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The Role of NSF's Support of Engineering in Enabling Technological Innovation

Phase II

Executive Summary

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THE ROLE OF NSF'S SUPPORT OF ENGINEERING IN ENABLING TECHNOLOGICAL INNOVATION: PHASE II

EXECUTIVE SUMMARY

SECTION I: HIGHLIGHTS AND MAJOR FINDINGS

Beginning in 1995, SRI International, under contract to the National Science Foundation, has been conducting studies of how NSF support for engineering, especially research and related activities, contributed to the development and commercialization of recent, significant innovations. The study is, to some extent, the engineering analog of several studies carried out in the late 1960s and early 1970s that sought to identify the origins in science of significant innovations. Using a retrospective, case study approach, Phase I of the study, completed in 1997, examined the Internet, magnetic resonance imaging (MRI), and reaction injection molding (RIM). The second phase of the study, just completed, focused on computer-aided design applied to electronic circuits (CAD/EC), optical fiber for telecommunications, and the cellular phone. Section I of the Executive Summary highlights the major findings from the second phase. Section II provides a more extensive account of the study's background, a description of how the three innovations studied in Phase II evolved, and a concluding section that draws upon all six cases.

To "bound" the cases, it was essential first to identify the technologies that underlie each innovation, as distinguished from the sociotechnical system that contributed significantly to the innovation's socioeconomic and other consequences. Among the technologies that constitute the innovation, it was next important to distinguish "intrinsic" from "supporting" technologies: intrinsic technologies are those that were developed as an integral part of the innovation; supporting technologies are essential to the functioning of the subject innovation, but already existed in the "environment," and so could be incorporated largely "as is." SRI studied only intrinsic technologies in detail, but the importance of supporting technologies and the possible role that NSF may have played in their realization are acknowledged. Furthermore, these are studies of how NSF's support of *engineering,* rather than the underlying knowledge that was necessary, contributed to the evolution of the intrinsic technologies in each of the six innovations. Although extensive fundamental knowledge provided the bases on which many of the innovations drew, it was only when there was a *direct link* between intrinsic technologies and fundamental knowledge that such contributions could be fully documented and acknowledged.

MILESTONES IN THE THREE PHASE II CASES

The evolution of optical fiber

early 1960s Elias Snitzer, American Optical, publishes pioneering papers on theoretical and observed mode behavior in cylindrical dielectric waveguides.

1966 Charles Kao and George Hockham publish "landmark" paper arguing that the high losses of light characteristic of existing glass fibers were caused by minute impurities in the glass and did not result from intrinsic limits of the glass itself.

1973 Robert D. Maurer and Peter C. Schultz of Corning Glass apply for patent on an optical waveguide using fused silica for both core and cladding. On the same day, Donald B. Keck and Schultz apply for patent on the inside vapor deposition method of producing optical waveguide fibers.

1974 John MacChesney and colleagues at Bell Laboratories provide detailed description of a commercially viable inside vapor deposition process for mass producing optical fiber.

1976 Corning sues ITT for selling fibers made by Corning's method of optical fiber manufacture, the first in a series of patent infringement suits in which Corning prevailed over the next 15 years.

1977 GTE announced first use of optical fibers in regular service.

1979 Corning begins production of optical waveguides in the world's first full-scale manufacturing facility in Wilmington, NC.

1980 AT&T installs and operates first standard commercial optical fiber system at 45 Mb/s using multimode fibers in Smyrna, GA.

1988 First transatlantic optical fiber cable laid.

1995 AT&T Submarine Systems and KDD install fiber-optic network across the Pacific Ocean.

1997 Completion of 27,300 km fiber-optic cable system linking Great Britain and Japan, consisting of two 5.3 Gb/s optical-fiber pairs.

The evolution of the cellular phone

1947 Cellular concept described in a technical memorandum at Bell Labs.

1950s FCC declines to allocate significant frequencies for mobile radio.
Bell Labs scientists & engineers continue low level of investigation into the cellular concept and publish a number of internal papers.

1960s FCC denies new spectrum for mobile radio, but convenes the "Advisory Committee for Land Mobile Radio Services" to examine the congestion in land mobile telephony.
AT&T "dusts off" cellular concept and begins serious work on it again.
The FCC opens Docket 18262 (known as the "Cellular Docket").

1970s FCC reallocates 115 MHz in the upper portion of the TV UHF band and sets aside new frequencies (64 MHz) for "land mobile communication." A decade of legal disputes over who gets what ensues.
Bell Labs files its classic "High-Capacity Mobile Telephone System Feasibility Studies and System Plan" report to the FCC.
The FCC grants experimental licenses and decides to authorize construction of two developmental systems: one in Chicago (licensed to Illinois Bell) and a second serving Baltimore, Md. and Washington, DC (licensed to American Radio Telephone Service Inc., now Cellular One, in partnership with Motorola).

1979 First commercial cellular system is installed in Tokyo by NTT.

1981 Nordic countries introduce a mobile phone system.
The FCC adopts rules creating a commercial cellular radio telephone service.

1983 Pilot commercial cellular system of Illinois Bell begins operating in Chicago. The second pilot system run by ARTS in partnership with Motorola begins operation in Baltimore/Washington on December 16, 1983.

1992 Cellular subscriber count tops 10 million.

1994 Bell Labs engineers Joel Engel and Richard Frenkiel win National Medal of Technology for their work in cellular telephony.

1995 Cellular subscriber count tops 25 million.

1997 Cellular Subscriber count tops 50 million.

The evolution of computer aided design applied to electronic circuits

early 1960s First digital integrated circuits available commercially.

early 1960s Hermann Gummel of Bell Labs develops first mathematical models of nonlinear transistor behavior.

mid 1960s Development of device analysis and circuit analysis techniques.
Internal software programs designed for circuit boards.

1969 Kuo and Magnuson publish classic text, *Computer Oriented Design Automation.*

early 1970s Donald Pederson and his students at Berkeley develop SPICE, the first universally applicable circuit simulation program, and make it widely available to industry.

mid 1970s Widespread use of programs for checking the physical layout rules for circuits.
Caltech Intermediate Form (CIF) computer language developed at Caltech by Carver Mead and Lynn Conway (Xerox PARC) allowed for the separation of circuit design and chip manufacturing processes.

1975 Computer aids necessary for design of complex integrated circuits.

late 1970s Daniel Siewiorek and Stephen Director at Carnegie Mellon formulate first comprehensive software design project that incorporated nearly all aspects of integrated circuit design.

1980s Successful commercialization of computer aided design software packages by firms such as Mentor Graphics and Cadence Design Systems.

1994 Firms in electronic design automation industry reach $1.4 billion in sales.

PATTERNS OF INNOVATION IN THE PHASE II CASES

Government, industry, university roles and interaction

- Low-loss optical fibers for communications were invented by industry, based on processes previously developed in industry.
- Federally-funded science and engineering activities played an indirect role in optical fiber, primarily by helping to train doctoral scientists and engineers who went to work in industrial R&D on optical fibers and related components and by supporting basic research at materials engineering centers.

- The FCC retarded development of the cellular phone during the 1950s and 1960s but stimulated it in the 1970s through spectrum allocation and other decisions.

- The military services and defense agencies in particular invested substantial sums in telecommunications research; a considerable amount of this money went to academic institutions.

- The evolution of computer aided design software, which eventually became embodied in successful commercial products marketed by hundreds of computer software and service providers, occurred within the context of government support for computer hardware and software development and use.

- Academia's contribution to computer aided design was not "science," but rather (1) pragmatic software developments in simulation and testing such as SPICE; and (2) students, trained in the use of these tools, who populated industry and in many cases extended the state of the art while employed there.

- During the 1960s and 70s there were extensive interactions in the field of design automation between industry and academia that took various forms: consulting, visiting professorships from industry, exchanges, and student internships in industry, that kept academia closely tied to industry needs and problems.

Relationships between fundamental research and technological development

- Early work on optical fiber was empirically driven, with fundamental research providing subsequent explanations of developments.

- Relationship between fundamental research and technology development was much closer in supporting aspects of fiber-optic communications, especially advances in lasers and network theory.
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- Most of the development effort in cellular phones consisted of continuous improvement in existing communications products and technologies and then the fusion of a number of existing technologies to produce a substantially improved product.

- Advancements in CAD/EC were incremental engineering steps and were not directly science-based. Fundamental knowledge was crucial, but it already existed (e.g., Boolean algebra) and could be applied (not without some effort) to the problem at hand.

NSF role

- In the field of optical communication, NSF played a strong leadership role within the relatively small areas it chose to address formally: supporting technologies such as opto-electronics. The choice reflected clear awareness of the dominance of industry in the development of commercially viable optical fiber.

- NSF funded regular industry-university meetings to promote information exchange among grantees in optoelectronics and related fields and also with researchers in industry.

- Until the late 1970s, there were very few academics working in telecommunications. Few academics proposed work in telecommunications to NSF, and few proposals were funded. This was a result of the dominance of AT&T in a regulated industry, a situation that changed with the breakup of AT&T and the emergence of numerous new, small firms.

- In the 1960s NSF, recognizing that computers were the key to advancements in many scientific and engineering fields as well as to graduate student training in science and engineering, provided massive support to universities to acquire and maintain state-of-the-art mainframe computing equipment.

- During the 1960s, research on CAD/EC was driven primarily by industry needs was supported by defense agencies, while the more theoretical aspects were supported by NSF.

- NSF supported the research of a number of key contributors to CAD/EC: Pederson, Breuer, Siewiorek and Director, and others.

- NSF program directors supporting CAD/EC used the workshop strategy to build academic capacity in the field by enlarging the community of interested university researchers, to facilitate university-industry interaction, and help guide program priorities.

Intellectual property protection

- Corning's dual strategy–-strong patent defense and vigorous technological innovation-–put the company in a position to capture much of the non-AT&T market for optical fiber that emerged after the AT&T breakup.

- Corning's cross-license with AT&T required Corning to adopt a much more aggressive approach to R&D on optical fibers and production improvements than they would have made if protected just by patents.

- Formal intellectual property protection was not an important factor in the development of the analog cellular phone, although it would become more so as development moved toward digital cellular.

- Intellectual property played a minor role in the evolution of CAD/EC because commercial development of software packages did not take the form of discrete vendors until well into the 1980s. Industry relied on trade secrets, and universities chose not to patent design automation software.

NSF'S ROLE IN ENGINEERING INNOVATION: MAJOR CONCLUSIONS FROM THE CASES

- NSF emerges consistently as a major, often *the* major, source of support for education and training of the Ph.D. scientists and engineers who went on to make major contributions to each innovation studied.

- Support of university research infrastructure emerges as the likely candidate for second place among NSF's most influential activities in the cases.

- NSF managerial strategies have a subtle but substantial effect on the way engineering innovations evolve. Key strategies in the 1970s and 80s were workshops involving academics and industry representatives that facilitated communication among researchers, expanded the set of academic researchers working on industrially-relevant problems, and helped shape NSF program directions.

- Without exception, the cases reveal the essential role that government support of education and training, especially graduate education through fellowships and research assistantships, had on engineering innovation. The Department of Defense and NSF dominate.

- A single, consistent pattern that stands out across all six cases is the critical role played by human capital in the form of individual inventors, technical entrepreneurs, and students trained in the state-of-the-art who could continue to push technical advance in business, academia, and government.

- In the case of the cellular phone and RIM, regulatory policy shaped the course of innovation in major but widely varying ways: FCC regulations first delayed, then spurred development of the cellular phone, while Congressional auto fuel economy and safety regulations virtually created the market for RIM.

- Technological innovation in the United States in the latter decades of the twentieth century involves contributions by, and interaction among, all three sectors: government, industry, and academia. The cases reveal clearly the importance of "invisible colleges:" engineers and scientists who share results and know-how via networks that span both cooperating and competing institutions. Isolation appears clearly as the enemy of innovation.

- Key contributors to all six innovations acknowledged their debt to fundamental research, sometimes to research done in the early part of the century or even in the previous century. Yet fundamental research played a supportive rather than central role in the development of the intrinsic technologies embedded in the six innovations studied.

- The six innovations evolved successfully largely in spite of, rather than because of, intellectual property protection.

SECTION II: SUMMARY OF PHASE II CASES AND STUDY CONCLUSIONS

BACKGROUND

The three cases of engineering innovation that constitute the core of this executive summary are the second set of a series of cases being conducted by SRI International as the central component of what was designed as a 4-year project. The project is examining how National Science Foundation support for engineering has contributed to the development and commercialization of recent, significant engineering innovations. The project is, to some extent, analogous to the several studies carried out in the late 1960s and early 1970s (Hindsight, TRACES) that sought to identify the origins in science of significant innovations. According to NSF, the project's purpose is

> to conduct a systematic examination of the antecedent discoveries, events, people, interactions, and conditions that lead to the evolution of the 12 most significant engineering innovations to have emerged in the preceding decade to: (1) document NSF's involvement in bringing about the innovations; and (2) evaluate the significance of NSF's role in the broader context of the innovations' development.

The innovations to be studied should have "emerged as significant in the last decade in broad technical areas that NSF has supported for decades." They should meet the following criteria:

- Considerable engineering content.
- A significant research component.
- An outcome that causes major changes in the quality of life, how tasks are performed, and/or the cost or efficiency of production.
- The likelihood of at least some NSF engineering involvement at some point in the innovation's evolution.

A Technical Review Panel was assembled whose responsibilities are to help select the innovations, provide background information on those selected, and review the cases completed in each year. The initial meeting of the Technical Review Panel took place in November 1995. At this meeting, the three innovations to be studied the first year were chosen:

- Magnetic resonance imaging (MRI)
- Reaction injection molding of polymer composites (RIM)
- The Internet.

The results of the first year's study may be viewed and downloaded at www.sri.com/policy/stp/techin. At the Panel's second meeting in December 1996, three additional innovations were chosen for study during the second year:

- Computer-aided design applied to electronic circuits (CAD/EC)
- Optical fiber for telecommunications
- The cellular telephone.

This executive summary covers considerably more than just the results of these three cases, however. One of the lessons learned from the first three cases was that in order to examine fully the contributions that the National Science Foundation has made to the evolution of major engineering innovations, it is essential to understand the several contexts within which such contributions originated. The relevant contexts that shaped the nature and extent of NSF contributions include the political and organizational environments in which engineering programs were initiated and operated within the Foundation; the financial support provided to engineering relative to other fields within the Foundation and relative to the support provided to engineering by other federal agencies; and the managerial strategies employed by NSF program directors and managers in planning, setting priorities, and selecting projects to support. Thus, as a prelude to the second set of cases SRI reviewed the engineering field's effort to define its proper niche within the Foundation, establish a stable organizational base, and develop managerial strategies that were effective in achieving the Foundation's broader objectives while accounting for the engineering field's unique place in research, education, and technological innovation. A summary of the results of this overview of engineering in NSF appears immediately below, followed by overviews of the evolution of the three innovations studied in the second year. Additionally, it was appropriate to look for patterns in the NSF role not just across the three cases carried out in the second year, but to include the three cases from the first year's research as well. Thus, the "Conclusions" section of this executive summary covers conclusions drawn from all six cases.

AN OVERVIEW OF ENGINEERING AT THE NATIONAL SCIENCE FOUNDATION[1]

Through the 1950s and 60s, engineering in NSF sought recognition internally while attempting to define a narrow range of research to support that was recognizably engineering rather than "applied science," yet was sufficiently "basic" to match the intent of NSF's charter. The term "basic engineering science" meant "any scientific activity that strengthened engineering practice;" work of "a true scientific nature and not routine engineering practice;" research that "provides the essential information and methods with which existing problems may be solved and new opportunities . . . recognized." Engineering program directors quickly concluded that supportable projects would not match traditional engineering disciplines but instead would be categorized according to underlying fundamental phenomena such as thermodynamics or fluid mechanics. Supportable projects would also tend to be interdisciplinary, frequently involving two or more engineering disciplines as well as science.

As this delicate balance became codified, understood, and accepted by the academic engineering community, the system was shaken in the late 1960s and throughout the 70s by a new mandate in NSF's authorizing legislation. This mandate introduced new terms, "applied research" and "research applications," that seemed to imply engineering, and new organizational forms designed to respond to it. NSF's response to the mandate also separated its support of engineering into multiple, changing loci. Even before the Daddario amendments, however, engineering at NSF was beginning to respond to larger societal problems by creating programs in problem-oriented areas such as earthquake hazards research. During the organizationally tumultuous 1970s, engineering research at the Foundation was supported from multiple and shifting locations, no doubt making strategic planning and priority setting a difficult task. It was not until the Research Applied to National Needs (RANN) Program was abolished and the Directorate for Engineering created in 1981 that engineering became focused and stabilized, achieving equal organizational status with the sciences.

From a first, small effort in 1962 to respond to larger social problems, engineering programs became increasingly proactive in the ways they set research priorities. In the early days, "proposal pressure" defined areas for emphasis. Then engineering program managers began to hold workshops, at first including only grantees and other academics but later including industry representatives. These workshops' purposes were to build stronger research communities, identify promising areas for research, and eventually bring industry's priorities into the priority-setting process. By the time the Engineering Directorate was created, approximately 30% of engineering research was problem-oriented, focusing on topics identified through numerous channels such as these workshops and outside advisory groups. Another significant management strategy, introduced in the 1970s but not becoming prominent until the 1980s, was to encourage industry-university research consortia to form around subjects of interest to industry. Over the years, centers programs such as the Industry-University Cooperative Research Centers and the Engineering Research Centers have become important vehicles for support of activities not amenable to single investigator or small group grants. Evidence of the relative effectiveness of this

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[1] A complete bibliography for this section is provided in the report upon which this executive summary is based.

and other strategies continues to be a subject of importance for NSF policymakers and program directors.

For over a generation NSF and DOD have been the major sources of support for academic research in the fields of fundamental science and engineering other than biomedicine. Thus, the nation's current generation of Ph.D. scientists and engineers and the contributions they have made to knowledge advancement and technological innovation can be attributed in no small degree to support from these two agencies of the federal government. In some fundamental engineering fields such as chemical and civil engineering NSF's relative contribution dominates. Tracing the intrinsic technologies that comprise recent engineering innovations to their roots in research and technology, and to the scientists and engineers who produced them, reveals the prominent influence of these two agencies and the mechanisms through which that influence is manifested.

SUMMARY: OPTICAL FIBER CASE

Low-loss optical fibers for communications were invented by industry, based on processes previously developed in industry. Federally-funded science and engineering activities played an indirect role, primarily by helping to train doctoral scientists and engineers who went to work in industrial R&D on optical fibers and related components of fiber-optic communication systems such as lasers, and by supporting basic research at materials engineering centers. Of the three Corning researchers who made the first low-loss optical fiber, one was supported as a doctoral student by a research grant to his thesis adviser from the NSF physics program, and another was supported by a graduate fellowship in engineering from NSF (the third received his Ph.D. in 1952, too early to be supported by NSF). NSF-funded basic research in solid-state physics, ceramics/glass engineering, and other areas was part of the knowledge base in the late 1960s, when the initial R&D on optical fibers was done. Although necessary as a building block, these contributions were too distant in time and indirect for researchers at Corning or Bell Laboratories to identify specific links to optical fibers. One researcher who had received basic research grants from NSF to study fluctuations in liquids went on to apply some of that knowledge with grants from DOD to developing a new way to make optical fibers, although that method was not ultimately competitive in the market.

The two most successful optical fiber companies—Corning and AT&T—were not very interested in taking federal R&D grants or contracts, preferring to keep their work proprietary. Corning did accept some Army and Navy contracts in 1972-1975 to study radiation effects and ways to improve mechanical strength (the latter work revealed the need to coat fibers immediately after they were drawn). Corning also received a Navy contract in the late 1970s to conduct a design study of single mode fibers and cables, which helped position Corning for when MCI and other buyers suddenly wanted large amounts of single mode rather than multi-mode after 1980. In each case, however, Corning was careful to avoid giving the government a position in the R&D for fabricating optical fiber.

DOD had been active in supporting early fiber optics R&D in small and start-up firms because of its possible applications in short-distance, noncommunication uses, such as instrument panel lighting and faceplates for radar screens. The Air Force supported the fundamental work on mode propagation in cylindrical dielectric waveguides at American Optical used by the Corning team. The superiority of fiber optics for military communications led DOD to fund R&D by other companies, such as ITT and Valtec, who would be responsive to DOD's needs (the military market was small from the perspective of AT&T and Corning), but those companies all made doped-core silica fibers by chemical vapor deposition and were successfully sued by Corning for patent infringements.

The universities were not very engaged in research relevant to optical fiber in the 1960s, and the applied research and development work was done in industry. At the time Corning was figuring out how to apply vapor deposition techniques to make low-loss silica fibers, the NSF Division of Engineering was supporting areas of research that might make a contribution to U.S. leadership in civilian technology. The Division started the optical communication systems program, among others, deeming it an area in which progress could be made that would be useful to industry. Since the criteria included ripeness of the scientific base and potential for impact, the program emphasized topics that leading academic researchers were already active in, not building a research program from scratch. Industry was not pushing for an NSF program in optical fiber research, because it seemed to have such work well in hand. The program thus funded established researchers in quantum electronics and communication theorists; it did not try to stimulate research in fiber optics at that time. Later, NSF became more active in supporting optical physics and engineering, including fiber optics, through its centers programs in the 1980s, but even the most recent major advances in optical communications have continued to come from industry.

Relationships between fundamental research and technological development

When Kao and Hockham set out in late 1964 to see if glass fibers could be used for optical communications, they found little basic information about the optical behavior of glass materials in the scientific literature and virtually nothing on its fundamental physical limits. A few years later when, inspired by Kao and Hockham's article, Corning researchers Maurer, Keck, and Schultz tackled the problem of using silica to make low-loss fibers, they too proceeded empirically.

This is not to say there was no fundamental research. There was, but it was the need to explain developments that fostered new research rather than the other way around. As a result, a large body of knowledge about optical fiber materials and the processes for making and testing them developed in industry in a short period of time. The research provided better understanding of what was being observed empirically, which industry supported because it helped fine tune the manufacturing process.

In the first 15 or so years (1966-1981) of fiber optic development, industry did not look to universities for knowledge about, or as a place to sponsor research on, optical fibers, although they built up their in-house R&D staffs by hiring doctoral and masters degree recipients from engineering and physics programs in the universities. That pattern changed in the 1980s. Corning, Bell Labs, and other optical fiber companies apparently saw the value of building a broader research base and began to affiliate with universities, first through Industry/University Cooperative Research Centers and then through Engineering Research Centers. The relationship between fundamental research and technology development was much closer in other aspects of fiber-optic communications, especially advances in lasers and network theory. Academic scientists and engineers working in those areas, including some NSF-supported grantees and graduate students, made fundamental contributions, as measured by awards and memberships in prestigious organizations (NAE and NAS).

NSF role

At the time of the original invention of low-loss optical fiber in 1970, NSF was just beginning to expand its original mission of supporting basic research and training to include support of research and training that was more applied in focus. Even as it initiated a program aimed at contributing to progress in optical communications science and technology, NSF was constrained by two realities. First, it did not want to support work that would otherwise be funded by industry, and industry R&D in optical communications was large and growing. Second, federal mission agencies—DOD and NASA in particular—were already supporting large amounts of R&D in optical communications, and even after the Mansfield Amendment, NSF would only be able to play a secondary role (at least until substantially larger budgets for university-industry research center programs came about in the 1980s). Nevertheless, NSF contributed in several ways.[2]

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[2] For the purposes of this study, these NSF support modes were defined as follows:

- **education:** support of graduate fellowships, traineeships, and research assistantships to major individual contributors to technologies intrinsic to the innovation studied.

Education. NSF had doctoral fellowship and traineeship programs for some hundreds of students a year, and through graduate research assistantships funded by its research grants, it supported the graduate work of thousands more in the 1960s. In 1969-1970, about half of all engineering Ph.D.s and 30 percent of all physics Ph.D.s went into industry. Not surprisingly, then, NSF supported the graduate education of some of those who contributed to optical fiber and related R&D. In particular, one of the three original inventors of the first low-loss fiber had had an NSF engineering fellowship in graduate school and another had worked as a graduate assistant on an NSF grant awarded to his thesis adviser.

Direct Research Support. NSF did not play a noticeable role in funding research directly relevant to optical fiber, consistent with the absence of materials work for fibers in the university programs and with the reality that the major firms were already pursuing large R&D programs in this area. NSF limited its organized effort to support optical communications research to two areas with strong academic bases—integrated optics and information system theory. Researchers funded by the OCS program contributed to the development of workable semiconductor lasers (but most of the work was supported by industry and DOD) and achieved a number of firsts in building integrated optical circuits (although the hoped for parallel with the developmental curve of electronic integrated circuits did not pan out).

Knowledge Base. The basic work in electromagnetic theory had been done before NSF existed. NSF funded some basic research on amorphous or noncrystalline materials and on solid-state physics during the 1950s and 1960s. When the head of the team that invented the first low-loss optical fiber published a review article in 1973, however, few of the 59 references were to academic researchers. In the research areas in which NSF chose to establish an active program, NSF-funded work became part of the knowledge base. For example, articles by a number of NSF-funded researchers and former students are cited in a basic overview of optical fiber telecommunications, in chapters concerning semiconductor lasers, detectors, integrated optics, optoelectronic devices, and receiver design.

Research Infrastructure. In 1977, the Division of Engineering created the National Research and Resource Facility for Submicron Structures to assist in universities and industry working on nanofabrication technologies and related fundamental physics and materials problems and on the miniaturization of advanced devices with submicron dimensions, including optical and optoelectronic devices. This facility enabled universities to work with state-of-the-art equipment in optoelectronics, a major supporting technology in optical communication.

Supporting Technology. NSF did not play a role in developing supporting technologies relating to optical fiber *per se*--splicing techniques, connectors, polymer coatings, or cabling. That work was done in industry. However, NSF did play a role in supporting research relevant to the development of the nonfiber components and devices needed in a fiber-optic communication system. Without these

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- **direct research support (of intrinsic technologies):** support of research projects whose results contributed directly to the development of technologies intrinsic to the innovation studied.
- **direct contribution to the knowledge base:** support of research in fields of knowledge upon which the innovation's intrinsic technologies drew for which there was documentation.
- **direct contribution to the research infrastructure:** instrumentation, equipment and facilities comprising the infrastructure upon which the innovation's evolution depended.
- **direct contribution to supporting technology:** research contributing directly to the development of technologies that supported, rather than were intrinsic to, the innovation being studied.
- **organizational leadership:** bold, innovative decisions or actions that helped to solve problems, remove roadblocks, or in other ways facilitated the innovation's development.
- **facilitation of interaction and communication:** support of workshops, centers, and other mechanisms for fostering communication among researchers within and across fields, and across institutional boundaries.

components, advances in the fiber alone could not have produced significant socio-economic impact on communication systems.

Organizational Leadership. The main leadership in optical fiber communications R&D was taken by industry researchers working through the OSA, IEEE, and other professional societies. The most important meetings in terms of sharing information and charting future research directions were the OSA/IEEE topical meetings on Optical Fiber Communications (1975 on) and on Integrated and Guided-Wave Optics (1972 on) organized by Stewart Miller at Bell Labs and Robert Maurer at Corning.

Interaction and Research Communication. NSF played a strong leadership role within the relatively small areas it chose to address formally. A forward-thinking program director sought out leading academic researchers and encouraged them to apply for funding that was, although peer-reviewed, set aside specifically for work on optical devices or optical communications systems. Although the program did not grow in accordance with initial plans, NSF sustained the program for 15 years. Importantly, the program funded regular industry-university meetings to promote information exchange among grantees and also with researchers in industry.

SUMMARY: CELLULAR PHONE CASE

From Fundamental Research to Flip Phones

Although some basic research, particularly research on the propagation characteristics of higher frequency bands, was essential to the development of cellular, most of the development effort consisted of continuous improvement in existing communications products and technologies and then the fusion of a number of existing technologies to produce a substantially improved product. At the time the cellular concept first surfaced in print at Bell Labs in 1947, the major technological challenges and a series of potential solutions were identified. Although many of these solutions could not be achieved at the time and in some cases would await developments in other fields (integrated circuits, for example), no major breakthroughs in knowledge were required to kick the development of cellular into high gear. In fact, that kick ultimately came not from the laboratory, but from events in the regulatory and business sectors. Not until the late 1960s, when the FCC sent strong signals that they were ready to make a significant allocation of frequencies for mobile radio, did the cellular development program at Bell Labs really get under way.

NSF Role

Despite this case's evidence indicating that NSF played little or no direct role in the development of the cellular phone, it would be erroneous to conclude that NSF "missed the boat" on cellular. In fact, NSF did the right thing in the early days of cellular development by staying out of mobile radio research, and made the right move to change its involvement years later when the market situation had changed. It is easy to overlook the fact that the technological and commercial environment for telecommunications in the 1950s, 60s, and 70s was very different than it is today. In those earlier decades, AT&T was the near-monopoly provider of virtually all telecommunications services. In addition, it owned and operated one of the nation's premier research facilities, Bell Laboratories. Besides conducting development activities for telecommunications systems to be fielded by AT&T, Bell Labs performed research which contributed to the nation's store of scientific knowledge in telecommunications as well as other important areas of science (the Nobel-winning discovery of the cosmic microwave background radiation comes immediately to mind). Not only was AT&T, through Bell Labs, the organization best positioned to conduct telecommunications research, it was virtually the only organization that could implement the results.

Had NSF made significant research investments in areas related to telecommunications in the 1950s, 60s, and 70s, observers of the day might well have asked why the Foundation was trying to compete with Bell Labs in an area already well addressed by the latter institution. Furthermore, Bell

Labs, as well as the other firms involved in telecommunications, had usually drawn their science and engineering staff from among graduates of traditional university science and engineering programs and provided them with the additional education, training, and the on-the-job experience required to work in specialized research areas. Thus, at that time, there was no strong demand for new graduates with specialized degrees in wireless or mobile radio. In the absence of such demand, it is not surprising that there were very few academics working in those areas. Neither is it surprising that few academics proposed work in telecommunications to NSF, nor that few proposals were funded.

However, in the late 1970s and 1980s, a number of things changed. The importance of many new types of telecommunications technologies and services and their critical national role as supporting technologies became obvious. In addition, the Bell System was broken up, and Bell's monopoly on most forms of telecommunications was lifted. Finally, many small telecommunications providers began to grow and enter new areas, such as cellular, and even more new telecommunications companies were being formed. Many of these companies became very successful and grew quite large. But there was very little public research or human capital to support these new firms that generally could not, as Bell Labs, Motorola, and other large firms had, train their own specialized manpower in-house. Academia, supported by NSF and others, began to respond.

As noted above, in the 1970s, as the cellular idea began to look promising, industry researchers began to meet more frequently, first at the specialized seminars held in Boulder, Colorado, and later at expanded sessions during mainstream telecommunications conferences. There they came into contact with the growing number of academic researchers in the field. In the 1980s and 1990s, a few cellular and wireless researchers from Bell Labs and Motorola left these companies for academia to develop programs in wireless communications or to found start-up companies to fill new technology niches in cellular and mobile communications. Academia began to pay more attention to the needs of this growing community, with new programs and centers focused on wireless, mobile radio and related areas. These programs were founded by retired veterans from the telecommunications industry as well as by the growing number of young academics who did their graduate work in telecommunications areas.

As the market for increased academic work in wireless, urban mobile radio, and other new areas of telecommunications grew, NSF began to change its awards profile. The number of awards related to telecommunications increased, and the Foundation began to pay more attention to these fields as several university programs in wireless entered the ranks of NSF supported centers. NSF support for the broad field of telecommunications grew substantially during the 1990's, reaching a peak in 1994.

Other Public Support

Other federal agencies played a more prominent role in supporting telecommunications R&D and thus had a tangential impact on the development of cellular. The military services and defense agencies in particular invested substantial sums in telecommunications research. A good deal of this money went to academic institutions, enabling them to support the education of graduate students. Several of the cellular pioneers SRI interviewed noted that they had undertaken some of their graduate work with support from defense sector funds. For some of the earlier cellular researchers, the G.I. Bill was also an important source of support, as it was for many other scientists and engineers of that era.

SUMMARY: COMPUTER-AIDED DESIGN APPLIED TO ELECTRONIC CIRCUITS (CAD/EC) CASE

Government-Industry-University Relationships

The evolution of computer aided design software, which eventually became embodied in successful commercial products marketed by hundreds of computer software and service providers, occurred within the context of government support for computer hardware and software development and use. In the 1950s, defense missions supported development of the computer itself (in which universities played a central role) as well as a number of related technologies such as interactive graphics and visual display terminals that later would become elements of commercial products. In the 1960s, defense demands for reliability in electronic devices spurred invention of the integrated circuit and led, indirectly, to development of computer-based design aids that made component placement, wiring, and printed circuit board layout more efficient. At this time NSF, recognizing that computers were the key to advancements in many scientific fields as well as to graduate student training in science, provided massive support to universities to acquire and maintain state-of-the-art mainframe computing equipment.

To focus specifically on the development of CAD/EC, during this period there were extensive interactions between industry and academia that took various forms: consulting, visiting professorships from industry, exchanges, and student internships in industry, that kept academia closely tied to industry needs and problems. Most observers conclude that, during the 1960s, technological leadership in CAD/EC was based in industry, particularly in a few large firms such as IBM and AT&T. Academia's contribution was not "science," but rather (1) pragmatic software developments in simulation and testing such as SPICE, which had wider applicability than the more powerful but highly specific tools developed internally in computer and semiconductor manufacturers; and (2) students, trained in the use of these tools, who populated industry and in many cases extended the state of the art while employed there. Industry was thus the primary source of incremental but cumulatively significant advances in CAD/EC.

In the 1970s the picture changed. Design automation had to this point been primarily the response to the high cost of routine operations handled manually, and secondarily to the increasingly complex problems that board and chip designers faced. By 1975 it was impossible to design state-of-the-art chips with the density of components required without computer aids. Industry struggled to meet these needs by expanding their in-house design staffs, while a few visionary academics looked further ahead, realizing that within ten years behavior-level synthesis, required by VLSI chips, would have to depend on computer aided design. Some of the leading universities, still closely linked to industry and, indeed, as a result of these linkages, understood yet looked beyond the short term needs of industry and proposed research that was responsive to far longer term requirements. There was a sizable response from government, primarily from NSF and DARPA, that in no small way contributed to the successful commercial development of CAD/EC software in the 1980s.

Fundamental Research and Technology Development

During the entire period of interest in this case, there was little evidence that the evolution of CAD/EC was retarded by the lack of fundamental scientific knowledge. The necessary underlying knowledge such as basic mathematics was there to be applied, producing incremental advances oriented more toward solving problems quickly and simply than elegantly. Advancements in CAD/EC were incremental engineering steps and were not directly science-based. This is not to deny the importance of fundamental knowledge--it was crucial, but it already existed (e.g., Boolean algebra) and could be applied (not without some effort) to the problem at hand.

Intellectual Property Protection

During the 1960s and 1970s, the major players in CAD/EC chose, for very different reasons, not to concern themselves with intellectual property protection of the software tools they produced. The central university figures were not motivated by interest in profits for themselves or for their institutions, at least through royalty payments. They felt that they, their students, and their universities would benefit more substantially through subsequent gifts and research contracts, and history seems to bear them out. Meanwhile, industry kept its software packages close to its collective chest, relying instead on the protection offered by trade secrets rather than copyrights. It may have a been a moot issue, anyway, since so many of these packages were designed for extremely narrow, internal applications. There was, at least among the industry leaders, some cross licensing, presumably a result of recognition that sharing of knowledge would benefit all more than would restricting its flow.

Once commercially available CAD/EC packages appeared on the market in the 1980s, patenting activity surged. However, it did so primarily among late entrants rather than the “old guard,” possibly because the early entrants relied on know-how and their reputation for service. Recent entrants to the market are patenting extensively, but that may be for reasons related more to staking a claim than any expectation that their profits will be a consequence of intellectual property protection.

NSF Role

NSF supported the research of a number of key contributors to CAD/EC: Pederson, Breuer, Siewiorek and Director, and others. That support was often supplemented, in some cases dominated, by additional support from defense agencies. During the 1960s, research that was driven primarily by industry needs (e.g., Pederson, Breuer) was supported by defense agencies, while the more theoretical aspects were supported by NSF. Advances that had immediate impact in the field were practical and incremental, not theoretical. With the advent of the 1970s, NSF’s new, more activist managerial stance appeared to bear fruit. Workshops involving university and industry researchers strengthened communication between the two sectors, helped chart NSF’s program directions, and identified industry-related research priorities to which academic researchers could respond. At the same time, industry representatives on NSF advisory committees and peer review panels could critique proposals for research. As exciting ideas emerged from university research, NSF program directors, encouraged by the larger climate within the Foundation of willingness to identify areas of promise and support them, used the workshop strategy to build academic capacity in the field by enlarging the community of interested university researchers. By the 1990s, for example, the number of academic institutions involved in VLSI research had multiplied severalfold. According to our interviewees, NSF is perceived as willing to speculate on promising yet risky areas of research. In the case of CAD/EC in the 1970s and 1980s, this strategy apparently has paid off.

THE ROLE OF NSF SUPPORT OF ENGINEERING IN ENABLING INNOVATION: CONCLUSIONS FROM SIX RETROSPECTIVE CASE STUDIES

Our conclusions are directed toward two broad objectives of this series of studies: first, to learn more about the processes by which significant engineering innovations evolve, and second, to understand better how the several modes by which the National Science Foundation supports research, education, and related activities influenced those processes. To address the first objective, SRI sought patterns across the six innovation cases in three categories:

- the interplay of government, industry, and universities as the innovations evolve;
- the role of, and interaction between, fundamental research and technology development; and
- the role of intellectual property protection.

To address the second objective, SRI looked in detail across the cases at the specific ways in which the following activities of the National Science Foundation may have influenced the evolution of these engineering innovations:

- education
- direct research support
- direct contribution to the knowledge base
- direct contribution to the research infrastructure
- direct contribution to supporting technology
- organizational leadership
- facilitation of interaction and communication.

Patterns of Innovation: Government, Industry, University Roles and Interaction

In nearly all six cases support for research and technology development by government, especially units of the Defense Department, played major roles. (D)ARPA and the Air Force supported research that led to intrinsic technological elements of the Internet: packet switching, TCP/IP, and routers, while NSF and (D)ARPA supported the computing infrastructure that constituted the university-based backbone of what was to become the Internet. Defense agency needs supported university research that produced the computer and peripherals. The computer-aided design tools developed in consort with the computer were initially a response to the need to design and manufacture the electronics for reliable missile guidance systems as quickly as possible. As CAD/EC tools addressed higher levels of design and synthesis in the 1970s, research support from defense agencies, commercial firms, and NSF was combined by university-based investigators as the forefront of research shifted from industry to academia. Although RIM was primarily an industry-developed innovation, the foundations laid in polymer chemistry by government support of university basic research, and by defense and NASA support of work on advanced polymer composites, yielded the knowledge and human capital upon which industry increasingly depended as they encountered roadblocks that required new knowledge about the behavior of composite materials.

Development and, especially, diffusion of MRI depended on government support of research. The development of MRI drew heavily on earlier investment by NSF in university research instrumentation and support of graduate students in analytical chemistry (nuclear magnetic resonance, or NMR, in particular), while development of prototype MRI machines and clinical trials relied substantially on NIH. Government support of research played lesser roles in optical fiber and the cellular phone, but in the case of optical fiber, potential military applications provided infusions of money for research and testing that speeded commercial development and helped support internal industry development costs. Even in the cellular phone case, probably the most “civilian” of our six innovations, there was at least some contribution by defense support of research on atmospheric radio propagation.

Without exception, the cases reveal the essential role that government support of education and training, especially graduate education, had on engineering innovation. Again, defense agencies and NSF dominate. Repeatedly, key contributors to the innovations studied attested to the importance of public support of technical education. In many cases (e.g., MRI, optical fiber) these contributors were direct recipients of public support while they were in graduate school, acknowledging that, without it, they probably would not have been able to go on to graduate education. In other cases (e.g., CAD/EC) they attested to the role of students as the primary mechanism of knowledge transfer between academia and industry; in still others (e.g., optical fiber) they noted that well-trained students were essential to achieving and maintaining company competitiveness. Indeed, if there is a single, consistent pattern that stands out across all six cases, it is the critical role played by human capital in the form of individual inventors (e.g., MRI, Internet, optical fiber), technical entrepreneurs (e.g., CAD/EC, cellular phone), and students trained in the state-of-the-art who could continue to push technical advance in all three sectors of the economy (all cases).

In the case of the cellular phone and RIM, regulatory policy shaped the course of innovation in major ways. Although the basic idea for the cellular telephone had existed since 1947, and much of basic technology existed at least to prove the concept, development languished until 1960, when the Federal Communications Commission was finally willing to allocate sufficient frequency spectrum to mobile radio. Development then proceeded rapidly in AT&T Bell Labs and Motorola, with the latter assuming considerable risk in pursuing its concepts in an area dominated by a regulated monopoly. In contrast, in the case of RIM, congressionally-mandated auto safety and fuel economy standards essentially created a market for new, light, elastic polymers and for processes that produced them efficiently for the huge automotive market. To a lesser degree, government efforts to control medical costs by certifying particular procedures and diagnostic techniques helped establish the market for magnetic resonance imaging machines in the mid-1980s, just as the demand for it was beginning to increase.

The cases also illustrate what is becoming common knowledge: technological innovation in the United States in the latter decades of the twentieth century involves contributions by, and interaction among, all three sectors: government, industry, and academia. In some cases the interplay among sectors is best characterized as the flow of key individual contributors across institutional boundaries (e.g., the Internet, CAD/EC, RIM). In others, it is more strongly represented by the unimpeded flow of knowledge across these boundaries (e.g., optical fiber, the cellular phone, MRI). But all cases exemplify both modes of interaction, and it seems evident that without them progress would have been far slower. The cases reveal clearly the importance of “invisible colleges:” scientists and engineers who share results and know-how via networks that span both cooperating and competing institutions. Isolation appears clearly as the enemy of innovation.

Patterns of Innovation: Fundamental Research and Technological Development

SRI studied engineering innovations, not scientific discoveries. Given that successful innovations typically require several decades to evolve from conception to success in the marketplace, it is not surprising that fundamental research was found to play a supportive rather than central role in the six cases. Key contributors to all six innovations acknowledged their debt to fundamental science and engineering, sometimes to research done in the early part of the century (e.g., MRI) or even in the previous century (e.g., CAD/EC). Beyond this, there is no consistent pattern, and certainly little evidence to support the “pipeline” model of innovation. Perhaps the closest to this model is MRI, which rests scientifically on the Bloch-Purcell experiments in nuclear magnetic resonance, but even in this case it was a totally unexpected turn of events, the application of an innovative variation of the resulting technology, nuclear magnetic resonance spectroscopy, to an entirely new field that led to MRI’s realization.

RIM was an industrial innovation that advanced incrementally using trial-and-error methods on the production floor until industry realized that, to remain competitive, fundamental knowledge would be required, knowledge that had to come from university laboratories. But as knowledge accumulated on RIM, the technology itself was superseded by other, related processes and by reinforced composites. The research-development story is still being played out in RIM. The cellular telephone, too, was based on existing technology. Roadblocks were not due to lack of fundamental knowledge, but to regulatory barriers and to thorny engineering problems. Optical fiber rested in part on previous theory--wave propagation in dielectric materials--but the knowledge on which the material itself was based was largely empirical. The procedure was to “try something promising; see if it works; if it does, find out why.” Yet it is important to note that supporting technologies such as the semiconductor laser, which made optical communications commercially feasible, were the direct result of fundamental advances in physics. In the case of CAD/EC, the early decades of development were fed by incremental engineering advances driven by industry and defense needs. Advancement was not retarded by lack of fundamental knowledge. The basic mathematical underpinnings existed, but had to be applied to the problems at hand. Finally, the Internet was problem-driven and technology-based. Again, there were no major roadblocks that required fundamental research to remove them.

Patterns of Innovation: The Role of Intellectual Property Protection

Without too much exaggeration, one can conclude from these six cases that the innovations evolved successfully in spite of, rather than because of, intellectual property protection. The Internet, probably the most widely-known innovation of the set and surely the one with the greatest social impact, was until a few years ago an entirely public innovation that is now yielding substantial private profits as well as public benefits. Clearly, the diffusion of this innovation was enhanced by the public character of its intrinsic technologies, especially TCP/IP. There was extensive patenting of key processes in RIM as well as of material formulations that fed its process, but neither seems to have hampered the rapid application of both classes of technology. Slight variations in the composition of material inputs were patentable, so that companies could develop their own formulations, claim slight differences in performance over those of their competitors, and maintain market share. No market dominance occurred from product patents, and process patents were difficult to protect in any event. In MRI, the story is still being played out, as Raymond Damadian continues to litigate, charging GE and other manufacturers with patent infringement, and recently winning in the courts. The original patents, held by the British Technology Group, generated revenue from royalties but did not inhibit other firms like GE and Siemens from investing heavily in both research and technology development. There was extensive cross-licensing, a common practice in the medical device industry. But in the end market share appeared to be more a function of know-how than of ownership of intellectual property.

On the surface, Corning's dogged, ultimately successful pursuit of infringement on its original patents on optical fiber would suggest that ownership was the key to their prominence, but a closer look reveals that Corning's market advantage was a product of continuing advances in process innovation, based on internal R&D, rather than of the company's ownership of process knowledge that in any event was continually being rapidly superseded. Nor did patents play a significant role in the cell phone case. Bell Labs would have a monopoly over the market (or so it assumed at the time), and Motorola, like Corning, based its profits on rapid rates of innovation, in which inventions could be protected in the short run by means other than patents. Finally, intellectual property protection played a minor role in CAD/EC until the late 1980s, well after the initial entrepreneurial firms had establish their markets. During the evolution of CAD/EC packages, universities did not seek patent protection, and there was considerable cross licensing among firms such as IBM and Bell Labs. Trade secrets generally were more important to industry than patents or copyrights in protecting intellectual property. In any event, the packages themselves were initially so company- and application-specific that serious threats from theft were probably not envisioned.

The NSF Role

Since its beginnings in the 1950s, the National Science Foundation has been second only to the National Institutes of Health in federal agency support of basic research in colleges and universities. In the case of support for basic engineering science at colleges and universities, the Foundation and the Defense Department together dominate all other federal sources. In our case studies of six engineering innovations, it is therefore not surprising to find that NSF emerges consistently as a major, often *the* major, source of support for education and training of the Ph.D. scientists and engineers who went on to make major contributions to each innovation.

Among the six activities that NSF funds, it is this support of education and training that emerges most consistently across all our cases as a significant influence on the evolution of engineering innovation. In some cases (e.g., MRI, optical fiber) key contributors were supported in graduate school on assistantships paid by NSF grants or graduate fellowships; in other cases (e.g., cellular phone, CAD/EC) NSF-supported research grants trained engineers and scientists who were parts of industry teams tackling the technical problems that blocked an innovation's advance; in still others (e.g., CAD/EC) NSF-trained engineers became the entrepreneurs who created new firms and markets.

Support of university research infrastructure emerges as the likely candidate for second place among NSF's most influential activities. In half the cases--the Internet, CAD/EC, and MRI--NSF provided major support for the infrastructure that enabled innovation to occur. In the Internet case, DARPA and NSF together provided the university-based computing infrastructure that was at once the birthplace of the Internet, its development site, the training ground for future entrepreneurs who would exploit its profit potential, and the source of key supporting technology such as the fuzzball router. DARPA provided the powerful centers of computing at a few selected universities, while NSF extended this capacity to other major research universities in the nation and linked them together with CSNET. In the MRI case, NSF's $90 million investment since 1955 in NMR instrumentation and research provided an unknown but certainly substantial fraction of the machines on which a generation of analytical chemists and scientists and engineers in related fields were trained. The results of research on these instruments and the students trained on them provided much of the knowledge and human capital from which leading MRI companies such as General Electric drew.

Direct support of research by NSF was a key to successful innovation in just one case: CAD/EC. Far-sighted, industry-linked university researchers produced the results on which the first commercially successful design tools were based, as well as the students who graduated and formed the companies that developed and marketed them. There was no single instance of "breakthrough" research on CAD/EC, nor a single inventor to be identified with the innovation. It evolved through a series of incremental steps, each seeking an engineering solution to a difficult problem. Alone among other sources of support for research on synthesis, NSF was willing to entertain and, eventually, encourage proposals to address problems in VLSI design that neither private firms nor federal mission agencies were interested in tackling--these problems were, presumably, considered to have greater future then near-term importance and obviously did not address more pressing, short term issues.

There is no doubt that NSF-supported research produced knowledge and technologies essential to the successful evolution of the other innovations we studied. The polymer chemistry of RIM, the optoelectronic components required for optical communication, the mathematics underlying algorithms used in MRI and CAD/EC, and the advances in circuit design and information theory necessary to realize hand-off in the cellular phone and packet switching in the Internet are only a few among a long list of the types of fundamental knowledge upon which all six engineering innovations drew. Our cases, however, focused necessarily on the intrinsic technologies, not on the supporting science and technology and their sources in underlying knowledge, thus leaving the specifics of fundamental research's contributions for subsequent investigators to document.

There is one case in which NSF's organizational leadership took a commanding, highly visible, and possibly unique role: the Internet. In the mid-1980s, NSF program managers, working within the highly supportive environment provided—at least at the level of NSF top management—took risks, developed highly creative solutions to difficult problems, and provided essential coordination among other federal agencies, academic researchers, and industry. A different set of decisions by NSF "would have led to a far different networking universe than the one we have today." NSF was a leader among equals in various coordinating committees, such as the Federal Networking Council, in which NSF is said to have played the dominant role. But as many observers of NSF's role in the Internet have commented, this situation is unlikely to be repeated.

The cases studied in the second year reveal subtle but important organizational roles that NSF now plays in engineering innovation. We conclude, provisionally, that NSF managerial strategies have a subtle but substantial effect on the way engineering innovations evolve. Beginning in 1970, top management in the Engineering Division were discussing ways to stimulate research on new problems. Methods included conferences, symposia, and talks with faculty members, explicitly intended to develop interest in particular topics such as earthquake engineering. Program directors were urged to visit universities and industry laboratories. One of the criteria for selecting new research topics for special emphasis was "potential for impact;" another was "contribution to U.S. leadership in technology." Shortly thereafter, NSF-supported workshops (proposed by university-based researchers) began to involve industry in a major way, so that the research agendas that emerged from these workshops were not the products of academics talking among themselves, but of discussion that included direct industry input. By 1978 the Engineering Division noted that it promoted industry-university interaction via workshops that numbered between 28 and 41 annually between 1974 and 1977. Also in the 1970s, NSF began experimenting with new ways to facilitate cooperation between industry and universities such as the Industry-University Cooperative Research Centers and Industry-University Cooperative Research Awards. The decade of the 80s saw considerable expansion of the centers mode of support.

The CAD/EC case provides the clearest example of the effects of this more proactive stance. Even so, it is a subtle example. Based on our interviews with NSF grantees and NSF program directors, and our readings of internal NSF program reviews, we conclude that NSF managers worked carefully but forcefully within the investigator-initiated proposal, peer review process to develop promising lines of research of potential relevance to industry, promote additional industry-university communication, and then expand the community of academic researchers working on these research problems. The primary mechanism appeared to be the periodic workshop, in which a lead university, at the forefront of research in a field, proposes a workshop to NSF. Prior to the decision to support or reject it, the proposal is reviewed by peers that include industry representatives. The resulting workshop further sharpens and extends the research issues, while bringing in additional potential researchers from academia. The workshop sparks interest (no doubt further encouraged by NSF earmarking of money for work in this field), and university research expands. Because of both direct and indirect ties to industry, the expanded university research also remains linked to industry problems, resulting in a large set of researchers working in an area such as VLSI design. From small beginnings at Carnegie Mellon and a few other institutions in the early 1970s evolved a program of research funded by NSF at an average total of several million dollars annually at dozens of universities. Our hypothesis is that the environment provided by NSF management in the early 1970s led to the creation of targeted programs and some risk-taking on the part of program directors, and to creative use of the workshop mechanism. The process was apparently instrumental to the successes realized by CAD/EC.

The optical fiber case offers evidence of a different kind in support of this hypothesis. Although NSF had an organized program in optical communication systems, it did not support research relevant to optical fiber development during the 1970s through that or any other formal program. Universities were not very active in this area, so there was little for NSF to build on. Relevant knowledge and expertise existed primarily in the glass industry. By 1972, Corning and Bell Labs were the only companies mounting major efforts to make optical fibers workable in telecommunication systems. At the same time, it was clear to researchers in all sectors that the major research roadblocks to optical communication were in optoelectronics, the components that generated optical signals to feed into the fiber, amplifiers, and receivers. NSF conducted several workshops during this period that included academics and industry researchers, so there was good communication among interested parties and some consensus on which problems were appropriate for academic researchers to tackle. NSF money, responding to proposals from academic PIs, went there. Thus NSF *should* have been in optoelectronics rather than in optical fiber itself.

At the risk of simplifying a complex picture and presenting a misleading sense of precision, the following tables present the above results in concise form. Note that the categories of influence--essentially high, medium, and low--are relative, broad and, intentionally, ill-defined. The tables are efforts to summarize qualitative analysis in tabular form, not to add an additional element to the analysis.

DETAILED NSF ROLE: READING ACROSS THE CASES BY NSF ACTIVITY

NSF Support Mode	RIM	MRI	Internet	CAD/EC	Fiber Optics	Cellphone
education	**	***	**	**	***	**
direct research support	**	*	*	***	*	*
direct contribution to the knowledge base	**	**	*	*	**	*
direct contribution to the research infrastructure	*	**	**	***	*	*
direct contribution to supporting technology	*	**	**	*	**	*
organizational leadership	**	*	***	**	**	*
facilitation of interaction and communication[3]	?	?	?	***	**	*

SUMMARY ASSESSMENT OF NSF SUPPORT VIA ABOVE MODES: READING ACROSS THE CASES

Internet	High
RIM	Moderate
MRI	Moderate/Low
CAD/EC	High
Fiber Optics	Moderate/Low
Cellphone	Low

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As stated in the GPRA strategic plan, the Foundation's mission is "To promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense; and for other purposes." The six cases illustrate in detail how a variety of different management and investment strategies actually operate to serve this mission. The cases necessarily cover only a small part of a much larger picture, but the richness of detail and greater understanding they offer provide valuable information on which to base both action and further research.

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[3] Insufficient data on interaction and research communication were available in the first three cases for an assessment to be made.