Kates, R.W. with National Academies Committee on Facilitating Interdisciplinary Research, 2005. Facilitating Interdisciplinary Research, National Academy Press.

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Interdisciplinarity in Industrial and National Laboratories

Although the major emphasis in this study is on the state of IDR in academic institutions, academic institutions make up only one part of a pluralistic research enterprise. Some large industrial and national laboratories, which constitute other elements of the enterprise, have deep traditions of interdisciplinary research (IDR), partly because their R&D strategies must be able to respond to complex problems or challenges that require expertise in multiple fields and technologies. For example, when most experiments or systems are being developed or constructed, there is no choice but to be interdisciplinary. Experimental work in a genetics laboratory is likely to involve biology, organic and inorganic chemistry, flow physics structures to hold pieces together, electric circuits and electrochemistry computation, etc. Top-down management structures allow for easy horizontal movement of researchers in response to skill needs. The challenge is the degree of professionalism and collaboration to be brought to a project that involves many disciplines, skills, professionals, students, and technicians that form the cooperating team for some or all the projects' life span.

Such nonacademic laboratories are essential to the national R&D enterprise for both their research and training functions in science and engineering. This chapter discusses a sampling of nonacademic practices that have assumed growing relevance as more research universities have developed ties with industrial and federal agencies.[1] Most of the few studies of nonacademic IDR were published several decades ago, before the recent and substantial changes in many practices, such as the down-sizing of industrial laboratories. This discussion is by necessity largely restricted to anecdotal information and examples that are intended to span a representative array of practices and settings.

Faculty members in many universities are increasingly involved in outside consulting, research partnerships, or entrepreneurial efforts of their own, and thorough knowledge of nonacademic practices can add value to their own careers.[2] In addition, most graduate students who acquire PhDs in science and engineering will find career opportunities in nonacademic research settings, where most of the new research positions are likely to be created over the next few decades.[3] For today's students—who may eventually work not only with researchers in different science and engineering fields but also in development, marketing, law, economics, ethics, or other non-research activities—it is doubly important to hone their skills in communicating with people in other fields and to gain exposure to IDR in nonacademic settings through cooperative programs, summer jobs, and other opportunities.

RESEARCH STRATEGIES AT INDUSTRIAL LABORATORIES

The first formal industrial R&D programs in the United States were organized just over a century ago. In 1900, for example, General Electric began funding the General Electric Research Laboratory in Schenectady, New York, to generate and use scientific knowledge. The nation's adoption of industrial R&D was prompted partly by Americans' exposure to industrial practices in Germany (the GE laboratory was directed by the German emigré Charles Steinmetz) and elsewhere in Europe (see Box 3-1), which emphasized the value of industrial research and industrial support for university research and graduate training.

The greatest expansion of industrial research came during the years after World War II, when the largest industrial laboratories—notably DuPont's Experimental Station in Wilmington, Delaware; IBM's Watson

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[1] For a discussion of the effects of recent changes on the "research-university complex," see Conn, R. "The Research University Complex in a New Era: An Inquiry and Implications for Its Relationship with Industry," Washington, D.C.: Government-University-Industry Research Roundtable, 1999.

[2] Frosch, R. "Research and development," *Encyclopedia of Applied Physics*, Vol 16, Hoboken, N.J.: VCH Publishers, Inc., 1996, p. 419.

[3] COSEPUP (Committee on Science, Engineering, and Public Policy), *Reshaping the Graduate Education of Scientists and Engineers*, Washington, D.C.: National Academy Press, 1995.

INNOVATIVE PRACTICE

BOX 3-1 Philips Physics Research Laboratory

An early example of industrial IDR was the Philips Physics Research Laboratory in the Netherlands, which adopted explicit interdisciplinary policies as long ago as the 1930s. R&D activities began with the lightbulb and expanded steadily toward new challenges as the possibility of products appeared: radio-receiver bulbs, then radios themselves, telephony systems, sound equipment, and a long history of S&T-driven electronic products, each of which required many skills to develop.

Gilles Holst, founder and first director of Philips, refused to divide his laboratories by discipline, arguing that a team working on, for example, magnetic ferrites should have not only physicists but also chemists, crystallographers, and electrical engineers. He also created a development process that involved back-and-forth communication between the central laboratory and small R&D operations in each of the factories. He promoted a laboratory culture in which both academic excellence and industrial excellence were stimulated, and corporate leadership acknowledged the industrial laboratories as indispensable in product diversification and new business activities.

Among Holst's laboratory-management principles were the following:

- Hire young, intelligent researchers who have some experience in scientific research.
- Do not overemphasize the specific details of the research they have done, but consider their overall abilities.
- Give researchers freedom and accept their individual peculiarities.
- Let them publish and participate in international scientific activities.
- Avoid over-stringent organization; allow authority to arise naturally out of competence.
- Organize the laboratory not according to different disciplines but by interdisciplinary teams.
- Allow freedom in the choice of research subjects, maintaining an awareness of company needs.
- In individual research projects, do not interfere in the details, and assign no budgets.
- Reassign skilled senior researchers from the laboratory to applied R&D.
- Let the choice of research projects be determined by the state of the art in scientific knowledge.

The success of Philips's approach can be seen both in specific outputs, such as the invention of the compact disk and its successor, the DVD, and in its continuing global competitiveness. It is one of the few consumer electronics companies that supports large and multidisciplinary R&D operations.

Research Center in Yorktown Heights, New York; AT&T's Bell Laboratories at Murray Hill, New Jersey, and Xerox's Palo Alto Research Center (PARC) in California—set global standards of excellence in problem-driven interdisciplinary research and development. By the end of the 20th century, industry was providing just over half the funding for the nation's R&D activities and the federal government just over 40 percent. Of the total R&D spending, just over one-fourth went to research and the rest to development—proportions that have been typical since World War II.[4]

Most centralized research laboratories experienced downsizing that began in the 1980s and a shift in emphasis from research toward development. Even so, industrial R&D has retained its interdisciplinary character and its inherent flexibility. Reasons for this according to experts cited and interviewed for this chapter include the hierarchical structure of industrial research; the more focused, less open-ended nature of its goals (for example, to produce a more effective vaccine or electronic display); and the lack of the kind of tenure system common in academe.

> Our work in Pfizer in discovering and developing new medicines is critically dependent on integrating advances in many other fields from physics, chemistry, materials sciences, and engineering to computer modeling and information technology. By sharing ideas from these fields, our scientists are able to create a critical intellectual mass that increases the creativity, the capacity, and the speed of innovation at Pfizer and other companies like us.
>
> William C. Steere, Jr., chairman of the board and
> chief executive officer, Pfizer, Inc.
>
> In Council on Competitiveness, Going Global: The New Shape of American Innovation, 1998, p. 6.

Some Models and Lessons from Industry

Virtually all industrial laboratories incorporate multiple disciplines of science and engineering, but an even greater degree of interdisciplinarity may occur during times of particular challenge. The examples below show how interdisciplinarity has been extended beyond the laboratory to reach throughout the corporate setting and even into customer relationships in

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[4] Hounshell, D. A. "The Evolution of Industrial Research in the United States" in *Engines of Innovation: U.S. Industrial Research at the End of an Era*, Boston, MA: Harvard Business School Press, 1996, pp. 13-15.

addressing the demands of global competition, shorter product cycles, and quickly shifting customer needs.

The Joint Programs of IBM

IBM, like other research-based corporations, has always emphasized IDR (Box 3-2). During the 1980s, however, when its profitable lines of hardware in computing and telecommunications evolved into unprofitable commodities, the firm learned how quickly the value of a research portfolio can decline. IBM kept its emphasis on IDR, but added a mechanism to more quickly communicate vital market facts to its researchers. The company developed a series of programs in advanced technology and early product development that were jointly planned, staffed, and funded by the research division and the appropriate product divisions and laboratories. Thus, both research and development activities benefited from the input of those who manufacture and market the outputs of research. That approach was extended to projects jointly developed by researchers and customers in recognition that the customer knows best what is most useful. The relationship between research and manufacturing has deepened with the creation of a manufacturing-research group within the research division, a move credited with saving hundreds of millions of dollars a year.[5]

The Reinvention of Xerox

The history of the Xerox Corporation has been described in numerous accounts, including John Dessauer's *My Years at Xerox: The Billions Nobody Wanted* (1971), which described the development of the xerographic technology that revolutionized office copying. Smith and Alexander's *Fumbling the Future* (1988) recounts Xerox PARC's invention of the paradigm that led to personal computing, client-server architecture, graphical user interfaces, local area networks, laser printing, bit maps, and other advances but brought Xerox almost no economic benefit. Indeed, the business decline of Xerox in the middle 1980s is a vivid example of how brilliant research may fail to support a corporation when results are not translated into product development, marketing, and sales.

In the late 1980s and early 1990s, corporate management recognized the lack of clarity about research's role and its integration into the total

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[5] Armstrong, J. "Reinventing research at IBM," in *Engines of Innovation: U.S. Industrial Research at the End of an Era*. Eds. Rosenbloom, R. S. and Spencer, W. J. Boston, MA: Harvard Business School Press, 1996, pp. 151-4.

INNOVATIVE PRACTICE

BOX 3-2 The Role of IDR at IBM[1]

IDR has been an integral part of IBM for 24 years and has allowed us to differentiate IBM from its competitors. One reason IBM has been able to sustain its basic-research program and remains the only large industrial basic laboratory today is its commitment to interdisciplinary teams.

Technology does not move along a linear path, and we need to have an interdisciplinary team already in place when problems come up. For example, when we had early evidence that bipolar transistors would soon reach the end of their ability to scale, it took scientists and engineers from many disciplines to spot the trend and find an answer. The answer was complementary metal oxide semiconductor (CMOS) technology. Companies that do not see the importance of IDR may not survive when times are challenging or when it is time to fundamentally change the direction of a company.

For IDR to be successful, a company must:

- Have an executive management team that believes in IDR and makes it a fundamental part of the culture. At IBM a physical sciences "coffee" has been held for 50 years to encourage talk across disciplinary boundaries.
- Form teams that include diverse skill sets. No research program has failed because it was an IDR program. Failures occur because there is an insufficient mass of the skills needed for an activity, such as having only one electrical engineer on a team when six were needed.
- Maintain an inventory of the diverse skills in the company. IBM's skills inventory has allowed appropriate interdisciplinary teams to be assembled quickly when needed for an urgent new project. Over time this "skill-finder" function has been automated.

Some of the lessons drawn from IBM's experiences may hold relevance for academe:

- Stimulate more interaction across disciplinary lines. At IBM more "points" are given in the personnel review process to people who interact and communicate across disciplines.
- Provide an incentive and reward system that encourages joint authorship of papers with those in other departments.
- Fund mini-sabbaticals in which a faculty member joins another department for a half-year every 3.5 years to understand the culture and challenges of other departments and disciplines.

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[1] From comments for the committee by Bernard S. Meyerson, IBM fellow, vice president, and chief technologist, IBM Systems and Technology Group.

business. Xerox's business was successfully reorganized around a single focus (the "document company"). One lesson from this history may be that interdisciplinary *research* alone is not always sufficient in an industrial setting. R&D activities must be integrated with the surrounding business, including manufacturing and marketing, if research results are to contribute to profitability.[6]

Colocation at Intel[7]

Intel, which chose not to create a corporate research unit, instead immerses researchers in the environment of the production line in its own version of interdisciplinary practice. The company's strategy was to recruit talented PhDs and spread them throughout the organization. The production line then became a seamless extension of the research laboratory; this allowed researchers to see perturbations, introduce bypasses, add steps, and explore variations in existing technologies with great efficiency. The company tries not to change production processes dramatically, but when a promising direction appears, it can set up a separate organization to explore it.

The principle underlying the strategy is that of "minimum information," set out by Intel cofounder Robert Noyce, guessing the answer to a problem and developing it as far as possible in a heuristic way. If that does not solve the problem, one starts over and learns enough to try something else. Clues are gathered from manufacturing engineers and others along the production line and from university collaborators with appropriate research expertise. In addition, the company maintains a small IDR group charged with staying abreast of broad developments in the semiconductor industry.

The "Skunkworks" Model

To counteract ingrained and nonproductive organizational patterns, the concept of the "skunkworks" was developed, first at Lockheed Martin, to give creative freedom to a small, hand-picked team that is geographically removed from the main physical plant. A skunkwork is a small, loosely structured corporate research and development unit or subsidiary formed

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[6] Myers, M. "Research and change management in Xerox," in *Engines of Innovation*. Eds. Rosenbloom, R. S. and Spencer, W. J. Boston, MA: Harvard Business School Press, 1996, pp. 133-49.

[7] Moore, G. "Some Personal Perspective on Research in the Semiconductor Industry," in *Engines of Innovation*. Eds. Rosenbloom, R. S. and Spencer, W. J. Boston, MA: Harvard Business School Press, 1996, pp. 165-74.

to foster innovation. The objective of the skunkworks may be sharply defined in terms of goal and timing. Notable skunkworks successes have included the U-2 and WR-71 Blackbird high-altitude spy planes, IBM's first personal computer, and Steve Jobs's breakthrough Macintosh computer at Apple. In one account of a successful skunkworks program, management researchers reported delivery of multiple related projects in a coordinated sequence that minimized the material and person-year costs, met new-product time-to-market deadlines by constructing production facilities in record time, met or exceeded company industrial standards, and created and documented new procedures for future projects.[8]

The concept of removing a small group with special autonomy has been criticized for lowering morale among those who are left behind and perceived to be "less than special."[9] But such resentment is less likely to form when a learning history of the project is carefully documented and provides for the transfer of new system tools to the main research facility.[10] An apparent lesson is that the skunkworks IDR model needs to be carefully adapted to each new setting.[11]

A New Degree of Interdisciplinarity?

Industry is expanding the character of IDR to address problems of global scale. Recently, a large, high-profile consortium was announced at Stanford University that not only is interdisciplinary but combines influential sponsors in widely different sectors of business: ExxonMobil, General Electric, Schlumberger, and Toyota. The 10-year, $225 million Global Climate and Energy Project (GCEP) will bring together leading scientists from universities, research institutions, and private industry to collaborate on fundamental precommercial research. The strategy is to intensify research on hydrogen and renewable energy, CO_2 capture and storage, combustion science, and other promising technologies with the objective of developing

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[8] Bommer, M., DeLaPorte, R., and Higgins, J. "Skunkworks approach to project management," *Journal of Management in Engineering*, Vol. 18, No. 1, January 2002, pp. 21-28.

[9] Schrage, M. "What's that bad odor at innovation skunkworks?," *Fortune*, Vol. 140, Issue 12, December 20, 1999, p. 338. Schrage writes, "This kind of 'innovation apartheid' may occasionally give birth to great new ideas, but it almost always breeds even greater resentment. Smart, capable people hate being marginalized."

[10] Bommer et al., p. 28.

[11] For example in a variant of the skunkworks model, a company seeds a small group that forms a startup company to work on a problem of interest to the parent company; if successful, the small company is then bought by the parent company.

energy systems that have low greenhouse emissions and can be used on a global scale.

Training PhDs for Interdisciplinarity

The training of new PhDs is too narrow, too campus-centered, and too long. . . . In my view, radical change is not required to improve the overall effectiveness of PhD-level training. Training by apprenticeship under the direction of an expert really does work: It provides both new research and training simultaneously. . . . We should explicitly encourage PhD students to spend time in 'user environments' outside the university as part of their apprenticeship—perhaps internships analogous to the co-op programs often used by undergraduate and master's degree students. The ultimate aim of these internships should be to provide technical work experience that is as unlike academic experience as possible. So, for some careers, internships in manufacturing are preferable to internships in a corporate research lab.

Industry can play a valuable role in planning for these internships. The willingness of firms to take on graduate students will depend on factors that vary by company, by industry, and with the economic climate. Small firms and start-up companies have the most to gain by such arrangements, and the most to give to students in the way of broad perspective. Many graduate schools are surrounded by small companies started from university science and engineering programs.

John Armstrong, retired IBM vice president for science and technology, in "Rethinking the PhD," Issues in Science and Technology, Summer 1994.

RESEARCH STRATEGIES AT NATIONAL LABORATORIES

Research in federal agencies is organized primarily to serve the scientific and technological objectives of their overall missions. Within that mandate, however, flexibility has evolved in recent years, especially among agencies whose missions have taken new directions. The evolution of missions is a natural consequence of broader societal change, such as the end of the Cold War and the growing urgency of environmental and energy issues.

National laboratories are maintained by many agencies, with the largest and best known funded by the Department of Energy (DOE), Department of Defense, National Institutes of Health, and National Aeronautics and Space Administration (NASA). Some of the facilities employ thousands of people and maintain the nation's most advanced technological equipment, affording unique opportunities for both research and training.

The national laboratories of DOE, the largest component of the national laboratory program, include those created to develop nuclear-weapons technology, beginning with the pioneering Manhattan Project. Many of the weapons laboratories have recently added multidisciplinary research programs in biology, medicine, chemistry, environmental science, energy efficiency, and other fields, diversifying the nation's research enterprise. For example, about half the research conducted at Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL), originally focused entirely on nuclear-weapons research, is now unclassified. As an indication of their changed missions, LLNL and LANL were the first two laboratories to begin working on the Human Genome Project, in 1983. Another typical example is LLNL's new Center for Accelerator Mass Spectrometry, which is used by researchers in numerous nonprofit foundations, non-DOE agencies, and private firms for isotope-abundance measurements..

> IDR hasn't gone as well when we didn't have a team that was well integrated, when we still had a bunch of solo investigators without sufficient passion to solve the larger problem. Team members have to know that they bring only a portion of the answer and have to respect the contributions of all members. We can't have a physicist thinking "I do more important work" because they are using a supercomputer because a geologist is mapping rock formations with a colored pencil.
>
> Norman Burkhard, Lawrence Livermore National Laboratory

Although national laboratories engage in the same kinds of long-term fundamental research found in university settings, most of their work resembles the top-down, project- and budget-driven activities typical of industry.[12] As noted in one report, "the laboratories are . . . capable of forming large, interdisciplinary research teams needed for certain types of 'big science' problems even where large facilities are not involved. Universities are not generally as well equipped to assemble teams to conduct closely coordinated, interdisciplinary research over an extended period."[13]

Because many graduate students will eventually work on solving big problems with large teams, internships and other work experiences in government laboratories can add valuable career experience. Roughly 26,000

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[12] Frosch, ibid. p. 419.

[13] Department of Energy. "Science and Engineering Roles" Chapter in Alternative Futures for the Department of Energy National Laboratories (known as the Galvin report) prepared for its chair by the Task Force on Alternative Futures for the Department of Energy National Laboratories. February 1995. *http://www.lbl.gov/LBL-PID/Galvin-Report/GalvinReport6.html#RTFToC50.*

scientists and engineers work in the 15 largest government research laboratories owned by DOE, for example. Some of the national laboratories are linked to or managed by research universities, so the national laboratory setting provides important opportunities for academic researchers to be involved in IDR. Some national laboratories have unique instrumentation for problem-solving, such as synchrotron facilities, and are engaged in solving problems of large magnitude and high risk, such as seeking novel sources of energy. Such large problems can be approached only by interdisciplinary teams that include special expertise.

Some Models and Lessons from US National Laboratories

Although no sampling of national laboratories can truly represent the enormous breadth of activities at such facilities, many of them have the same ways of applying IDR to address complex problems, organizing their personnel and activities to facilitate IDR, and promoting practices of possible value to universities that wish to incorporate more IDR. The following discussion of these practices is distilled from the comments of leading scientists at three institutions:[14]

- Oak Ridge National Laboratory (ORNL), a DOE laboratory in Oak Ridge, Tennessee, was created in 1943 to produce plutonium for the Manhattan Project. It is administered by a limited-liability partnership of the University of Tennessee and Battelle. While continuing its weapons research, it now has multiple missions in materials, instrumentation, advanced computing applications, robotics, energy-technology development, computational biology, nanotechnology, environmental change, geographic information systems, and other fields.
- LLNL, in Livermore, California, was founded in 1952 as the nation's second nuclear-weapons laboratory (after LANL). Also funded by DOE and run by the University of California, it has a diverse portfolio of science and engineering programs.
- Jet Propulsion Laboratory (JPL), funded by NASA and managed by the California Institute of Technology, was founded in 1944 in response to Germany's V-2 program to develop rockets for the Allied war effort. It became part of NASA in 1958 and now manages the Mars Rover mission, Cassini Saturn mission, and other efforts to explore the Solar System and Earth.

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[14] Thomas Wilbanks, corporate fellow, Oak Ridge National Laboratory; Edward Stone, former director, Jet Propulsion Laboratory; and Norman Burkhard, acting associate director, Energy and Environment Science Directorate, LLNL.

Importance of IDR at National Laboratories

IDR has been important to all national laboratories since their foundation. They all use large, multidisciplinary teams to attack problems that require a wide array of skills, often in both science and engineering, and that are too complex for research teams based in any single discipline.

Former ORNL Director Alvin Weinberg compared the role of the national laboratories with research in other sectors as follows: Universities set their research priorities by the perspectives of academic disciplines; industrial organizations set R&D priorities according to marketing and profitability goals; and national laboratories set their priorities according to global, national, and social needs. These needs must often be addressed by R&D that is both multidisciplinary and too long term or risky to produce near-term results or profits.

Strategies of National Laboratories in Recruiting and Organizing IDR Teams

Because of the interdisciplinary nature of their work, national laboratories tend to hire people who want to work on teams. As one manager said, "A lone investigator working on a single problem might have to turn out award-winning results to get the same pay and performance recognition as a team person." In hiring, the laboratories look first for people who are technically skilled; beyond that, they look for communication skills, writing skills, and evidence that they work well with people outside their own disciplinary space. Those who are hired but find that they do not want to work on teams usually "self-select" to move elsewhere.

Work at the national laboratories is often organized as a matrix system, with staff assigned to broad fields of science rather than single disciplines. Research programs are organized and promoted by cross-cutting program offices. Program leaders may set about addressing problems or topics by building teams from scratch. That is done by approaching people who have relevant skills and inviting them to discuss the problem at hand. Those who exhibit a passion for the problem and see clearly how their own work fits into a common vision tend to self-select for collaboration. The discussion groups may expand into local or multi-institutional IDR centers of excellence, often adding expertise from additional fields.

To facilitate IDR, JPL employs interdisciplinary scientists who are focused on broader scientific questions. The researchers function as "gluons" among the science teams, providing a broader view of science and systemwide issues.

> IDR is becoming more important as we try to understand how systems work. While many fundamental, single-discipline questions remain to be addressed, science and engineering are ready to address much bigger questions, such as ecologic and planetary systems. No single discipline has the capability to even start addressing whole systems.
>
> Edward Stone, Jet Propulsion Laboratory

When IDR Works Well

As implied above, IDR works best when it responds to a problem or process that exceeds the reach of any single discipline or investigator. For example, astrobiology, a major NASA initiative to explore the origins and distribution of life, is a subject that requires the participation of multiple disciplines (see Box 6-2).

At LLNL, an urgent topic is the effect of global climate change on regional water supplies. Estimating such an effect requires diverse experts who can collaborate on a chain of linked questions: atmospheric scientists to set up global-climate models, computer experts to run the models, statisticians to do output analyses of precipitation, surface hydrologists to study river flow, groundwater hydrologists to study subsurface movement, aerosol physicists to study cloud structure, and so on. "We couldn't begin to address this topic without interdisciplinary collaboration," said Norm Burkhard, the project manager, "and even when we need specialists to bore down deep in a specific problem, they are usually successful only if they can talk about their work with the people around them."

When IDR Is Less Successful

The commonest cause of underperformance of IDR is the failure of a team to gel or function collaboratively. That may happen for various reasons: individual members may place the importance of their own work ahead of the team vision, devalue the contributions of other team members, or lack leadership. Other contributing causes of lower-than-expected outcomes may be inadequate recognition for contributions to teams, low participation or understanding by senior staff members, inadequate time for participants to establish close working relationships, and insufficient funding.

On occasion, a culture gap between participating fields is not bridged. In the case of some early robotics research, for example, mechanical engineers and software engineers had widely different approaches. To the first group, a robot with adequate sensors had little need for software; to the second group, an abundance of mechanical sensors was a sign of inadequate software. Such cultural gaps must be bridged through persistent interaction and mutual efforts to understand other disciplines.

How IDR Has Changed Over the Years

Answering research questions at national laboratories requires more disciplines and collaboration than in the past. The same is true at universities, where more individual researchers are working together on small teams. The researchers themselves are likely to have transcended disciplinary boundaries in their own work. "Thirty years ago, the difference between a physicist and a chemist was obvious," said Norm Burkhard. "Now we have chemists who are doing quantum-level, fundamental studies of material properties, just like solid-state physicists. There's almost no difference."

More research today is defined or driven by the priorities of funding. When funding is scarce, laboratories may respond by decreasing the size of projects and encouraging more "stove-piping" by disciplinary units—an unwillingness to branch out beyond their own confines. That reduces the ability of laboratories to support complex, expensive projects and to cross disciplinary boundaries.

Lessons of National Laboratories for Academic Institutions That Wish to Facilitate IDR

Because so much interesting science of today involves complex systems, university researchers want to engage in the IDR required by systems questions. But national-laboratory scientists agree that IDR must be a valued part of institutional culture if it is to succeed. If a department or institution rewards only work that produces publications for journals in a narrow disciplinary field, academic researchers will respond accordingly.

One strategy that universities may adopt is to follow the practice of national-laboratory directors in setting aside funding to use as IDR seed money. At DOE laboratories, this seed money is important for launching projects in new directions. Universities could use such funding (which is now often used to hire new faculty) when existing faculty propose a major new initiative or interdisciplinary center. Without such startup assistance, it is difficult for established researchers to reorient their research, because funders may be hesitant to shift toward an unproven approach. In such cases, it is important for universities to lead, not follow, the funding agencies.

Another potentially valuable lesson is the use of sunset clauses. The National Science Foundation (NSF) Engineering Research and Science and Technology Centers have a 10-year life span, in recognition that they will support new subjects vigorously but not indefinitely (see Box 8-2). The University of California uses such a process for research centers and institutes that it runs: after 5 years, a panel of reviewers asks whether the program should remain an institute or it should begin a phaseout period with the objective of moving to a new subject.

Other steps suggested by the national-laboratory scientists are to

- Provide encouragement and rewards to move bright, early-career staff out of too-narrow disciplinary pursuits. For instance, an approach used in a few universities that run government laboratories is to put some tenure-track positions in issue-oriented "soft money" centers as a way to offer job security to promising nontenured staff with IDR interests.
- Encourage and reward team research rather than discouraging it. For instance, at least one division at ORNL has given every author of a joint publication the same performance credit as those who write single-author papers.
- In allocating discretionary research support, give priority to proposals that include and represent IDR.
- Encourage influential senior R&D staff to appreciate, participate in, and serve as role models for IDR, in part by making it an element in annual performance reviews.

> Lessons have been learned from decades of hard experience about how to facilitate IDR. First, involve only people who find unraveling a complex transdisciplinary issue at least as important as their own discipline. Second, discourage "disciplinary entitlements," where something is accepted as truth because one discipline says so. Third, be sure all team members know that their reputations will be affected by the success or failure of the enterprise—that everybody's name will be on the product. Fourth, spend a lot of time in replacing disciplinary stereotypes with personal relationships and recognize the critical importance of leadership in both style and substance.
>
> Thomas Wilbanks, Oak Ridge National Laboratory

INTERDISCIPLINARY RESEARCH IN JAPAN

Japan's Ministry of Economy, Trade, and Industry (METI)[15] places heavy emphasis on IDR. Specifically, the National Institute for Advanced Interdisciplinary Research (NAIR) is one of 15 research institutions of the Agency of Industrial Science and Technology (AIST). The AIST laboratories concentrate on R&D programs judged to be capable of raising the level of Japan's technology.

NAIR was founded in January 1993 with an objective of pursuing IDR themes covering fundamental and frontier subjects of industrial science. It is portrayed as an innovative attempt to overcome institutional boundaries by bringing together scientists of diverse specialties—not only from research institutes under AIST and the Science and Technology Agency but also from universities and research organizations in the private sector.

Recent NAIR research projects include

- The Atom Technology Project (nanotechnology).
- The Cluster Science Project (experimental and computational study of the character of clusters).
- The Bionic Design Project (cell and tissue engineering and molecular machines).
- Next Generation Optoelectronics (large-capacity optical memory).

Each of these projects brings numerous disciplines together to solve specific cutting-edge problems of current interest.

NAIR management is based on four principles: extensive openness, flexibility and mobility of staffing, international collaboration, and objective evaluation of research progress. Although NAIR does employ researchers, most research staff members are drawn on a temporary basis from government, industrial, academic, and foreign organizations. That provides an interesting contrast with the US national laboratories, which support large permanent staffs.

GOVERNMENT-UNIVERSITY-INDUSTRY RESEARCH COLLABORATIONS

As more faculty researchers become interested in applications of their research results and industries place greater emphasis on short-term outputs, new IDR partnerships are emerging between academe, industry, and government.[16] In general, the collaborations yield substantial benefits for

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[15] The giant Ministry of International Trade and Industry, which had supported S&T research since its formation in 1949, lost power after the liberalization of trade and was reorganized as METI in 2001.

[16] Government-University-Industry Research Roundtable (GUIRR), "Overcoming Barriers to Collaborative Research: Report of a Workshop," Washington, D.C.: National Academy Press, 1999. University-government collaborations, such as the NSF-funded engineering research centers and science and technology centers, have generally succeeded in blending the two cultures. The growth of new government-university partnerships, however, has not been as rapid as the growth of industry-university partnerships.

all partners.[17] Box 3-3 provides an illustration of this for hard-disk-drive research.

University-industry collaboration, in particular, has proliferated over the last 2 decades, propelled partly by the Patent and Trademark Laws Amendments of 1980 and revisions, commonly referred to as the Bayh-Dole Act. One effect of these changes was to rationalize and simplify federal policy on patenting and licensing by universities of the results of publicly funded research.[18] A second contributing factor has been the revolutionary advances in university-based life-science research. Locating corporate research laboratories near major research universities creates more opportunities for these partnerships. As noted above, much of modern life science is inherently interdisciplinary, so these collaborations call for new, effective IDR strategies.

While the value of IDR partnerships is clear, practices for effective collaboration between universities and industry must be considered up front, including[19]

- Allocation of intellectual-property rights.
- Concerns over publication, copyright, and confidentiality.
- Regulation, liability, and tax-law issues.
- Concerns over foreign access.
- The involvement and best interests of graduate students.
- Infrastructure-related impediments to interdisciplinary and interdepartmental research.

Structuring and managing partnerships that produce gains for all partners take experience, careful planning, and continuing attention if universities, in particular, are not to risk compromising their educational focus.[20] Effective practices for surmounting such barriers include building trust between partners, efforts to understand the culture of the partner organization, attention to the misuse of students as "employees" of research sponsors, fair sharing of indirect costs, disposition of intellectual-property and patent rights to encourage the widest possible use of research tools, and

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[17] Roessner, J. D. "University-industry collaborations: Choose the right metric," *Science's Next Wave*, June 1996.

[18] Mowery, D. C. "Collaborative R&D: How effective is it?," *Issues in Science and Technology*, Fall 1998. U.S. General Accounting Office, *Technology Transfer: Administration of the Bayh-Dole Act by Research Universities*, GAO/RCED-98-126, Washington, D.C., 1998.

[19] GUIRR, ibid. p. 7.

[20] For an extended discussion of this issue, see Bok, D. *Universities in the Marketplace: The Commercialization of Higher Education*, Princeton: Princeton University Press, 2003.

INNOVATIVE PRACTICE

BOX 3-3 Establishing an Interdisciplinary Environment for Hard-Disk-Drive Research

The best example of a product of industrial IDR is perhaps the hard disk drive (HDD) found in most computers and now beginning to appear in consumer applications and cell phones.

The first HDD was developed by IBM in the middle 1950s. It consisted of a spinning disk coated with a layer of small magnetic particles. An electromagnetic transducer positioned over the disk on an air bearing provided the writing field and inductive readout capability. The HDDs of today have the same basic design, but the medium is a thin magnetic metallic film, and readback is accomplished with a thin-film sensor whose resistance reflects the magnetic data pattern on the disk. The critical dimensions—the head-to-disk spacing, the thickness of the recording layer, and the spacing of data on the disk—are all in the range of nanometers, so it has become necessary for advances in one of these aspects to involve all the others. That requires the cooperation of materials scientists, mechanical engineers, chemical engineers, signal-processing engineers, and magnetism specialists.

There were many HDD companies in the 1980s. Many bought disks and heads and simply assembled the HDDs. Today, it is important to be vertically integrated on the basis of interdisciplinary technology development. By being vertically integrated, one can ensure that the heads and magnetic media are appropriately matched or perhaps compensated for by the design of the detection scheme.

To support such interdisciplinary technology, the industry has taken several steps. One is educational. In the early 1980s, it became obvious that traditional disciplines were not broad enough to train a “disk-drive engineer,” Consequently, the industry encouraged and financially supported the formation of interdisciplinary centers in data storage. The most notable are at Carnegie Mellon and the University of California, San Diego. The centers bring together faculty that represent all the disciplines required in the design of high-performance storage systems. Curricula have been developed to expose students to all the scientific fundamentals required to produce this remarkable electromechanical device.

Because even the largest companies in the industry do not have expertise in all the disciplines required, the industry has pooled its resources through a consortium, the International Storage Industry Consortium, to develop technology road maps that identify where research is required to maintain the growth of the technology. The research is carried out by companies and universities that have the appropriate expertise. Thus, industry has, in effect, established a worldwide research environment to accomplish its interdisciplinary goals.

sensible agreements on publication delays to maintain the openness of the university research environment.[21]

CONCLUSIONS

As suggested earlier, more contemporary data are needed to understand how IDR is managed in industrial and national laboratories. The prevalence of IDR has increased enormously since early studies on IDR in these settings was done, but yet even such fundamental questions as the following are not easily answered:

- How important to the success of IDR are the size and complexity of the organization?
- Does IDR work as well in small companies as in large ones?
- Does IDR work better for some types of problems than others?

In the absence of rigorous scholarly attention to such questions, we can still conclude that each sector performing and supporting IDR—academe, industry, and government—can learn from the best practices of other sectors. Researchers and administrators in institutions where IDR is unusual or neglected may be able to find helpful models in institutions where IDR is the norm, especially industrial and national laboratories. For example, they can observe how people behave when they are put together with others in teams, how researchers communicate across the barriers of knowledge domains, how large projects can be created and managed, and how projects can be disbanded when their usefulness comes to an end. They may also make wider use of other successful practices, for example, to

- Explore flexible organizational structures that permit shifting of resources and personnel to research subjects of highest promise.
- Establish reward systems that recognize outstanding performance in interdisciplinary research.
- Clarify and focus the mission of the laboratory or institution.
- Provide flexibility and support to small groups in seeking new knowledge.
- Organize laboratories not by discipline but by broader subjects of science or particular challenges.
- Use facilities and experts not available in their own institutions to solve specific problems.

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[21] GUIRR, ibid. pp. 8-13.

In general, academe might find industrial practices that facilitate cognitive and social aspects of IDR and large-scale management of IDR helpful. One must recognize that the performance of IDR in academe occurs in its own particular institutional setting with its own conditions of rewards, budgeting, and especially responsibility for training the next generation of researchers.

FINDINGS

Although research management in industrial and government settings tends to be more "top-down" than it is in academe, universities may benefit by incorporating many IDR strategies used by industrial and national laboratories, which have long experience in supporting IDR.

Collaborative interdisciplinary research partnerships among universities, industry, and government have increased and diversified rapidly. Although such partnerships still face substantial barriers, well-documented studies provide strong evidence of both their research benefits and their effectiveness in bringing diverse cultures together.