CHAPTER VI: CONCLUSIONS

In this chapter we offer tentative conclusions based not only on the three cases that appear in the present report, but also on the three cases studied in the previous year: magnetic resonance imaging (MRI), reaction injection molding (RIM), and the Internet. 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 activities of the National Science Foundation influenced those processes. To address the first objective, we seek 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, we look 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 support of research
- contribution to the knowledge base
- contribution to the research infrastructure
- contribution to supporting technology
- organizational leadership.

We conclude the chapter by relating these results to the National Science Foundation’s mission as elaborated in its most recent strategic plan.

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

In nearly all six cases support for research and technology development by government, especially agencies 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, 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 (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 to at least 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

We 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 we found fundamental research 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. The comment by one of the inventors of optical fiber speaks to this overarching, powerful influence:

> "Corning looks at its core technologies this way: We think of ourselves as good in certain areas; scientists have to be good at something. We identify those core competencies that Corning must have. We identify a project that we think will succeed commercially, and

> hope to have the array of competencies we need for potential commercialization . . . . NSF provides the nation with the core competencies to do the projects that will come along in ten years" (Keck interview).

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, it 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, nor a single inventor to be identified with the innovation. It was 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 industry nor federal mission agencies was 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, 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. Mandelbaum and Mandelbaum (1993: 62) observed that 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 were able to document this only partially for two reasons. First, and most importantly, managerial strategies in engineering and, presumably, other units within the Foundation began to exhibit much greater variety and proactive stances beginning in the 1970s, but not achieving their current range until well into the 1980s. This situation is described in the overview chapter of this report. The major consequence is, at least for present purposes, that only in the latter stages of evolution of *all six* innovations is the impact of any changes in NSF managerial strategies likely to be observed. The criteria for choosing innovations to be studied required that the innovation already manifest significant social, economic, or other impact. Given this, an innovation would have to have entered commercial markets (or their equivalent, in the case of the Internet) by the late 1980s. With research and development times for major innovations typically measured in decades, tracing current innovations to the points at which NSF activities such as research, education, and infrastructure support might have had an influence pushes the impact periods into the 1960s, well before NSF engineering management strategies began to evolve and diversify substantially, and prior to substantial documentation of NSF strategies and related activities. So the deck was stacked, at least in terms of efforts to identify the impact of NSF managerial strategies on the first six cases selected.

The second reason for our inability to examine fully the impact of NSF managerial strategies is that doing so became an explicit objective of only the three cases described in this report. A comparison of these with the previous three cases will quickly reveal that almost no attention was paid in the first set of innovations to what was going on, organizationally and managerially, within NSF that might have influenced their evolution. The first three cases were intended to be experimental, and one of the lessons learned was that a focus on NSF impacts and influence generally could address not questions concerning NSF managerial strategies. The second set of cases is suggestive of what might be learned by examining innovations whose promise of significant social and economic impact is just emerging, when NSF activities of the 1970s and 1980s would be far more likely to have had any influence.

From this year's cases 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.

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. The relevant section of the chapter is titled, “What NSF Did Not Do.” We saw there that, 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. As Corning’s Donald Keck observes, “NSF *should* have been in opto-electronics, [not optical fiber itself]” (Keck interview, 1997).

Innovation Cases and the NSF Strategic Plan[1]

According to NSF's GPRA-compliant strategic plan, NSF expects these outcomes from its investments:

- Discoveries at and across the frontier of science and engineering;
- Connections between discoveries and their use in service to society;
- A diverse, globally-oriented workforce of scientists and engineers;
- Improved achievement in mathematics and science skills needed by all Americans;
- Meaningful information on the national and international science and engineering enterprise.

The first three of these outcomes pertain to the six modes of funding support we considered in examining NSF's role in engineering innovation. The strategic plan lists a number of "investment strategies" under each of the outcomes desired. The six case studies we have conducted illustrate how many of these investment strategies actually work in practice; they cannot be used to test the strategies' overall effectiveness or to assess the relative payoffs from different ones.[2]

Nearly all of the investment strategies listed under the "discoveries" outcome were clearly at work in the three cases for which we have information about such strategies. Promising ideas as identified through merit review of competitive proposals were supported (all cases); program officers took "informed risks" in areas where consensus on appropriate directions is just beginning to form (particularly CAD/EC and optical fiber); cooperative research efforts were encouraged (all cases); instrumentation and facilities were supported (especially CAD/EC, MRI, the Internet); investigators were encouraged to link research and education (all cases).

The plan states further, relative to the second desired outcome, that "Linking advances in science and engineering with their potential uses generates a productive exchange of knowledge, information, and technologies. These linkages accelerate innovation, often yielding new insights into the underlying research." Again, several cases illustrate how this works in practice, but the CAD/EC case does so most forcefully and clearly. The merit review process involving industry reviewers facilitates this (CAD/EC, optical fiber); targets of opportunity with impact on society were identified for support (all cases); collaborative research between industry and universities was encouraged[3] (RIM, CAD/EC); linkages with other agencies was encouraged (CAD/EC; optical fiber, the Internet); students were exposed to cutting edge research with the potential for application (all cases).

Finally, the third outcome is elaborated as follows: "The competence and capabilities of the nation's science and engineering workforce keep America at the forefront of innovation and technological progress." We concluded earlier in this chapter that NSF's investment in trained

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[1] The NSF GPRA-compliant strategic plan, based on *NSF in a Changing World*, can be found on NSF GPRA Home Page.

[2] This would require an entirely different research design from the one used in the case studies.

[3] As we have seen, full implementation of the range of organizational strategies for encouraging cooperative research did not occur until the 1980s, when the Industry/University Cooperative Research Centers program was fully operational and the Engineering Research Centers program had begun. In all six cases, examples of formal industry-university cooperative research arrangements appeared either as an integral part of the innovation history or as an aspect of current or subsequent supporting research.

professionals resulted in a consistent and powerful influence across all six cases. The cases further illustrate several of the investment strategies listed in the plan: support training through fellowships, traineeships, and research assistantships; involve students with pioneering research; develop partnerships for broad-based, multi-disciplinary training.

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 we believe the richness of detail and greater understanding they offer provide valuable information on which to base both action and further research.