verlag, Berlin Heidelburg, 2004, 336 pp.

products. Pinpointing that cause required the combined efforts of many scientific and technical disciplines; solving the problem itself required the collaboration of physical scientists, engineers, economists, and social scientists.

Similarly, the human-genome mapping project was a complex undertaking that depended on extensive collaboration across many fields, including the biological and computational sciences. Basic questions of life—how living beings grow, how the brain functions, why many animals need to sleep, how retroviruses function—share the characteristic of complexity, and understanding them, even in part, depends on multiple disciplines. Gaining such understanding will almost certainly require deep expertise both at the subsystem level and at the interdisciplinary level—and the integration of these two levels. It is important to note that depth in research is not confined to single-discipline investigations. Statistical mechanics, for example, unites physicists and mathematicians in studies of substantial depth.[7]

If science and engineering deal with extremely complex systems, the same is true for studies of human society. How human societies evolve,

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[7] Kafatos and Eisner, ibid. p. 1257.

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make decisions, interact, and solve problems are all matters that call for diverse insights. Very fundamental questions are inherently complex. For example, why do humans kill each other? Why does hunger persist in a world of plenty? Answering such questions successfully requires collaboration across the natural sciences, social sciences, and humanities.

The Drive to Explore Basic Research Problems at the Interfaces of Disciplines

Some of the most interesting scientific questions are found at the interfaces between disciplines and in the white spaces on organizational charts. Exploring such interfaces and interstices leads investigators beyond their own disciplines to invite the participation of researchers in adjacent or complementary fields and even to stimulate the development of a new interdisciplinary field. Examples include the following:

- Biochemistry was long ago considered an interdisciplinary activity; today it has departmental, program, or similar structural status in most major universities.
- The field of cognitive science has evolved in response to questions that could not be answered by single disciplines. Today the Cognitive Science Society embraces anthropology, artificial intelligence, neuroscience, education, linguistics, psychology, and philosophy.[8]
- As biology has become more quantitative, its points of overlap with the mathematical sciences and the physical sciences have become more numerous and important. Today, the computational and statistical power of mathematics and the research facilities of the physical sciences are required for making sense of, for example, genomics, proteomics, epidemiology, structural biology, and ecology.
- Ecology and economics (and other social sciences) have a common origin, at least in name, and, increasingly, a common field—ecologic economics—that aspires to facilitate “understanding between economists and ecologists and the integration of their thinking” with the goal of developing a sustainable world.[9]

That many of the most interesting scientific questions are lodged in the interstices between disciplines can also be seen in various activities that honor outstanding creativity. For example, although the MacArthur Foundation fellow awards are not given on the basis of interdisciplinarity, to

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[8] See Appendix D on the development of disciplinary societies.

[9] The Web site of the International Society of Ecological Economics is *http://www.ecologicaleconomics.org*.

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judge from brief biographies, two-thirds to three-fourths of MacArthur fellows in science appear to work in interdisciplinary fields.

The Need to Solve Societal Problems

Human society depends more than ever on sound science for sound decision making. The fabric of modern life—its food, water, security, jobs, energy, and transportation—is held together largely by techniques and tools of science and technology. But the application of technologies to enhance the quality of life can itself create problems that require technological solutions. Examples include the buildup of greenhouse gases (hence global warming), the use of artificial fertilizers (water pollution and eutrophication), nuclear-power generation (radioactive waste), and automotive transportation (highway deaths, urban sprawl, and air pollution).

EVOLUTION

BOX 2-2 The Development of Microwave Radar at MIT's Radiation Laboratory[a]

The development of radar (radio detection and ranging) during the 1940s was largely accelerated by military needs in World War II. Members of the scientific community recognized the value of radar to the war effort. In the United States, the effort to expand microwave radar capabilities was concentrated at MIT's Radiation Laboratory, which was staffed by civilian and academic scientists in many disciplines. Projects included physical electronics, microwave physics, electromagnetic properties of matter, and microwave communication principles.

The "Rad Lab" was responsible for almost half the radar deployed in World War II and at one point employed almost 4,000 people working on several continents in government, industrial, and university laboratories. What began as a British-American effort to make microwave radar work evolved into a centralized laboratory committed to understanding the theories behind experimental radar while solving its engineering problems.

The Rad Lab was formally shut down after the end of World War II in 1945, but in 1946 the Basic Research Division was incorporated into the new Research Laboratory of Electronics at MIT. Research continued on problems in physical electronics and microwave physics. Modern techniques were applied to physics and engineering research, and engineering applications were emphasized in microwave communication.

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[a] MIT Radiation Laboratory series Volume 28. Ed. Henney, K. Available at *http://www.brewbooks.com/ref/rl/ref_radlab_v28.html*; G.Goebel, Microwave Radar & The MIT Rad Lab. Available at *http://www.vectorsite.net/ttwiz3.html*; Lab's Microwave Traditions at RLE. RLE currents, Vol. 4, No. 2—Spring 1991. Available at *http://rleweb.mit.edu/radlab/radlab.HTM.*

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An indication of interdisciplinarity in response to societal needs is the success of large, sustained endeavors, many of which continue to this day. During World War II, for example, science and engineering demonstrated the ability to strengthen military power rapidly (see Box 2-2). The 3-year Manhattan Project (1942-1945) to develop an atomic bomb was an interdisciplinary effort requiring researchers from many fields and subfields of science and engineering, from the wide sweep of chemistry and physics to the specific skills of uranium refinement, isotope separation, plutonium purification, nuclear decay measurement, nuclear-waste disposal, and radiation biology.

Another example is the National Cancer Act, signed by President Nixon in 1971. The act authorized an interdisciplinary research effort involving a vast sweep of biomedical disciplines, from genetics and cell biology through clinical care, bioethics, and biostatistics. Cancer research has always been among the most interdisciplinary of fields, mirroring the complexity of the many diseases it addresses.

Researchers continue to apply the 20th century's revolutionary genetic insights to unravel the structures and functions of proteins (see Box 2-3). This investigation influences every aspect of the life sciences, at every level, from molecular arrangements to clinical, population, and ecologic studies.[10]

The Stimulus of Generative Technologies

Generative technologies are those whose novelty and power not only find applications of great value but also have the capacity to transform existing disciplines and generate new ones. An early momentous example was the use of microscopes by Hooke and van Leeuwenhoek to view "cubicles," or cells, in animal and plant bodies and to make it possible to see living "animalcules" (bacteria) with their own eyes—both critical steps along the path to modern molecular biology.

A recent example of a generative technology has been the development of the Internet, whose popular form is only about 10 years old. The Internet

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[10] Yet another example can be found in Branscomb, L., Holton, G., and Sonnert, G. *Cutting-edge Basic Research in the Service of Public Objectives: A Blueprint for an Intellectually Bold and Socially Beneficial Science Policy*. Consortium for Science Policy Outcomes, Arizona State University, May 2001. Available on-line at *http://www.cspo.org/products/reports/scienceforsociety.pdf* (Based on a workshop sponsored by the David and Lucile Packard Foundation and the Alfred P. Sloan Foundation.) The report makes the case for use-inspired or "Jeffersonian" basic research and includes a master list of questions in science and technology, most of which require interdisciplinary approaches. Holton, G., "What Kinds of Science are Worth Supporting?" The Great Ideas Today, Encyclopedia Britannica, Chicago, 1998.

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EVOLUTION

BOX 2-3 Protein Structure Determination Using X-Ray Crystallography[a,b]

The knowledge of protein structures is critical to fighting disease with drugs. In recent years, the development of new techniques to determine protein structure, combined with rapid improvement in computer technology, has allowed protein-structure determination to proceed at a rate that is keeping pace with advances in biomedical science. In the case of x-ray crystallography, its development and wide use in protein-structure determination–which spanned a century–began with no knowledge of its value for biomedicine.

X rays were first discovered in 1895, and the diffraction of x rays by electrons in crystals was first demonstrated in 1912. In the 1930s, x rays were aimed at crystals of biological molecules, but it was not until Perutz and Kendrew determined the molecular structure of hemoglobin and myoglobin in 1960 that the value of x-ray crystallography in protein science was realized. In the 1970s, synchrotron radiation (see Box 2-5) was harnessed as a source of x rays for protein crystallography, and the 1990s saw a great increase in the number of protein structures determined with this technique. Research to develop the technology was an interdisciplinary endeavor. Its long-term nature should remind those who facilitate IDR that support of basic research can often have payoffs that are not immediately visible and are often outside the field in which they were initially envisioned.

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[a] Dill, K. Strengthening Biomedicine's Roots. *Nature* 22 400:309-310. July 1999.

[b] History of X-ray Crystallography and Associated Topics. Available at *http://www.dl.ac.uk/SRS/PX/history/history.html.*

has both enhanced connectivity between people and revolutionized access to information, transforming the ability to interact and collaborate across space and time. It has special relevance to the world of research, for which it offers ways to work in large, distributed teams, enlarge the educational enterprise, provide access to data on time and spatial scales never possible before, and design powerful new tools to transform the processes of discovery, learning, and communication (see Box 2-4).

Dramatic declines in the cost of processing, storing, and transmitting information are transforming science and engineering disciplines. Some experts have called on the National Science Foundation and other science agencies to launch a bold new initiative in cyberinfrastructure, which would play the same role in supporting the knowledge economy that roads, power grids, and rail lines have played in supporting the industrial economy.[11]

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[11] Revolutionizing Science and Engineering through Cyberinfrastructure. Report of the National Science Foundation Advisory Panel on Cyberinfrastructure. February 3, 2003. Available at *http://www.cise.nsf.gov/sci/reports/toc.cfm*.

INNOVATIVE PRACTICE

BOX 2-4 The Knowledge and Distributed Intelligence (KDI) Funding Initiative

The rise in computer power and connectivity is reshaping relationships among people and organizations and transforming the processes of discovery, learning, and communication. The knowledge and distributed intelligence (KDI) funding initiative at the National Science Foundation (NSF) was created in 1998 to find ways to model and make use of complex and cross-disciplinary scientific data.[a] KDI supported interdisciplinary projects of individuals or groups that took advantage of changes in how research was being done, such as increases in computing power and connectivity among researchers. The initial solicitation had three foci of research: knowledge networking, learning and intelligent systems, and new computational challenges. The KDI initiative has sponsored research that analyzes living and engineered systems in new ways, and it encourages investigators to explore the cognitive, ethical, educational, legal, and social implications of new types of learning, knowledge, and interactivity.

A program assessment was carried out in 2002. NSF recognized that metrics have to be developed that match the goals of the research program. To that end, KDI grantees were invited to a workshop to determine how projects were organized and managed, to identify the projects, outcomes, and to catalog suggestions that might help future grantees in their execution of KDI-sponsored projects.

The evaluation[b,c] provides interesting information about tools, research directions, outreach, and student training. Management of collaborative and multidisciplinary research projects was a substantive issue. Project success depended largely on coordinating interactions among researchers. Dispersion of participants, rather than interdisciplinarity, was the most problematic aspect of KDI projects. Projects with principal investigators in multiple universities were substantially less well coordinated and reported fewer favorable outcomes. Project-related conferences, workshops, and other regular meetings appeared to reduce the adverse effects of dispersion. The assessment identified a number of needs for further support, including management tools that would increase the ease with which project participants interact over the lifetime of the project.

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[a] The original KDI solicitation is available at: *http://www.nsf.gov/pubs/1998/nsf9855/nsf9855.pdf.*

[b] Cummings, J. and Kiesler, S. (2004) KDI Initiative: Multidisciplinary Scientific Collaborations. NSF Report. Available on the NSF KDI Home Page: *http://www.cise.nsf.gov/kdi/about.html.*

[c] Taking stock of the KDI: Science of Evaluation. *http://www.cise.nsf.gov/kdi/eval.html.*

This cyberinfrastructure might be composed of distributed, high-performance computers, online scientific instruments and sensor arrays, multidisciplinary collections of scientific data, software toolkits for modeling and interactive visualization, and tools that enable close collaboration by physically distributed teams of researchers (see Box 2-5 and Box 9-7).

EVOLUTION

BOX 2-5 Tool-Driven Interdisciplinary Research: The Advanced Photon Source (APS) at Argonne National Laboratory

The Advanced Photon Source (APS) at Argonne National Laboratory is a national synchrotron-radiation light-source research facility. Commissioned in 1995, the APS is funded by the US Department of Energy, Office of Science, Office of Basic Energy Sciences.[a] Members of the international research community use high-brilliance x-ray beams from the APS to carry out basic and applied research in materials science; biology; physics; chemistry; environmental, geophysical, and planetary science; and innovative x-ray instrumentation.

Researchers come to the APS as members of collaborative access teams (CATs) or as independent investigators. CATs comprise large numbers of investigators with common research objectives and are responsible for design, construction, funding, and operation of beamlines at the facility. CATs must allocate 25 percent of their x-ray beam time to independent investigators or groups not affiliated with CATs.

The APS was designed to accommodate up to 32 CATs, of which over 20 are in operation. One of the interdisciplinary industry-university collaborations established to take advantage of APS resources is the University of Michigan-Howard University-AT&T Bell Laboratories (MHATT) CAT, formed in 1989. MHATT-CAT studies range from basic protein dynamics to the behavior of solid-state lasers. According to one of the directors of the MHATT-CAT, University of Michigan Physics Professor Roy Clarke, "a very important part of the project is to establish high-speed communications that link participating institutions and the facility at the APS, so that our students, particularly our undergraduate researchers, can participate actively in the research while attending classes on their respective campuses."[b]

Others CATs are run by university or industry teams. To enhance communication among and between teams, the APS Web site provides a linked list of CATs and offers a listserver for inter-CAT communication. The APS Web site also lists meetings of interest to facility users and highlights recent research by posting abstracts and figures on its home page.

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[a] APS: Advanced Photon Source at ANL. Home page: *http://epics.aps.anl.gov/aps.php.*

[b] Elgass, J .R. (1994) Clarke co-directs project at Argonne photon facility. The University Record. University of Michigan. March 28, 1994. Accessed March 29, 2004 at *http://www.umich.edu/~urecord/9394/Mar28_94/2.htm.*

Advocates of cyberinfrastructure believe that it will allow a growing number of researchers to collect, process, analyze, and make available volumes of information that trigger shifts in the kinds of scientific questions that can be pursued; simulate systems of greater complexity and importance; and more easily work across scientific disciplines. For example, the National Science Foundation has funded a "National Virtual Observa-

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tory"[12] that is likely to transform astronomy. Within a few years, comprehensive sky surveys will be generating petabytes (quadrillions of bytes) of data every year. The long-term goal is to make this data available to every researcher, along with the databases, data mining algorithms, and visualization tools needed to make sense of it. Researchers believe that this information abundance will lead to qualitatively new science, such as statistical astronomy that analyzes the large-scale structure of the universe, and automated searches for exotic or previously unknown types of celestial objects.

Magnetic resonance imaging (MRI) is another example of a generative technology. The Nobel Prize in medicine and physiology for 2003 was awarded to chemists Paul Lauterbur and Peter Mansfield to honor their work that led to MRI. Their research grew out of a fundamental interest in using the magnetic resonance effect to produce images in proton-containing matter. MRI and positron-emission tomography (PET), with ancillary mathematical advances in tomographic analysis, have revolutionized many aspects of medical diagnosis and opened opportunities for safe experimentation with human subjects in the cognitive sciences.[13]

CONCLUSIONS

The potential power of IDR to produce novel and even revolutionary insights is generally accepted. Ultimately, however, the value of IDR to the scientific enterprise depends on the extent to which individual researchers are free to engage in it. IDR must be not only possible but also attractive for students, postdoctoral fellows, and faculty members.

FINDINGS

Interdisciplinary research (IDR) is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice.

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[12] US National Virtual Observatory. *http://www.us-vo.org/*.

[13] In one view, "new technologies are now driving scientific advances as much as the other way around. These technologies are enabling novel approaches to old questions and are posing brand-new ones." Leshner, A. I. "Science at the leading edge," *Science* Vol. 303:729. Feb. 6, 2004.

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"I CAN REMEMBER WHEN ALL WE NEEDED WAS SOMEONE WHO COULD CARVE AND SOMEONE WHO COULD SEW."

IDR is pluralistic in method and focus. It may be conducted by individuals or groups and may be driven by scientific curiosity or practical needs.

Interdisciplinary thinking is rapidly becoming an integral feature of research as a result of four powerful "drivers": the inherent complexity of nature and society, the desire to explore problems and questions that are not confined to a single discipline, the need to solve societal problems, and the power of new technologies.

Social-science research has not yet fully elucidated the complex social and intellectual processes that make for successful IDR. A deeper understanding of these processes will further enhance the prospects for creation and management of successful IDR programs.

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