6

How Funding Organizations Can Facilitate Interdisciplinary Research

Many kinds of organizations in addition to academic institutions provide funding for scientific and engineering research, including federal and state agencies, private foundations, corporations, and nonprofit organizations. Congress and state legislatures also play major roles in determining research priorities for the nation and states. All funding organizations, because of the financial and other resources they can potentially bring to bear, can develop and press for reforms that facilitate interdisciplinary research and education.

A VISION FOR FUNDING ORGANIZATIONS THAT WISH TO PROMOTE INTERDISCIPLINARY RESEARCH

Some organizations may hesitate to become involved in interdisciplinary research (IDR) to the extent that it requires risk-taking and administrative complexities that may be greater than those of single-discipline programs. It is helpful, however, to recall the "drivers" of IDR described in Chapter 2, which indicate that today's most pressing research and societal questions are often best addressed by interdisciplinary approaches.

Convocation Quote

In our mind, it takes a multidisciplinary approach to address a number of critical, important problems that are mission areas for the Defense Department, but we also think that it does three things. It accelerates research progress by bringing groups of people together to address the problem. It expedites the transition of research into products that can actually be used by the Defense Department and the community in general. Most importantly perhaps, it prepares students to think in an interdisciplinary manner and prepares them to be a more agile sort of workforce.

William Berry, director, Office of Basic Research, Department of Defense

Those whose missions are aligned with IDR can promote it with several strategies. They may wish to have a substantial influence on the direction and productivity of research, support emerging fields that have insufficient support elsewhere, emphasize the educational and training components of interdisciplinary work, or develop more effective evaluation and review measures that help to select and sustain the best projects and people. By pulling and adjusting their own levers of influence, funding organizations play a critical role in facilitating IDR.

Congress has shown its support of IDR, indicating, for example, in the fiscal year 2004 Consolidated Appropriations Act that the National Science Foundation's Research and Related Activities account "supports . . . critical cross-cutting research which brings together multiple disciplines. The conferees urge the Foundation in allocating the scarce resources provided in this bill and in preparing its fiscal 2005 budget request to be sensitive to maintaining the proper balance between the goal of stimulating interdisciplinary research and the need to maintain robust single issue research in the core disciplines."[1]

BARRIERS ENCOUNTERED BY FUNDING ORGANIZATIONS IN SUPPORTING IDR

Like academic institutions, funding organizations may face significant barriers in facilitating IDR—some that originate in their own traditions and others that are inherent in the nature of IDR. Most of the barriers discovered during this study have to do with the complex nature of IDR:

[1]US Congress. House Committee on Appropriations. 2003. H.R. 2673—*Making Appropriations for Agriculture, Rural Development, Food and Drug Administration, and Related Agencies for the fiscal year ending September 30, 2004, and for other purposes*. 108th Cong., H.R. 108-401:1167.

- Effective review of IDR proposals may not be possible with traditional peer review that relies primarily on experts in a single discipline.
- Funding organizations often find IDR programs more difficult to plan and develop than single-discipline programs because IDR programs may require extra time to build consensus and introduce researchers to new languages, knowledge, and cultures.
- Funders, like other organizations, have insufficient knowledge about the best ways to solicit IDR proposals and evaluate IDR programs.
- It is not always easy to manage the transition of an IDR project from startup to larger-scale, longer-term project funding so as to maintain program momentum.

Among the top recommendations to funding agencies from survey respondents were developing strategies to facilitate IDR, implementing a more effective review process, and rethinking funding allocation strategies (see Figure 6-1).

Barriers to IDR exist even in the most experienced funding organizations. For example, the National Science Foundation (NSF) has long been a pioneer in promoting IDR (see Figure 6-2). A recent comprehensive study of NSF policies found that "NSF's priority areas demonstrate an interdisciplinary perspective, especially as evidenced by the extent of cross-directorate funding." However, the same study cautioned that "highly variable attention to interdisciplinary research in NSF's strategy, budget, and public documents does not communicate a consistent message." It also found that "no effective mechanism is in place to track or set performance goals for interdisciplinary research that can be used for planning, budget, and management decision making" and that "NSF's two merit review criteria say relatively little with regard to interdisciplinary research."[2]

Additional difficulties were reported by investigators applying for agency funding. Applicants interested in interdisciplinary work felt disadvantaged relative to applicants focusing on single disciplines because of relatively short submission deadlines, pressure to understate costs for IDR proposals, the page limit on proposals, the difficulty of teaming administratively with investigators in different institutions, and lack of a well-defined review path for IDR proposals.[3]

Those findings may say more about the general challenges of funding any large IDR project or initiative than about the shortcomings of a particular agency. Indeed, state and federal budgeting systems, combined with

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[2]National Academy of Public Administration (NAPA), "National Science Foundation: Governance and Management for the Future," April 2004, pp. 61-89.
[3]NAPA, ibid. p. 102.

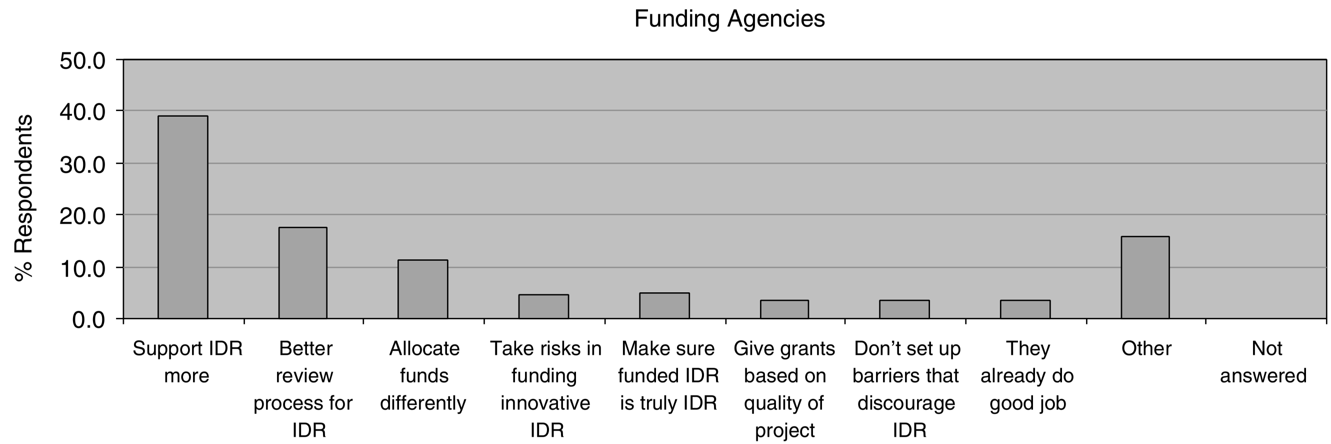
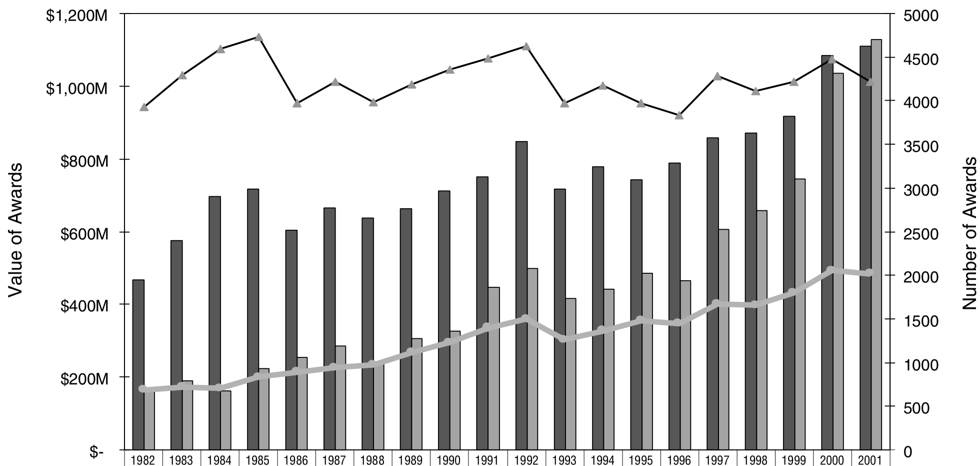


FIGURE 6-1 Recommendations to funding agencies.
NOTES: Survey Question: "If you could recommend one action that funding agencies could take that would best facilitate interdisciplinary research, what action would that be?" The top three recommendations for funding agencies (n = 266) were to provide more support for IDR (39.1 percent, to develop and implement a more effective review process for IDR proposals (17.7 percent), and to rethink funding allocation strategies (11.3 percent).



	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
By $ - SIRPs	$467M	$576M	$698M	$717M	$603M	$666M	$638M	$663M	$712M	$750M	$847M	$716M	$779M	$743M	$789M	$859M	$871M	$917M	$1,084	$1,110
By $ - >=2 PIs	$168M	$189M	$161M	$224M	$255M	$286M	$238M	$306M	$327M	$448M	$498M	$415M	$442M	$485M	$464M	$606M	$658M	$744M	$1,037	$1,129
By # - SIRPs	3931	4298	4597	4737	3970	4221	3984	4186	4353	4491	4626	3976	4178	3968	3837	4284	4111	4221	4472	4215
By # - >=2 PIs	690	720	706	832	891	942	969	1118	1227	1389	1498	1261	1365	1477	1445	1671	1663	1794	2051	2016

FIGURE 6-2 Trends in teams: Single vs. multiple investigator awards at the National Science Foundation, 1982-2001.

NOTES: There has been a steady trend in research, reflected in NSF funding, towards awards with more than one PI. This predates any recent initiative and actually helped influence the move toward interdisciplinary initiatives in recent years. While the growth area is in multiple PI awards, single investigators won about half of the funding and two-thirds of the awards in fiscal year 2001. This compares with seven-eighths of the funding and three-quarters of the grants for single investigator research proposals in fiscal year 1982.

SOURCE: From Vernon Ross, Budget Operations and Systems, NSF, from a presentation given at the National Academy of Engineering, October 3, 2003. While the NSF supports IDR, it has no operational definition of IDR. In a study of NSF which covered IDR, the National Academy of Public Administration concluded that the best current measure of IDR at NSF is multi-investigator grants. (See footnote 2.)

long-term mission strategies, place substantial constraints on the funding activities of every public agency.

Convocation Quote

No single program can be a forcing function. Creativity, good research, good ideas and research questions are not owned by a single program. Dedicated program champions at both DOE headquarters and at the laboratories are critical because integration needs leadership.

Marvin Singer, senior adviser, Applied Energy Program,
Office of Science, Department of Energy

SUPPORT FOR IDEAS AND INITIATIVES

Nonetheless, some funding organizations, especially federal agencies with research-based missions, have built large IDR programs by responding to the drivers of IDR described in Chapter 2, especially the inherent complexity of nature, the desire to follow questions to the interfaces of disciplines, and the need to address multifaceted societal issues.

Both public and private funding organizations have been successful in linking their missions with an interdisciplinary vision. NSF, the only agency whose primary mission is to support science and engineering research and education, has been a leader and exemplar in supporting individuals, projects, and multi-institution programs for IDR. Its science and technology centers and engineering research centers, for example, have served as a model for interdisciplinary centers at universities that work in partnership with industry (see Box 8-2) and its research training grants (see Box 8-4). Other IDR initiatives include the Mathematical Sciences: Innovations at the Interface, the Biocomplexity in the Environment: Integrated Research and Education in Environment Systems program, and the former Information Technology Research program.

Similarly, the National Institutes of Health (NIH) has adopted its own interdisciplinary vision. Noting that "the traditional divisions within biomedical research may in some instances impede the pace of scientific discovery,"[4] NIH has constructed a new strategic roadmap intended "to lower these artificial organizational barriers and advance science." To do so, the agency has announced a series of awards specially aimed at supporting IDR (see Box 6-1), including awards for "training of scientists in interdiscipli-

[4] *http://nihroadmap.nih.gov/interdisciplinary/index.asp.*

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BOX 6-1 NIH Roadmap: Research Teams of the Future

Interdisciplinary research is an important initiative of the 2003 National Institute of Health (NIH) Roadmap.[a] One of the three themes of the roadmap is "Research Teams of the Future." It is becoming more obvious that as research problems become more complex it is often necessary to amalgamate a research team with many disciplines to tackle a research problem effectively. However, NIH found that the traditional divisions in biomedical research in some instances may impede scientific discovery. The purpose of their IDR initiative is to develop innovative ways to combine skills and disciplines to accelerate discovery of fundamental knowledge and advance existing knowledge.

Several grants and funding opportunities were created to help to facilitate IDR.[b] Included are training grants for graduate students and postdoctoral scholars (the T90),[c] a curriculum development award,[d] and a short intensive course for researchers at all career levels to receive formal training in another discipline.[e] The goal of the various programs is for researchers to "emerge with sufficient understanding of a new discipline(s) that they can meld it with their previous training to generate new interdisciplines with novel research strategies."

[a]Roadmap home page *http://nihroadmap.nih.gov/index.asp.*

[b]NIH Roadmap Interdisciplinary Initiative home page *http://nihroadmap.nih.gov/interdisciplinary/grants.asp.*

[c]Kozel, P. "NIH's Roadmap to the Future" *Science's Next Wave*. January 2004. *http://nextwave.sciencemag.org/cgi/content/full/2004/01/08/4*? Training for a New Interdisciplinary Research Workforce (T90) *http://grants.nih.gov/grants/funding/t90.htm.*

[d]Curriculum Development Award in Interdisciplinary Research (RFA-RM-04-007) *http://grants.nih.gov/grants/guide/rfa-files/RFA-RM-04-007.html.*

[e]Short Programs for Interdisciplinary Research Training (RFA-RM-04-008) *http://grants.nih.gov/grants/guide/rfa-files/RFA-RM-04-008.html.*

nary strategies; creation of specialized centers to help scientists forge new and more advanced disciplines from existing ones; and initiation of forward-looking conferences to catalyze collaboration among the life and physical sciences, important areas of research that historically have had limited interaction."

Other major federal efforts are explicitly interdisciplinary in concept, including the Multidisciplinary Research Program of the University Research Initiative (MURI), a multi-agency Department of Defense program that supports research teams "whose efforts intersect more than one traditional science and engineering discipline"[5] (see Box 6-2); the Interagency

[5]*http://www.onr.navy.mil/sci_tech/industrial/muri.htm.*

INNOVATIVE PRACTICE

BOX 6-2 The Department of Defense Multidisciplinary University Research Initiative

One way for funding organizations to support interdisciplinary research is to establish specific grants programs that reward interdisciplinary approaches. The US Department of Defense (DoD) Multidisciplinary University Research Initiative (MURI)[a] is specifically targeted at proposals that "intersect more than one traditional science and engineering discipline." The program disperses about $150 million per year and represents about 10 percent of DoD's overall basic research program.

MURI is designed to complement the core research supported by the department, which consists primarily of single-investigator approaches. Examples of subjects to be considered for funding by MURI are "Hybrid Bio-Mechanical Systems" and "Micro Hovering Aerial Vehicles with an Invertebrate Vision Inspired Navigation System." Goals for the program include bringing researchers together to expedite discovery and training students to think in an interdisciplinary manner. Like many examples of IDR, these grants are motivated by specific engineering goals that require advances in basic understanding to occur at the interface of diverse fields. As William Berry, the director of the Office of Basic Research at the Pentagon, has said, "Think of the end at the beginning."[b] In this case, the engineering goals are derived partially from the mission of the funding agency itself and partially from the researchers' vision for the kind of technology they want to create.

[a]MURI 2004 Program Solicitation. *http://www.onr.navy.mil/sci%5Ftech/industrial/363/muri.asp*.

[b]Berry, B. Comments at Convocation on Facilitating Interdisciplinary Research. January 29, 2004, Washington, D.C. *http://www7.nationalacademies.org/interdisciplinary/Convocation_Agenda.html*.

Education Research Initiative (IERI);[6] the National Aeronautics and Space Administration (NASA) astrobiology program (see Box 6-3);[7] and the government-wide National Nanotechnology Initiative, beginning in FY 2005, of which NSF will have the largest share.

[6]The IERI pairs information-technology (IT) researchers with those in another field interested in using cutting-edge IT to help solve problems. The goal of the initiative is to support scientific research that investigates the effectiveness of educational interventions in reading, mathematics, and the sciences as they are implemented in varied school settings with diverse student populations. *http://www.ed.gov/offices/OERI/IERI/*.

[7]For this program, according to NASA, "interdisciplinary research is needed that combines molecular biology, ecology, planetary science, astronomy, information science, space exploration technologies, and related disciplines. The broad interdisciplinary character of astrobiology compels us to strive for the most comprehensive and inclusive understanding of biological, planetary and cosmic phenomena." *http://astrobiology.arc.nasa.gov/*.

INNOVATIVE PRACTICE

BOX 6-3 NASA Fosters the Development of Interdisciplinary Fields

Federal agencies can play a pivotal role in launching IDR by providing funding for developing fields. As part of its Origins Program,[a] the National Aeronautics and Space Administration (NASA) has committed to promoting research in astrobiology, the interdisciplinary study of life in the universe.

The NASA Astrobiology Institute (NAI)[b] was created in 1998. Initially, 11 research proposals were selected; today, there are 16 participating institutions. Lead teams are supported by NASA through 5-year cooperative agreements with the Ames Research Center. Team members are from different disciplines—including physics, astronomy, geology, and biology—and often from different geographic locations. A major goal of NAI is to train a new generation of astrobiologists; to this end, NAI sponsors seminars, workshops, and professional training courses.

In addition to the lead teams, NAI fosters astrobiology research through support of research focus groups. These groups typically stimulate new fields of research and promote collaborations within and outside of NAI. Focus group proposals are typically for 3 years. NAI provides support for postdoctoral fellowships through the NASA-National Research Council Associateship Program. An NAI research scholarship provides stipends and research-related travel funds to graduate students and postdoctoral scholars so that they can circulate between two or more of the lead teams.

[a]NASA Origins Program home page *http://origins.jpl.nasa.gov/index1.html.* Accessed April 30, 2004.

[b]Astrobiology Institute home page *http://nai.arc.nasa.gov/index.cfm.* Accessed April 30, 2004.

The Defense Advanced Research Projects Agency (DARPA) is a subagency that has served as a global model for interdisciplinary effectiveness (see Box 6-4). By promoting high organizational flexibility and lowering barriers to collaboration, DARPA has been able to support innovative, cross-disciplinary projects at every level of complexity, including the open-ended research that led to major features of the Internet. Its Defense Science Office draws program officers from diverse disciplines and has directed strong support toward IDR projects. The R&D structure of the Department of Homeland Security was modeled explicitly on DARPA, as recommended by the National Academies.[8]

An essential feature of such new funding models is innovative, risk-taking leadership in the funding body. For example, those mentioned above

[8]National Research Council. *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism*. 2002. Washington, DC: The National Academies Press, pp. 335-57.

EVOLUTION

BOX 6-4 The Defense Advanced Research Projects Agency

The Defense Advanced Research Projects Agency (DARPA),[a] created in 1957 in the wake of Sputnik, has a long record of supporting high-risk, interdisciplinary research. DARPA is probably best known for its support of the ARPANET, the precursor to today's Internet, and stealth technology. In 1960, it began to fund the interdisciplinary laboratories, which played a critical role in fostering materials science and engineering in the United States. By the time DARPA transferred the program to the National Science Foundation in the early 1970s, it was supporting 600 faculty in physics, chemistry, metallurgy, materials science and engineering, and electrical engineering. More recently, DARPA launched a research program in FY 2000 called Bio:Info:Micro,[b] which funded six interdisciplinary teams of researchers in biology, information technology, and microsystems technology to deepen our understanding of neuroprocessing and regulatory networks.

DARPA has been successful in supporting high-risk, high-return IDR for a number of reasons,[c] among them:

1. Solicitations are focused on hard problems or emerging scientific and technical opportunities, not disciplines.
2. Offices are not organized around disciplines. At least 13 science, engineering, and medical disciplines are represented in the 20-person technical staff of DARPA's Defense Science Office.
3. The Department of Defense is willing to invest a small percentage of its budget (less than 1 percent) in radical innovation, but this tiny fraction of their budget is substantial—$3 billion.
4. DARPA continuously recruits high-quality program managers, who generally stay for 4-6 years. This ensures a steady stream of new ideas.
5. DARPA program managers are responsible for developing research programs. They define the problems, typically through continuous interactions with the research community on the one hand and the user community on the other hand. Thus, they are familiar both with the national technology capabilities that need to be developed and with the cutting-edge science and engineering issues, barriers, and opportunities that, if addressed with serious resources and creative interdisciplinary approaches, might lead to revolutionary advances.
6. DARPA program managers not only develop the programs but manage proposal solicitation and selection. Thus, they have complete control over which proposals to fund. They encourage risky and less mature ideas than are normally tolerated at agencies that rely on the more traditional peer-review process.
7. DARPA has no "entitled constituencies" and can fund research in academe, industry, and national laboratories
8. DARPA is willing to fund larger grants, which are often necessary to put together a "critical mass" of researchers in different disciplines.
9. DARPA program managers often play a hands-on role in encouraging interaction between the research teams they are funding.

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[a]DARPA home page. *http://www.darpa.mil/.* Accessed April 30, 2004.

[b]Bio:Info:Micro Program Solicitation. *http://www.darpa.mil/baa/ra00-14.htm.*

[c]Dubois, L. H. "DARPA's Approach to Innovation and Its Reflection in Industry." In *Reducing the Time from Basic Research to Innovation in the Chemical Sciences*. A Workshop Report of the Chemical Sciences Roundtable. 2003. Washington, D.C.: The National Academies Press.

have all encouraged exploratory and frontier research beyond the perceived boundaries of disciplines by providing opportunities for networking and special initiatives. Some funding organizations have also developed new proposal-review procedures to ensure expertise in each discipline represented in a project or proposal.

Finally, funding organizations can promote more public-private collaboration. In Europe, the Organization for Economic Co-operation and Development (OECD) Futures Projects offer a pragmatic approach to focused, multidisciplinary research and policy analysis on future-oriented themes involving both governments and private-sector participants. Futures Projects are launched when there is no appropriate committee or directorate to address a theme or when the interdisciplinary nature of the theme does not lend itself easily to treatment by a single or even several directorates.[9]

SUPPORT FOR PEOPLE AND PROGRAMS

In addition to funding new ideas and initiatives, funding organizations can focus their resources on opportunities to fund programs and people at various stages of their careers and in curriculum reform and interdisciplinary education. The stages, described in Chapter 4, have considerable overlap in the sense that all researchers, from undergraduates to senior faculty, have interests and motivations in common and benefit from similar kinds of support in addressing interdisciplinary research and education.

Convocation Quote

When MacArthur selects people to participate in research networks, it is more about their interest to go beyond their own paradigm and to be interested in a collaborative endeavor. Leadership is the key in terms of the success of our network. These people are honest brokers. They are generative. They are intellectually curious. They are about facilitating the work.

Laurie Garduque, program director for research at the John D. and Catherine T. MacArthur Foundation

[9]OECD Futures Program home page. *http://www.oecd.org/department/0,2688,en_2649_33707_1_1_1_1_1,00.html*. Accessed April 30, 2004.

Graduate Students

A goal of the National Science Foundation's (NSF) Integrative Graduate Education and Research Traineeships (IGERT) program (see Boxes 4-1 and 8-4) is to "prepare scientists for careers at the interstices of disciplines and in non-traditional settings."[10] The IGERT program has particular relevance to this study in that it was stimulated in part by a previous Committee on Science, Engineering, and Public Policy (COSEPUP) report on graduate education.[11] The training grants, which are allocated to institutions and then to the students themselves, are especially important in light of reduced support for graduate students by some agencies and foundations.[12]

Postdoctoral Scholars

Funding organizations can consider shifting some of their resources to supporting postdoctoral scholars. Postdoctoral scholars with a solid base in one discipline may become more productive if they have opportunities to learn and work in additional disciplines. Such support can be used for additional training, laboratory visits, and coursework. The Burroughs Wellcome Foundation supports an Interfaces in Science program that provides transitional funding for postdoctoral scholars and faculty with backgrounds in physics, mathematics, computer science, and engineering who want to explore aspects of biology[13] (see Box 6-5).

Faculty

A useful mechanism for junior or senior faculty to gain new skills and master new disciplines is a portable fellowship, such as that in the Sloan Fellows Program,[14] which can be designed for use in the institution or beyond. Such support may be hard to find in the traditional salary or grant

[10]Hackett, E. J. "Initiatives at the U.S. National Science Foundation," In Weingart, P. and Stehr, N. *Practising Interdisciplinarity*. Toronto: Unviersity of Toronto Press. 2000, p. 251. The NSF IGERT program states "the program is intended to catalyze a cultural change in graduate education, for students, faculty, and institutions, by establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries." *http://www.nsf.gov/pubs/2004/nsf04550/nsf04550.htm*.

[11]National Research Council, *Reshaping the Graduate Education of Scientists and Engineers*, Washington, DC: National Academy Press. 1995.

[12]For example, the Howard Hughes Medical Institute recently ended its research training fellowships for graduate students.

[13]*http://www.bwfund.org/programs/interfaces/index.html*.

[14]*http://www.sloan.org/programs/scitech_fellowships.shtml*.

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BOX 6-5 Burroughs Wellcome Fund Career Transition Awards

In 2002, the Burroughs Wellcome Fund (BWF) established a grant program to support young investigators working at the interfaces between biology and other disciplines. The program, titled Career Awards at the Scientific Interface, recognizes the potential role that physical, chemical, and computational sciences can play in innovative biological fields, such as genomics, quantitative structural biology, systems modeling, and nanotechnology.[a] In 2002, eight postdoctoral students were awarded grants; in 2003, seven grants were awarded.

Like Burroughs Wellcome's original career-awards program,[b] which was designed to facilitate the critical transition from postdoctoral training to tenure-track faculty positions, the Scientific Interface program provides $500,000 over 5 years to support 2 years of advanced postdoctoral training and 3 years of a faculty appointment. The program specifically encourages interdisciplinary work and training. First, candidates are required to hold a PhD in chemistry, physics, mathematics, computer science, statistics, or engineering and must propose a research project that addresses questions in biomedical science. Second, the foundation expects award recipients to continue their interdisciplinary cross-training and provides grant funds for travel to scientific meetings and for advanced coursework in biology. Finally, award recipients are required to form collaborations with well-established investigators outside their own fields.

[a]Burroughs Wellcome Fund. *2005 Career Awards at the Scientific Interface*. *http://www.bwfund.org/programs/interfaces*.

[b]Pion, G. and Ionescu-Pioggia, M. "Bridging Postdoctoral Training and a Faculty Position: Initial Outcomes of the Burroughs Wellcome Fund Career Awards in the Biomedical Sciences." *Academic Medicine*. 2003, 78(2):177-186.

structure. A more flexible option may be to support summer immersion experiences (see Box 4-1) or grants for workshops in emerging areas (see Box 6-3).

Similarly, funding organizations can spur fledgling IDR initiatives by providing seed money. Like venture funding at the early stage of formation of a firm, seed funding provides flexibility that is not available in many grants to shape innovative or experimental programs. Even modest amounts of seed funding can have a strong catalytic value in supporting demonstrations and visible pilot programs (see Box 6-6). Following that strategy, the Mellon Foundation provides some flexible funding for junior faculty engaged in IDR; similarly, the Beckman Foundation issued a request several years ago for proposals for high-risk IDR deemed insufficiently developed for funding by large agencies. Initiatives of those kinds are often more appropriate for private foundations than for federal agencies, which tend to fund programs that have already been launched.

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BOX 6-6 Fullerene Research at Rice University

In 1993, a faculty task force led by Richard Smalley defined a nanotechnology initiative at Rice University that built on interdisciplinary strengths in science and engineering. By 1997, several new faculty members had been hired, a new 70,000-ft^2 laboratory had been completed, and the Center for Nanoscale Science and Technology opened its doors.[a,b] The interdisciplinary research infrastructure provided by the center has provided Rice University a leadership role throughout the transition from basic research to development and commercialization of nanotube technologies.

The wide diversity of scientific applications for fullerene-based molecules not only laid the foundation for extensive interdisciplinary collaboration among scientists at Rice but helped to foster worldwide interest in carbon compounds. The carbon technology has made it possible to produce superconducting salts, three-dimensional polymers, catalysts, materials with new electric and optical properties, sensors, nanotubes,[c] and solar cells.[d]

Grants from the National Science Foundation, the National Aeronautics and Space Administration (NASA), and the Department of Defense have funded the development of laser-oven production facilities, which became the commercial operation Tubes@Rice Inc. for supplying the world with research quantities of nanotubes. That process was licensed to DuPont for its use in manufactured display technologies, and DuPont and NASA purchased Rice's laser-oven single-wall nanotube (SWNT)-generating apparatus. A more scalable process based on a conversion of carbon monoxide to SWNTs was then developed. Called the HiPco process (high partial pressure of carbon monoxide), it was patented and commercialized by Rice University.[e]

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[a]Center for Nanoscale Science and Technology Web page *http://cnst.rice.edu/index.cfm.*

[b]In the midst of this campaign, Rice University chemists Smalley and Curl with colleague Harold Kroto were awarded the Nobel Prize for their unique work with buckminsterfullerene, clusters of 60 carbon atoms (C60) that are bound into a stable and symmetric soccer ball configuration The Royal Swedish Academy of Sciences. *Press Release: The 1996 Nobel Prize in Chemistry*. *http://www.nobel.se/chemistry/laureates/1996/press.html.*

[c]Shelley, S. *Carbon Nanotubes: A Small-Scale Wonder. Chemical Engineering,* February 2003.

[d]Bethune, D. S. and Johnson, R. D. "Atoms in carbon cages: The structure and properties of endohedral fullerenes." *Nature* 366:123-29.

[e]Nanotechnologies Inc. Web site: *http://www.cnanotech.com/.* Accessed March 29, 2004.

SUPPORT FOR INSTITUTIONS AND FACILITIES

A third strategy that funding organizations can follow is to support new institutions or facilities or to provide support to existing institutions for reforms or innovations that cannot be achieved under current conditions. For example, some funding organizations have chosen to support major new programs and centers by providing essential space, specialized personnel, and facilities:

- The University of Illinois at Urbana-Champaign negotiated a $40 million gift from the Arnold and Mabel Beckman Institute to build an interdisciplinary research center. The initiative began when the vice-chancellor asked faculty to develop an IDR proposal (see Box 5-6).
- Stanford University negotiated a gift from Jim Clark, founder of Netscape, to build the Bio-X facility, explicitly designed to foster IDR in biology and medicine. Research proposals and decisions about which researchers will receive space at the new facility are faculty-initiated. The facility brings together biologists, clinicians, engineers, chemists, physicists, and computer scientists to stimulate innovative thinking (see Box 9-6). Janelia Farm, conceived and funded by the Howard Hughes Medical Institute, is a similar building designed expressly to foster IDR (see Box 6-7).
- The Fred Kavli Foundation was recently formed to support three interdisciplinary fields: cosmology, neuroscience, and nanoscience. The foundation has funded nine institutes in universities (eight in the United States and one in Europe), has created four professorships at California universities and will begin awarding research prizes in 2007.

Specific funding and support mechanisms may help institutions facilitate IDR:

- *Encourage proposals that have multiple Principal Investigators (PIs).* They can supplement the standard model of funding a single investigator by funding IDR teams. Grants inviting team proposals can provide explicit recognition of the effectiveness of collaborative leadership.
- *Fund the collaborative process as well as interdisciplinary team research.* Rather than focusing funding wholly on research, funding organizations can experiment with funding the collaborative process, which includes travel, meetings, training, and other activities through which investigators learn one another's language, culture, and knowledge. In the committee's survey, respondents' top recommendations for institutions, project leaders, principal investigators, educators, postdoctoral scholars, and students focused on enhancing communication between researchers. Over 20 percent of the respondents stated specifically that interdisciplinary researchers need time to develop effective networks and research strategies.

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BOX 6-7 Creating Spaces for Interdisciplinary Research[a]

Slated for completion in early 2006, the Howard Hughes Medical Institute (HHMI) Janelia Farm Research Campus will serve as an intellectual hub for several hundred scientists in diverse disciplines. HHMI expects to spend about $500 million to construct the campus and put its scientific programs into place. The initial construction will provide the laboratories to accommodate a permanent research staff of 200-300. Additional laboratories and facilities will be built for visiting researchers and for core scientific support staff and administration. Janelia Farm includes about 760,000 ft^2 of space, housing the research laboratories and support areas, a conference center, and housing for more than 100 visitors.

The scientific programs at Janelia Farm are designed to further collaboration and flexibility among scientists. Research teams will be kept small, and team leaders are expected to stay actively involved in bench research, not just manage or guide it.

Janelia Farm's two primary scientific agendas are to establish a continuing research program at the interface of emerging technologies and their application to biomedical problems and to make available project-oriented "surge" space where visitors can come together and use new technologies to solve problems. Janelia Farm provides the facilities, finances, and freedom for scientists to pursue collaborative, interdisciplinary research, bringing members of their research groups, to work for periods ranging from a few weeks to several years.

The architectural designs of the buildings and the laboratories are aimed at achieving both of Janelia Farm's central objectives—collaboration and flexibility. Thus, design is guided by three principles that HHMI has gleaned from its considerable experience in creating successful work environments for scientists:

- Understand the researchers' needs and their preferences.
- Keep work spaces standardized and rational.
- Make the spaces adaptable to accommodate changes in research.

[a]Janelia Farm home page *http://www.hhmi.org/janelia/*. Accessed April 30, 2004.

Convocation Quote

The calls we got from grantees in our interdisciplinary science program were not about extensions to the grants or budget. They were, "Could you help us figure out how to get the collaboration to work more effectively?" Collaboration is the bedrock of interdisciplinary research work. That is an area we think a funder interested in fostering interdisciplinary work ought to focus on: "glue money" to support meetings, bringing people together, travel, learning how to work together, and some of the team training aspects.

Barry Gold, Program Officer, Conservation and Science,
The David and Lucile Packard Foundation

- *Make grants of longer duration.* Longer-term grants, with sufficient safeguards to ensure that progress is being made, can be helpful in supporting IDR efforts because extended startup periods are often required.
- *Fund studies of the social aspects of the interdisciplinary process.* There is insufficient understanding of the motivations, modes of working, external pressures from the larger community, and other aspects of initiating and sustaining IDR in a given environment. A valuable contribution would be funding for research on the creation and implementation of new models for providing the interactions and dialogues that hold IDR together, such as "collaboratories."

Recent interagency discussions and focus groups with researchers and university administrators sponsored by the US Office of Science and Technology Policy found several areas of agreement on how to facilitate IDR (see Box 6-8). Many of their findings parallel and support those in the present report.

REVIEWING PROPOSALS FOR INTERDISCIPLINARY ACTIVITIES

Funding organizations, through the mechanisms they use to approve or reject grant proposals, have great influence over the kinds of research proposals that are funded in this country. As discussed in Chapters 5 and 8, those mechanisms often evaluate proposals from the point of view of one or several disciplines, by using review panels that may have little expertise in IDR. Expertise in IDR, as well as in the constituent and related disciplines, is required to review multidisciplinary projects fairly and award credit for the contributions of project members.

Funding organizations can help to improve the review process in at least two ways. First, they can reform their own mechanisms of review by ensuring adequate breadth among the pool of researchers who review IDR proposals, in addition to the necessary depth of expertise in specific disciplines. Second, they can support additional study and experimentation with current and alternative mechanisms for reviewing IDR.[15] Funders might consider, as an example, the multistage process familiar in Europe, where the judgment of disciplinary experts is combined in various ways with the

[15] In its recent study of NSF funding procedures, the National Association of Public Administration recommended that "NSF ensure that review procedures for interdisciplinary research are transparent" and "NSF establish supplementary review criteria that will help to assess the quality of interdisciplinary effort in those programs where both single and multiple discipline proposals compete for a common pool of funds." NAPA, *National Science Foundation: Governance and Management for the Future*, April 2004.

TOOLKIT

BOX 6-8 OSTP Business Models Initiative

In spring 2003, the National Science and Technology Council of the Office of Science and Technology Policy established the Research Business Model subcommittee to find out more about the changing nature of scientific research and how the changes are affecting the success of research sponsored by federal agencies. Through a series of workshops,[a] the subcommittee learned more about how research is being performed and how federal agencies might improve support of research that is interdisciplinary.[b]

Working groups identified two main drivers for IDR: the nature of societal problems and the growing complexity of research problems. They found that IDR is enabled by a number of dynamic characteristics of the scientific enterprise, including

- Disciplinary strength.
- Increased accessibility of data.
- Increased computing power.
- Increased power and accessibility of scientific instrumentation.
- Increased communication and the Internet.
- Ease of collaborating across institutional and programmatic borders.

The participants in the groups suggested a number of interesting models that sponsoring agencies could use to support IDR:

- Providing a mechanism to acknowledge collaborating investigators.
- Facilitating collaboration and agreements between and among institutions, including the national laboratories.
- Examining the need for the purchase, technical operation, and upgrading of large, shared instrumentation independent of individual projects.
- Breaking down of funding stovepipes within and between agencies.
- Interagency harmonization of award terms and conditions for similar research programs.
- Encouraging "grand challenges" or roadmaps.

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[a]Alignment of Funding Mechanisms with Scientific Opportunities, October 27, 2003 Workshop Summary from NSTC's Regional Forum on Research Business Models *http://rbm.nih.gov/afmso.html*.

[b]Gabriel, C. Comments at Convocation on Facilitating Interdisciplinary Research, January 29, 2004, Washington, D.C., *http://www7.nationalacademies.org/interdisciplinary/Convocation_Agenda.html*; "Ten Research Business Models Objectives Cleared by NSTC Science Committee." *The Blue Sheet*, 2004. 47(011):3.

"We study, we plan, we research. And yet, somehow, money still remains more of an art than a science."

judgment of those who have extensive experience in interdisciplinary work (see Box 8-5).

CONCLUSIONS

Funding organizations at all levels and of all sizes have great opportunities to facilitate both disciplinary and interdisciplinary research (see Box 6-9). Indeed, some of them have been pioneers in promoting steps suggested in this report, such as creating special IDR initiatives that can be critical to the evolution of a vital but complex field.[16]

Some funding organizations have also recognized that research fields and methods are now so interdependent that it may not be possible to fund "just microbiology" or "just physics." Instead, they have found it desirable, in addressing objectives in some fields, to support a wide framework of disciplines simultaneously. For example, to support a program in the life sciences, an organization may have to fund mathematics, probability, chemistry, computer science, biomedical engineering, and other relevant fields, as well as biology.

By extending and adapting procedures developed earlier to evaluate research proposals for single-discipline topics, funding organizations may

[16]An example is the rapid effort by NIH to launch a program of vaccine development against agents of bioterrorism.

EVOLUTION

BOX 6-9 The Emergence of Biomedical Engineering: A Case Study in Collaboration among Researchers, Societies, and Funders[a]

The roots of biomedical engineering[b] reach back over 200 years to early developments in electrophysiology. Biomedical engineering has evolved through the collaboration of engineers and clinical scientists. The profession has been characterized by the emergence of separate societies with a focus on field-specific applications. As a step toward unification, an umbrella organization, the American Institute for Medical and Biological Engineering,[c] was created in 1992.

The earliest academic programs began to take shape in the 1950s. In the early 1960s, the National Institutes of Health (NIH), petitioned by researchers to develop educational programs for bioengineers, took three steps to support the emerging field. It created a program-project committee under the National Institute of General Medical Sciences to evaluate program-project applications, many of which served biophysics and biomedical engineering. Then it set up a biomedical engineering training study section to evaluate training-grant applications, and it established two biophysics study sections. A special "floating" study section processed applications in bioacoustics and biomedical engineering.

The field received a large push when The Whitaker Foundation[d] was created in 1975. In 1992, the Whitaker Foundation initiated large grant programs designed to help institutions to establish or develop biomedical engineering departments or programs. By 2002, Whitaker had contributed more than $615 million to universities and medical schools to support faculty research, graduate students, program development, and construction of facilities.

The National Science Foundation (NSF) and NIH, individually and collaboratively, have helped to provide a structure for research efforts. NSF established the Biomedical Engineering Division in the Directorate of Engineering in 1990. In 1991, NIH and NSF set up a collaborative workshop on biomedical engineering training.[e] The NIH director established the Bioengineering Consortium[f] in 1997, and in 2000 the National Institute of Biomedical Imaging and Bioengineering (NIBIB)[g] was created by Congress.

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[a]History of Biomedical Engineering. Whitaker Foundation Web site. *http://www.whitaker.org/glance/history.html.* Accessed April 30, 2004.

[b]Bioengineering integrates physical, chemical, mathematical, and computational sciences and engineering principles to study biology, medicine, behavior, and health. It advances fundamental concepts; creates knowledge from the molecular to the organ systems levels; and develops innovative biologics, materials, processes, implants, devices, and informatics approaches for the prevention, diagnosis, and treatment of disease, for patient rehabilitation, and for improving health. NIH Working Definition of Bioengineering. July 24, 1997. *http://www.becon2.nih.gov/bioengineering_definition.htm.*

[c]AIMBE home page *http://www.aimbe.org/.* Accessed April 30, 2004.

[d]Whitaker Foundation home page. *http://www.whitaker.org/.* Accessed April 30, 2004.

[e]*Summary of the NIH/NSF Workshop on Bioengineering and Bioinformatics Research Training and Education* (June 13-14, 2001) *http://www.nibib.nih.gov/training/NIHNSF/NIHNSF Training.pdf.*

[f]BECON home page *http://www.becon2.nih.gov/becon2.htm.* Accessed April 30, 2004.

[g]NBIB home page *http://www.nibib.nih.gov/.* Accessed April 30, 2004.

be able to overcome some important current barriers to IDR. Funding organizations can be most effective when they engage in extensive dialogue with leading practitioners to learn where the opportunities are greatest.

FINDING

The characteristics of IDR pose special challenges for funding organizations that wish to support it. IDR is typically collaborative and involves people of disparate backgrounds. Thus, it may take extra time for building consensus and for learning of new methods, languages, and cultures.

RECOMMENDATIONS

Funding Organizations

F-1: Funding organizations should recognize and take into consideration in their programs and processes the unique challenges faced by IDR with respect to risk, organizational mode, and time.

For example, funding organizations can seek to

- Ensure that a request for proposals does not inadvertently favor funding a single-discipline project over an IDR project; for example, by including limitations on funding amounts, duration of funding (successful IDR teams often take longer to build and to coalesce), scope, and allowable travel and other budget items, all of which would militate against IDR.
- Develop funding programs specifically designed for IDR, for example, by focusing research around problems rather than disciplines.
- Provide seed-funding opportunities for proof-of-concept work that allows researchers in different disciplines to develop joint research plans and to perform initial data collection or for new organizational models or project approaches that enable IDR.
- Provide support for universities for shared research buildings, large equipment, or specialized personnel (machinists, glassblowers, and computer and electronic technicians).
- Provide funding mechanisms that allow researchers to obtain training in new fields.
- Fund programs of sufficient duration to allow for team-building and integration of research efforts.
- Provide funding mechanisms so that universities (including those from different countries) can work together to address societal problems that each would be challenged to address alone.

Develop mechanisms for budgetary flexibility in long-term, multi-institutional grants.

- Acknowledge, for projects that require more than a single principal investigator (PI), the equal leadership status of multiple PIs when "co-PI" is ambiguous.
- Remove administrative barriers to, and explicitly encourage, partnerships between universities, industry, and federal laboratories to facilitate IDR.

F-2: Funding organizations, including interagency cooperative activities, should provide mechanisms that link interdisciplinary research and education and should provide opportunities for broadening training for researchers and faculty members.

They can

- Require institutions that receive IDR funding to demonstrate support for interdisciplinary educational activities, such as team teaching.
- Provide, to the extent allowed by the funding organization's mission and guidelines, special grants to support interdisciplinary teaching.
- Designate funds for IDR meetings that encourage interaction between researchers in different disciplines so they can learn about the research in other fields and network with other researchers with whom they might collaborate.
- Support sabbaticals and leaves of absence for studies that focus on interdisciplinary scholarship.
- Ensure that their staff is knowledgeable about interdisciplinarity.

F-3: Funding organizations should regularly evaluate, and if necessary redesign, their proposal and review criteria to make them appropriate for interdisciplinary activities.

For example, funding organizations can

- Develop criteria to ensure that proposals are truly interdisciplinary and not merely adding disciplinary participants.
- Encourage IDR proposals that fall within the compass of the organizations' overall missions even if they cross internal organizational boundaries or do not fit specific (review) divisions.
- If they are organized along disciplinary lines, develop policies and practices for funding research that may have a major impact on research in other disciplines, for example, by awarding a mathematics section grant to a mathematician to work on a life-sciences project.

F-4: Congress should continue to encourage federal research agencies to be sensitive to maintaining a proper balance between the goal of stimulating interdisciplinary research and the need to maintain robust disciplinary research.