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NATIONAL SCIENCE BOARD

THE ROLE OF THE NATIONAL SCIENCE FOUNDATION IN ECONOMIC COMPETITIVENESS

Statement and Committee Report

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STATEMENT OF THE NATIONAL SCIENCE BOARD ON THE NATIONAL SCIENCE FOUNDATION AND ECONOMIC COMPETITIVENESS

(Adopted by the Board October 14,1988)

Competitiveness

Given a diverse and unfettered economy such as the US has and should preserve, the keys to economic performance and competitiveness are:

- **Investment** — in economic capacity generally; in people, through education; and in innovation, through R&D;
- **Management** of production and implementation of technology; and
- **Innovation** — technical change in all forms.

To each of these the National Science Foundation can and should actively contribute. Many of its programs represent investment in the nation's economic and innovative capacity. Both its direct education programs and its research programs invest in education, and its research programs contribute directly to investment in R&D, particularly at the high-risk, high-payoff frontiers of science and engineering. And some NSF education and research programs, particularly in engineering, can help improve US capacity to manage production and implement technology.

Science and technology base

The vast and growing body of scientific and technical knowledge, people trained to build and use it, and the infrastructure that enables them to get their training and perform their functions constitute our "science and technology base". They give us a capacity we can bring to bear quickly on any technology problem posed by market and other social needs, or on any technology opportunity presented by a breakthrough invention or discovery. They put us in "readiness" to innovate.

Our science and technology base has been and currently remains a source of special US strength and leadership in economic performance and international competition. But that advantage could all too easily slip away — may be slipping away already — to aggressive competitors with growing scientific and technical sophistication. We cannot afford to stand pat.

To keep pace with our expanding economy, the growing importance of science and technology to the economy, and the intensifying competition we face from abroad, the nation, and in particular the Federal Government, should be increasing investment in our science and technology base.

The NSF should give its first priority to maintaining and steadily expanding the nation's science and technology base so as (among other purposes) to keep pace with the needs of our economy and to sustain our "readiness" to innovate.

In maintaining and expanding the science and technology base the NSF also contributes to other public needs — to health, to wise environmental protection and management, to understanding and solving social problems, to teaching and learning, and to human curiosity, aesthetic appreciation, and culture. We reconfirm and reassert those aims of the NSF as well.

NSF's success in helping to build and maintain our science and technology base has derived in good part from the methods it employs.

The NSF should adhere with confidence and perseverance to those mechanisms — the proposal system, peer review, and external advice — that preserve decentralization, diversity, and "evolutionary" progress in the work that NSF supports.

Education

If compelled to single out one determinant of US competitiveness in the era of the global, technology-based economy, we would have to choose education, for in the end people are the ultimate asset in global competition.

In particular, education builds our science and technology base.

- It prepares scientists and engineers to perform the research from which new knowledge emerges and to educate subsequent generations.
- It prepares practicing technologists to participate in design, development, and production of technical innovations.
- It prepares the general workforce.

Education in mathematics, science, and engineering, which NSF is charged to support "at all levels", is especially relevant in all three respects.

The NSF should visibly and forcefully join in national efforts to introduce broad systemic reforms in elementary and secondary education — particularly, but not solely, as regards math and science.

The NSF's own programs at the elementary and secondary levels should give high priority to training teachers of science and math, to developing improved science and math curricula and materials, to expanded use of new technologies in the classroom, and to research and experimentation on learning of math and science.

The NSF should continue to pursue the initiative to improve undergraduate science and engineering education called for by the National Science Board in 1986, with emphasis on laboratory development and instru-

mentation, undergraduate research participation, faculty professional development, and improvement of courses and curricula.

The NSF should continually review and revise support for graduate students through improved fellowships and emphasis on improved graduate student participation in research projects.

From the perspective of economic competitiveness (as well as other perspectives) NSF programs and management efforts designed to help bring women, minorities, and the economically, socially, and educationally disadvantaged into the mainstream of science and engineering deserve continued focus.

Engineering and other technology-oriented fields

Engineering and other technology-oriented fields relate especially directly to economic performance and competitiveness. In particular, it is practicing engineers who directly manage and implement the "chain of innovation" — drawing upon the scientific and technical knowledge built up from research and translating it into new products, processes, and services. The role of the National Science Foundation in engineering has been evolving rapidly in recent years and continues to evolve.

Engineering is different from science. Synthesis is the aim of engineering, and the defining activity in engineering is design. Engineering employs science — both science from other fields and "engineering science" generated internally — as means to the end of producing something new. But engineering cannot abstract as science does from the complexities and uncertainties of the real world; it must reckon with them directly. Moreover, engineering integrates analysis with synthesis while dealing with constraints of budget and deadlines; concerns such as health, safety, and environmental impact; and the political and social setting generally.

In general, those whom NSF supports should not be doing engineering development, but, as in science, building the base of knowledge and trained people to be drawn on by those who later develop products and processes via the normal "chain of innovation". They should be doing so with special emphasis on the distinctive synthetic and integrative aspects of engineering. Among other things, this emphasis should encompass the scientific basis for the process of design; revolutionary new designs of all types; systems operation and optimization; and the processes of production, manufacturing, assembly, and construction. NSF should also continue to support analytic "engineering science" to provide the tools of engineering, as it always has.

Similarly, NSF programs in the computer sciences, chemistry, materials science, the biosciences, and other fields with potential for contributing to new technology should recognize and support synthesis-oriented work that builds the science and technology base which will later find widespread use by practicing technologists in developing industrial and commercial technology.

The Board confirms as appropriate the NSF's recent expansion of attention to engineering and to fundamental work on design, manufacturing, process, systems, and related "synthesis" activities, both in engineering and in other technology-related fields.

In these fields no dichotomy need be or should be drawn between "basic" and "applied" research. One of four primary criteria the Board has long since adopted for selection of research projects addresses the "utility or relevance of the research" and is "used to assess the likelihood that the research can . . . serve as the basis for new or improved technology or assist in the solution of societal problems". Furthermore,

Where appropriate, NSF long-range plans and budget presentations should directly address the potential areas of application for each field.

On the other hand, NSF should not be funding what industry can and will do for itself. Where the value of research depends on production and marketing realities, moreover, industry is better positioned to judge that value and is subject to salutary market discipline. In many cases the best solution may be joint funding by both NSF and industry. Certainly in these areas NSF should be employing the best scientists and engineers in industry as peer reviewers and advisory panelists.

NSF efforts to improve engineering education — an urgent task — should focus on reintroducing and reemphasizing synthesis as the engineer's characteristic task; on integration of analysis and synthesis with constraints of time and money and wider social and environmental concerns; on updating obsolescent laboratory equipment and facilities; and on encouraging more American engineering students to go on to graduate school.

Infrastructure and international

The speed and efficiency with which scientists, engineers, and technologists obtain from each other and from the store of scientific and technical knowledge information that helps them perform their functions is assuming unprecedented importance in global economic competition. The NSF, as befits its statutory charge to "foster the interchange of scientific and engineering information", has in the past helped to build resources and channels for transfer and diffusion of knowledge. But NSF no longer has any separately budgeted program or organizational champion for such activities, which are dispersed to the individual directorates.

The Board asks the Director to assess whether the programs of the Foundation are well organized to address continually the needs of the country in knowledge transfer, and to make recommendations based on his assessment.

Contacts, collaborations, and movements among people are the best means for diffusing scientific and technical knowledge and knowhow.

NSF should recognize and respond to activities in the research community that foster connections in research

and innovation across sectoral, institutional, R&D-spectrum, and disciplinary lines.

The US scientific and technical communities should be assigning high priority to building our ability to compete in other countries and to draw on science and technology developed there. This will require language training, translation of foreign literature, and increased international experience and exposure for US scientists and engineers, as well as improved intelligence on science and technology developments in other countries.

Programs that inspire and encourage US scientists and engineers to become more actively involved with scientists and engineers in other countries, and that otherwise build US capacity to absorb science and technology from and compete in other countries, are appropriate for continued NSF focus.

PREFACE

Economic "competitiveness" is on the front burner. The emergence of a worldwide economy in which US firms and workers must compete and signs that the US is losing its edge in that worldwide competition have compelled the attention of the country, the Congress, and the Executive Branch. The National Science Board established a Committee on the Role of the National Science Foundation in Economic Competitiveness to consider the role and responsibilities of the National Science Foundation in improving the country's economic performance and competitiveness.

Many of our recommendations and much of our report endorse current NSF programs and methods. We make no apology for this. Recent evaluations confirm, and most scientists and engineers know from concrete experience, how much the National Science Foundation has contributed, with relatively small resources, to the strength and excellence of American science and technology. That strength and excellence represent the one aspect of competitiveness in which the United States retains the clearest lead. The current programs and methods of the NSF helped to build that lead and deserve to be reaffirmed and protected. For the sake of economic competitiveness they also deserve to be extended, especially in engineering and other technology-oriented fields; in math, science, and engineering education; and in building US capability to draw upon and benefit from the growing strength of science and technology in other countries.

The Committee wishes to acknowledge help and advice it has received. Within the National Science Foundation, Dr. Irwin Pikus, now of the Department of Commerce, was our original Executive Secretary; Robert Andersen ably filled that role thereafter and provided considerable substantive input; Dr. Harvey Averch provided a thorough bibliography and summary of the relevant economic literature as well as scholarly advice and review at numerous stages; Dr. Alan Shinn provided both substantive input and editorial assistance; many members of the staff, particularly in the Engineering Directorate and the Division of Science Resources Studies, provided specific information and data; and several staff members offered valuable comments on earlier drafts of our report.

Externally Dr. Martin Neil Baily earlier provided us a thoroughgoing economic analysis on *Science and Technology and the Competitiveness Problem* on which we have drawn heavily. We were also strongly influenced by the writings of Dr. Stephen Kline, Dr. Richard Nelson, and Dr. Nathan Rosenberg. We received thoughtful comments on an earlier draft report from Drs. Baily, Kline, Nelson, and Rosenberg, and from Dr. Lewis Branscomb, Dr. Dale Compton, Dr. Irwin Feller, Dr. Frank Levy, Dr. Alan Magazine, Dr. Edwin Mansfield, Dr. Gary Saxonhouse, Dr. Bruce Scott, and Dr. John Zysman (on behalf of himself and colleagues at the Berkeley Roundtable on the International Economy).

All these contributed greatly, even if we have in some respects departed from their thinking and recommendations. Copies of Dr. Baily's report, of the external comments on the earlier draft, and of that draft are available through the National Science Board office at NSF.

Warren J. Baker, Cochairman
William F. Miller, Cochairman

Annelise G. Anderson
Frederick P. Brooks, Jr.
John C. Hancock
Charles L. Hosler
Howard A. Schneiderman

Charles H. Herz, Staff Liaison
Robert M. Andersen, Executive Secretary

I. COMPETITIVENESS

Those who authorize and support Government programs — the President, his aides and advisors, the Congress, and ultimately the American people — do so with the thought that those programs will be useful in meeting public needs. By no means are all such public needs narrowly economic. The bulk of Federally supported research, for example, draws its rationale from other missions, such as defense and health. The National Science Foundation too supports research, education, and related activities for other than narrowly economic reasons — for the contributions they make to health, to wise environmental protection and management, to understanding and solving social problems, to teaching and learning, and to human curiosity, aesthetic appreciation, and culture. Indeed, many NSF programs and NSF-supported projects contribute primarily to such ends as these and only secondarily, if at all, to economic competitiveness as such — which is fine. We want explicitly at the outset to recognize and reaffirm these other and important aims of what NSF does and should do.

Still, contributions to our economy and competitiveness probably rank first among those things for which the people and their representatives look to NSF. They are in any case the focus of this Committee's charge. We therefore concentrate on them and on those NSF-supported programs and projects that contribute most directly to US economic performance.

A. A real and long-term concern

There are three reasons why concern with American economic competitiveness ought to persist beyond any passing political fad as a continuing, long-term, steady focus of national policy:

1. *A global economy.* The world has changed. US firms, most of which once could focus almost exclusively on US competition and the US market, find themselves engaged with foreign competition in both US and world markets. US workers, who once could count on higher wages or salaries than similarly skilled workers elsewhere in the world because of privileged membership in the world's strongest economy, find themselves in far more direct competition with foreign workers. The US as a nation, which for the quarter century after World War II dominated the world economy, now is challenged for world economic leadership. We compete in what has become a global economy; how we manage in that competition will over the long haul determine the prosperity of our people and the influence of our nation.

2. *A measure of performance.* Success or failure in global competition is also one measure of the extent to which we are realizing our economic potential at home. Though growing rapidly, trade still represents only about 11 percent of US gross national product. So economic performance at home still affects Americans much more than trade competitiveness and resulting shifts in our terms of trade or balance of trade. Yet over the long term those shifts do reflect how well our economy has performed in comparison with the economies of other nations and hence, implicitly, in comparison with its own potential.

3. *A spotty record.* In fact, the US has for most of the past fifteen years been losing ground and leadership in global competition to key competitors, especially Japan, countries in the European Community, and newly industrializing countries of the Pacific Rim. The real value of our currency has eroded long-term against their currencies, and our economic productivity and standards of living have grown much more slowly.[1] In the past few years we are doing better. Yet particularly considering the extent to which we have financed recent growth with foreign debt, it is far too soon to relax.

B. Keys to competitiveness

Much has been said and written about US competitiveness — so much, often with such self-serving overtones, as to obscure basics on which most experts agree. Chief among these are investment, management, and innovation.

In the real estate business, according to a familiar aphorism, three things are crucial: "location, location, and location". For economic performance and competitiveness, it is fair to say, the counterparts are investment, investment, and investment:

1. *Investment in economic capacity generally.* For the US to be successful in global economic competition we will have to raise our national savings and investment markedly. We have compounded low private savings with huge Federal budget deficits that divert savings from investment to Government spending — most of which does little or nothing to build economic capacity. Japan has been outsaving and outinvesting us by a wide margin for many years, and so have several other nations. This must change if we are to retain world economic leadership and if our people are to regain a world-leading standard of living.[2]

2. *Investment in people,* through education.[3] The US must post big gains in educational achievement if our people are to realize their potential and compete effectively with

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[1]See M.N. Baily, *Science and Technology and the Competitiveness Problem,* Study prepared for the National Science Board, 5-11 (1987); M.N. Baily and A.K. Chakrabarti, *Innovation and the Productivity Crisis* (Brookings 1988).

[2]See G.N. Hatsopoulos, P.R. Krugman, and L.H. Summers, "U.S. Competitiveness: Beyond the Trade Deficit", 241 *Science* 299 (1988).

[3]Edward Denison estimates that between 1929 and 1982 fully thirty percent of US growth in measured business ouptut per person employed was attributable to increased educational attainment of the workforce, as measured only by years of schooling. *Trends in American Economic Growth, 1929-1982* (Brookings Institution, 1985) at 15. This leaves out growth in measured output attributable to gains in the content and quality of education and growth in unmeasured output attributable to improved education.

workers abroad — workers often less well paid than in the US, but highly motivated and increasingly well educated. The US is lagging badly in elementary and secondary education, and cannot take continued superiority in higher education for granted either. Economic competitiveness will require major investments in and continued public attention to our educational system.

3. *Investment in innovation,* through R&D. Not all innovation is attributable to R&D, but R&D has by now clearly emerged as indispensable to industrial innovation. Our principal competitors are outinvesting us in civilian R&D.[4] This too must change if we are to remain competitive.

These three forms of investment build up the productive assets — including trained people and technology — that our economy deploys. Another key to competitiveness has to do with the way in which we manage those assets:

4. *Management of production, implementation of technology.* The US has been markedly outperformed recently in efficient production and continuous product and process improvement. Our industries need to do much better at putting technical sophistication into process development, at manufacturing efficiently and with proper attention to quality, at designing for manufacturability, at shortening the cycle of product generations, and at speeding the introduction of incremental product and process improvements. Though strongly challenged, we still lead the world in conceiving and launching new technologies. Too often, however, we are losing industrial leadership in those same technologies to others who do a better job of implementing and extending them.[5]

All these things also bear on innovation. Since the pioneering work of Robert Solow, for which he recently received the Nobel prize in economics, experts on economic growth have come to agree that innovation — technical change in all forms — is the single most important source of such growth.[6] Nor is the evidence for that conclusion confined to technical studies. It is all around us — in new and improved products from almost every field of manufacturing; in improved industrial processes and automation; in improved seeds and strains and improved methods and machinery for agriculture; in faster and cheaper transportation; in the accelerated advance and widespread application of microelectronics, computers, and telecommunications; and so on.

All three forms of investment contribute to innovation. R&D does so most directly, perhaps, but new plant and equipment typically incorporates and stimulates new technology, and it takes highly educated people to initiate and implement innovation. Management of production and implementation of technology also set the pace of innovation and over the longer term determine who captures its benefits.

C. The NSF and competitiveness

On each of these keys to economic competitiveness and performance the National Science Foundation has a contribution to make:

1. The NSF programs on which this report focuses are a kind of investment — a particularly important kind — in the nation's economic and innovative capacity. They ought to be understood as investments and to operate as such. They are not a form of consumption, nor do they exist for the satisfaction of the scientists and engineers whose work they fund.

2. Some NSF programs invest directly in education, in fields — math, science, and engineering — that bear strongly on economic competitiveness. NSF research programs too include a major — arguably even a primary — component of investment in education, for they fund the advanced training of students and post-doctoral researchers and they contribute to the freshness and currency of professors who perform research, but also teach.

3. NSF research programs contribute directly to investment in innovation through R&D — particularly at the high-risk, high-payoff frontiers of science and engineering.

4. Some NSF education and research programs, as will appear, can and do contribute to our capacity to manage production and to implement technology.

Thus the NSF is in the thick of things where competitiveness and innovation are concerned. NSF is small, but its role is central. Its resources are limited, but highly leveraged. It can make a difference.

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[4]"If only nondefense R&D is considered, West Germany and Japan have been ahead of the U.S. in R&D spending for 15 years, and their rate of civilian R&D investment as a percentage of GNP has been rising faster than that of the U.S. for the past 5 years." *Science and Engineering Indicators—1987* at 77.

[5]See, e.g., R.E. Gomory and R.W. Schmitt, "Science and Product", 240 *Science* 1131 (1988); S.S. Cohen and J. Zysman, *Manufacturing Matters* (Basic Books 1987).

[6]Measurement difficulties plague attempts to pin the conclusion down quantitatively, but those who have made the attempts, notably Denison, confirm the basic conclusion. *Trends in American Economic Growth, 1929-1982* at 28-31.

II. THE SCIENCE AND TECHNOLOGY BASE

A. How innovation happens

Many people have the idea that science and engineering mainly contribute to economic performance by generating new discoveries and inventions that become new products and processes. Sometimes they do. But more typically the innovative process starts with market findings or with cost and quality goals. In the product cycles of established industries the "chain of innovation" thus initiated normally starts with a concept design, which leads in turn to detailed design and test, then to production, and finally to marketing — with the progression reversed routinely by feedback among the stages. Established process and assembly technologies typically evolve by a very similar path.

Professor Stephen Kline, who has described this path in careful detail,[1] emphasizes that it is not new research, but the accumulated body of scientific and technical knowledge built up by research over many years, which serves as "the first line of reference" in ordinary industrial innovation:

> "Any modern technical person beginning a task in innovation will not turn first to research. On the contrary, one turns first to the current state of the art, then to personal knowledge about the governing principles of the field. After that, one goes to the literature, consults colleagues, calls in leading experts. Only when all that does not suffice does one start research. Even then, many innovation projects we now attempt routinely would be not only infeasible but . . . literally unthinkable without the vast accumulated storehouse of knowledge attained by several centuries of work by many, many workers in the appropriate fields of research. For example, the design of an aircraft jet engine would be infeasible and unthinkable without a solid grounding not only in Newton's laws of mechanics and the elaboration of them in fluid mechanics, elasticity, dynamics of machinery, but also numerous other special fields of knowledge that modern technical teams take for granted (e.g., chemistry, thermodynamics, control theory . . .)."[2]

Of course, research discoveries do directly initiate innovation, clearing away former technical obstacles to satisfying longstanding market potential or enabling whole new and unexpected technologies. Even such breakthroughs, however, lead to new products and processes through the same "chain of innovation" — again drawing from the accumulated store of scientific and technical knowledge built up over long years of prior research. Moreover, the researchers who achieve breakthrough discoveries themselves draw from the same store. Townes' original idea for the laser, for example, drew heavily on quantum theory, and specifically on an observation of Einstein's concerning "stimulated emission of radiation" that dated from 1917.[3] By now, of course, laser technology itself has become part of the accumulated store to be drawn on indefinitely by others.

High-temperature superconductivity, to take another example, has become the latest candidate for a major enabling research discovery. The technologists who would produce practical commercial products from the new superconducting materials, as well as the researchers who would extend our understanding of the phenomenon, are now drawing upon extensive bodies of knowledge built up by previous research in low-temperature superconductivity, ceramics, chemistry, and atomic physics, among other fields.

B. The base

This description of the innovative process draws attention to the pervasive role in innovation and hence in economic performance of three primary ingredients:

1. A vast and growing body of scientific and technical knowledge.
2. People with training and current expertise to add to that body of knowledge and to draw upon it for design, development, and production.
3. An infrastructure of institutions, equipment, information repositories, and information networks that enable those people to be educated and informed and to build and draw on that knowledge.

These ingredients constitute our "science and technology base". They give us a capacity we can bring to bear quickly on any technology problem posed by market needs (or by military and other social needs), or on any technology opportunity presented by a breakthrough invention or discovery. They put us in "readiness" to innovate. Without being sufficient for economic competitiveness, they are essential to it — especially for a country that depends for economic leadership, as we do, upon high-technology leadership.

We RECOMMEND:

> **To keep pace with our expanding economy, the growing importance of science and technology to the economy, and the intensifying competition we face from abroad, the nation, and in particular the Federal Government, should be increasing investment in our science and technology base.**

Our science and technology base has been and currently remains a source of US strength and leadership in economic

[1] Dr. Kline's model is fully developed in his monograph *Research, Invention, Innovation, and Production: Models and Reality* (February 1985).

[2] *Id.* at 13. It is because the innovative process thus pervasively draws on the "vast accumulated storehouse of knowledge" that identifying all the research which contributed to a particular innovation is an almost endless task. See *Technology in Retrospect And Critical Events in Science*, Illinois Institute of Technology Research Institute (1968); *Project Hindsight*, Office of the Director of Defense Research and Engineering (1969).

[3] As described by Townes in the November issue of *Science 84* at page 153.

performance and international competition. But that advantage could all too easily slip away — may be slipping away already — to aggressive competitors with growing scientific and technical sophistication. We cannot afford to stand pat. The President's proposal to double the budget of the National Science Foundation over five years, with emphasis on programs that bear on economic performance, is an element of the needed remedy. Steady, strong, and growing support for research, education, knowledge transfer, and related activities is essential — at the NSF certainly, but in other agencies and by other means (such as a permanent and fully effective R&D tax credit) as well.

Such support is essential even in times of budget stringency. Perhaps the deepest destructiveness of Federal deficits is that they draw down productive investment in our economy, of which investment in research and education is particularly critical. Curtailing Federal investment in those areas exacerbates, not solves, that problem. We ought instead to be increasing such investment, temporarily sacrificing current consumption to do so.

C. NSF's role

The National Science Foundation's core statutory responsibilities focus on the science and technology base and on the readiness to innovate they afford the nation.

It is NSF's responsibility for the base — not any false notion of "purity" or disinterest in the useful application of results — that properly underlies NSF's historic emphasis on "basic" research. In basic science and technology, with the major innovations that tend to flow from them, the United States remains the world leader. The National Science Foundation is far from solely responsible for this US strength, but it is the one institution charged with the overall health of the enterprise, and it has fulfilled that charge with widely recognized success.

A recent evaluation brought to our attention strikingly confirms this success.[4] Notwithstanding that the NSF finances only a small fraction of all US research, it has apparently been the prime source of support for research that resulted in major scientific or engineering prizes. Even excluding fields in which NSF is the main source of Federal funding, almost half the prize-winning work had major support from NSF, and more than half had at least some NSF support.

Nor has NSF's role and success been confined to research. Many, perhaps most, of our leading scientists, engineers, and technologists have been supported and encouraged at one point or another in their training and education by NSF research assistantships, NSF fellowships, NSF undergraduate or precollege science study programs, or other NSF programs.

In our healthily pluralistic system of support for science and engineering NSF also serves as what is sometimes called the "balance wheel" — ensuring that the base is maintained and grows in fields and subfields of science and engineering not provided for by other funders with narrower concerns and missions, and even where short-term applications are not immediately apparent.

These functions remain the core NSF contribution to the nation's economic performance and competitiveness, as well as to other national goals. NSF can and should take on wider responsibilities, but those should build on this central charge, not detract from it.

Hence we RECOMMEND:

The NSF should give its first priority to maintaining and steadily expanding the nation's science and technology base so as (among other purposes) to keep pace with the needs of our economy and to sustain our "readiness" to innovate.

This general responsibility encompasses virtually the whole range of science and engineering, from mathematics to physics, biology, and computer science. As reconfirmed at the outset of this report, NSF's care for the science and technology base serves other public needs as well as, and in many fields more than, economic performance and competitiveness. On the other hand, its work in engineering and some fields of science addresses economic performance and competitiveness especially directly. We have therefore devoted a subsequent chapter of our report to engineering and to such other fields.

D. NSF's methods — proposals, peer review, external advice

NSF's success in helping to build and maintain our science and technology base has derived in good part from the methods it employs. Those methods reflect conditions for successful innovation and economic advance so subtly pervasive in our system that they can be overlooked or taken for granted. Among these are diversity, decentralization, competing ideas and experiments, and general freedom from political constraint.[5] In supporting research the NSF and certain other Federal agencies have preserved these same conditions, by the use of three related mechanisms: the proposal system, peer review, and external advice.

Research under the proposal system does not respond to detailed plans or directions established by the funding agency. Rather the agency announces fields of science and engineering within which proposals will be welcomed from widely dispersed and diverse performers, bringing to bear a range of ideas and expertise far greater than could be concentrated in a Government agency or in any other one place.

Next, from among proposals peer review selects out those judged best. It decentralizes project-level decisions on research directions and resources by placing them mostly in the hands of multiple reviewers. Since reviewers change continually, peer review provides many opportunities for an idea to be offered and

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[4] *Sources of Financial Support for Research Prize Winners*, NSF Report 87-87. This study was performed by NSF's internal evaluaton staff. The rather straightforward design of the survey on which it is based allowed little room for bias in the results.

[5] See N. Rosenberg & L.E. Birdzell, *How the West Grew Rich* (Basic Books, 1986), especially Chapter 8, "The Link between Science and Wealth"; R.R. Nelson, *Understanding Technical Change as an Evolutionary Process* (North Holland, 1987); C.H. Herz, *Research: Framework for a Federal Role* (work in preparation based on studies for and discussions in this Committee).

tested. And within the bureaucracy, the accepted authority of peer reviews gives each program officer some insulation from centralized or political control of project decisions.

Thus it is not only the wisdom of reviewers that ensures the value of the supported research. Reviewers are usually wise enough to approve most of the best research proposals and weed out most of the worst — a nontrivial contribution. But they probably cannot judge finely between proposals in the middle of the distribution. That hardly matters. The system supports merit in subtler, yet more fundamental, ways. It provides both a mechanism and a shield for dispersed decisionmaking. At the same time it both protects and reinforces a system of professional reward and advancement based on the decentralized judgments of scientists or engineers.[6]

Similar functions are served by actively including diverse and constantly changing representatives from the scientific and engineering communities in NSF decisions on program directions and resources at more aggregated levels. Partly this is accomplished through formal advisory committees or formal consultation with organizations such as the National Academies of Science and Engineering. Partly it is accomplished through informal contacts and consultations of all sorts. At NSF the National Science Board itself both participates in this process and serves as its ultimate exemplar.

NSF's striking success in its primary functions over many years owes much to its reliance on these devices.

We therefore RECOMMEND:

The NSF should adhere with confidence and perseverance to those mechanisms — the proposal system, peer review, and external advice — that preserve decentralization, diversity, and "evolutionary" progress in the work that NSF supports.

[6]The "old boy network" charges frequently leveled against peer review point up a real danger (though not, according to several careful studies, a statistically demonstrable current actuality). But they miss the point that the proposal system and peer review are in truth the best protection against development of cozy relationships and restriction of support to a narrow group of insiders.

A. Education and competitiveness

If compelled to single out one determinant of US competitiveness in the era of the global, technology-based economy, we would have to choose education.

Today most factors of production — fuels, materials, components, financial capital, and even technology — are internationally mobile in unprecedented degree. But people still mostly stay at home. In the end they are the ultimate asset in global competition. They as individuals compete with workers elsewhere to whom the other factors of production can move, and their success depends on knowledge, skills, and work habits they initially learned in school. The contribution of education to their *individual* economic competitiveness thus deserves to be our first point of emphasis.

Beyond doubt, however, the education of our people is also crucial to the competitive success of factories, offices, and other economic units in the United States, and hence to the competitive success of the US as a nation. In particular, people with scientific and technical training are the heart of our science and technology base, which education builds in four ways:

First, it prepares scientists and engineers to perform the research from which new knowledge emerges and to educate subsequent generations.

Second, it prepares practicing technologists to participate in design, development, and production of technical innovations. The technologist draws first on his or her own skills and knowledge, initially gained through education, and then draws on other knowledge resources with which education has built familiarity.

Third, it prepares the general workforce. The speed and efficiency with which innovations can be introduced and extended depends on the general skills, understanding, and resulting flexibility of everyone involved in implementing them. That in turn depends in good part on the level and quality of education those persons have obtained.

Fourth, it prepares citizens to reasonably assess the benefits and risks of new or controversial technologies, such as nuclear power and recombinant DNA, which may contribute to economic productivity and competitiveness, but also entail risks.

Education in mathematics, science, and engineering is, of course, especially relevant in all four respects. NSF has a responsibility for education in these fields "at all levels", which it discharges both through direct science and engineering education programs and through research participation.

B. Graduate education

At the graduate level of science and engineering education the NSF has a lead role. Through fellowships and research assistantships, the Foundation has long supported graduate education and research training for a large share of leading US scientists and engineers.

Not coincidentally, though many other Federal agencies and institutions also contribute, the US possesses the world's most successful system of graduate research and training in scientific and technical fields. That system has much to do with our paramount position in science and frontier technology, which in turn has had much to do with our post-war leadership in high-technology trade. Graduate students are taught and introduced to research by the best researchers we have, and their graduate education is coupled with research training in our world-leading research universities. Indeed, the contribution that NSF research programs make to graduate education and research training is at least as important to economic performance as the results of the research.

US graduate education and research draw students from around the world. The large and growing percentage of foreign graduate students in key fields, particularly in engineering and computer science, has raised concerns about training competition and transferring our technology abroad. But what should really concern us is not the large number of foreign graduate students in US universities, but the low and declining numbers of native-born graduate students. US companies and universities are becoming increasingly dependent on "imports" of technical talent from other countries.

From 1970 to 1986 the share of all US doctorates in science and engineering granted to foreigners on nonimmigrant visas rose from 11.5% to 23.0%. Over the same period the share of those doctorates going to US citizens dropped from 81.6% to 71.5%. In engineering the drop for US citizens over the same period was from 73.6% to 44.6%, in physical sciences from 83.7% to 69.3%, and in mathematics from 84.1% to 54.4%. For computer sciences the data only go back to 1977, but from that year to 1986 the share of US doctorates going to US citizens dropped from 85.7% to 54.6%.[1] Data for current graduate students, not surprisingly, show a similar pattern.[2]

Part of this problem, as described below, originates before graduate school. Part, however, has to do with incentives. Taking graduate training has become unattractive, economically and otherwise. Particularly in some fields of engineering and computer science, where salaries are high in industry, continuing for the masters or doctorate degree requires large financial sacrifice. The subsequent return on this sacrifice is apparently not high enough to induce many American college graduates to pursue postgraduate training.

We RECOMMEND:

NSF should continually review and revise support for graduate students through improved fellowships and emphasis on improved graduate student participation in research projects.

[1]*Science and Engineering Doctorates, 1980-86*, prepared by NSF Division of Science Resources Studies (1988).

[2]*Selected Data on Graduate Science/Engineering Students and Postdoctorates by Citizenship*, prepared by NSF Division of Science Resources Studies (1986).

C. Undergraduate education

Undergraduate education too plays a major role in economic performance. For engineers the undergraduate degree is usually the final professional degree. Most of the nation's leaders in businesses and on farms complete their education as college graduates. So do most government officials and elementary and secondary teachers. The knowledge and skills with which they emerge, and especially the capacity they have acquired to continue learning throughout their careers, will determine economic competitiveness — both theirs as individuals and ours as a country. In our technology-oriented era they and the country will especially need knowledge and skills in mathematics, science, and engineering. Moreover, the attractiveness and quality of undergraduate courses and laboratories go far to determine whether we can induce top students to go on to graduate school in those fields.

For these reasons, among others, we cannot afford to take strength in undergraduate education for granted, particularly not in technical fields. In 1986 the National Science Board, through a specially constituted Committee, conducted a thorough examination of the state of undergraduate education in science, mathematics and engineering.[3] It found much room for improvement, including "serious problems" in three areas:

> "Laboratory instruction, which is at the heart of science and engineering education, has deteriorated to the point where it is often uninspired, tedious, and dull. Too frequently it is conducted in facilities and with instruments that are obsolete and inadequate. * * * It is being eliminated from many introductory courses."
>
> "Faculty members are often unable to update their disciplinary knowledge continuously or maintain their pedagogical skills, and are largely unable to make skilled use of computers and other advanced technologies. In some fields there are serious shortages of qualified faculty."
>
> "Courses and curricula are frequently out-of-date in content, unimaginative, poorly organized for students with different interests, and fail to reflect recent advances in the understanding of teaching and learning; the same is true of instructional materials now in use. Insufficient faculty energies are devoted to improving the quality of instruction and its appeal to any others than those enrolled as majors in their field."[4]

The Undergraduate Education Committee urged NSF to exercise leadership of a nationwide effort in undergraduate education, using its public prominence plus high leverage programs to prompt activity by those — in state and local governments and in academic institutions — directly responsible for the health of colleges and universities.[5] We agree. Though its role is less dominant at the undergraduate level, the NSF is unique among Federal agencies in being broadly charged with concern for science and engineering education. It already has long-established working relationships with colleges and universities and with their faculties. It influences incentives that affect the priority faculty assign to undergraduate teaching, in and out of their fields. Its programs also bear directly on the primary problems facing undergraduate science and engineering education; they can represent what the earlier Committee called "a significant presence".

The earlier Committee recommended that NSF programs in undergraduate education be significantly increased, and the NSF's current plans would more than double support for programs addressing all three of the problem areas described above and providing support for undergraduate research participation.

We RECOMMEND:

> **NSF should continue to pursue the initiative to improve undergraduate science and engineering education called for by the National Science Board in 1986, with emphasis on laboratory development and instrumentation, undergraduate research participation, faculty professional development, and improvement of courses and curricula.**

Economic performance and competitiveness will be particularly affected by undergraduate engineering education, which is separately dealt with in Chapter IV of this report.

Though much can be done to improve undergraduate science and engineering education, the most serious problem we face at the undergraduate level may be the extent to which the undergraduate experience for many students must be devoted to remedial courses and otherwise repairing deficiencies in their precollege preparation. This is part of a larger problem that we believe is seriously impairing American competitiveness and economic performance.

D. Elementary and secondary education

The United States is now facing up to a crisis in elementary and secondary education. A spate of strongly worded high-level reports have documented and decried the state of US public education, and have proposed strong remedies.[6] The main problems are now familiar: inadequate exposure to demanding subjects; low "time on task" at school; flagging enthusiasm for learning; and poorly prepared, underpaid, underappreciated teachers — all leading to demonstrably sub-par student performance on objective tests.

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[3] *Undergraduate Science, Mathematics, and Engineering Education,* Report of the National Science Board Committee on Undergraduate Science and Engineering Education (1986).

[4] *Id.* at 2.

[5] *Id.* at 7.

[6] *A Nation at Risk: The Imperative for Educational Reform,* Report of the National Commission on Excellence in Education (1983); *A Nation Prepared; Teachers for the 21st Century,* Report of the Task Force on Teaching as a Profession, Carnegie Forum on Education and the Economy (1986); *Investing in our Children: Business and the Public Schools,* Committee for Economic Development (1985); *Time for Results: The Governors' 1991 Report on Education,* National Governors' Association (1986).

The problems are particularly severe in math and science.[7] For example, in standardized mathematics and science tests US eighth and ninth graders now score at or near the bottom among students from developed countries, far below their world-leading counterparts in Japan.[8] Moreover, while in Japan, Germany, and the Soviet Union all students take at least one course in mathematics and one in science each year in high school, 84% of US students take no high-school physics, 65% avoid high-school chemistry, 23% take no biology, 62% skip Algebra II, and 48% take no geometry.[9] Many students come to college so poorly prepared in math and science that majors in those fields or in engineering are almost out of the question. But these problems are part of the systemic crisis; they cannot be solved independently.

The reports on the systemic crisis have combined with concerns of citizens, employers, and parents to initiate reform. Governors particularly, in many states and through their National Governors' Association, have made education top priority. Some improvements have been made. In many states teachers' salaries have been increased and dubious restrictions on who can teach relaxed. The quantity and quality of applicants to teacher preparation programs are up. Student test scores for a time began to recover slightly, though lately they have leveled off again. But what has been done is not yet nearly enough.

Indeed, restoring standards and achievement on what once sufficed as "basics" will fall short in two respects.

> First, the relevant "basics" have changed. Math "facts" and computation, basic reading, and other discrete, easily-measured skills, though essential, no longer equip students for life and work. In modern conditions students need "ability to reason and perform complex, non-routine intellectual tasks."[10]
>
> Second, restoring the standards of the past will not make our kids competitive. In the future, one of the recent reports observes, "high-wage level societies will be those whose economies are based on the use on a wide scale of very highly skilled workers, backed up by the most advanced technologies available",[11] and so "our schools must graduate the vast majority of their students with achievement levels long thought possible only for the privileged few".[12]

The sweeping reforms that are needed will require big changes and will be expensive. They can bring great future returns, but only, as with any form of investment, at the cost of present sacrifice. For that reason if no other, they will require a sustained exercise of political will. No brief burst of concern and enthusiasm like the one inspired by Sputnik will suffice.

In face of these systemic needs NSF education programs by themselves, even if doubled or tripled, would be futile — a trickle where we need a tide, directed to what are at this stage secondary issues. Such programs can improve training for teachers, for example, but cannot change certification restrictions, salaries, status, and working conditions so as to attract top people to teaching. They can improve curricula and materials for math and science, but cannot require students to take those courses or increase their time on those tasks.

NSF should therefore be actively joining in the struggle for systemic reforms. The leadership of the Foundation, including the Board, the Director, and other senior NSF officials — not just the Assistant Director for Science and Engineering Education — should accord this responsibility high priority, speaking out whenever they can and making common cause with other responsible leaders, especially state governors, to inform the American people about what needs to be done and about the high stakes for them and for their children.

We RECOMMEND:

> **The NSF should visibly and forcefully join in national efforts to introduce broad systemic reforms in elementary and secondary education — particularly, but not solely, as regards math and science.**

Then, as part of a wider tide of educational improvement, NSF programs can make a signal contribution within NSF's special responsibility for math and science education. Given (i) the current severe shortage of teachers truly qualified to teach math and science, (ii) the compounding of that problem by impending increases in student enrollments and teacher retirements, and (iii) limits on the extent to which salaries and other incentives can be raised to attract more and more highly qualified teachers into science (problems all largely beyond NSF's control), the major challenge NSF needs to address is how we can get the most from the teachers we will have. Part of the solution is to "leverage" the teacher by making it possible for kids to do more learning by themselves and from each other, under the guidance of the teacher.

We identify three prime paths to that goal:

1. Training for teachers, both in the substance of the subjects they teach and in effective use of the new materials and technologies.

2. Improved curricula and materials, particularly ones that will take advantage of the new technologies and make

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[7]This is a common theme in the previously cited reports and is detailed in *Educating Americans for the 21st Century*, Report of the National Science Board Commission on Precollege Education in Mathematics, Science and Technology (1983). The most recent report is from the Educational Testing Service and based on the 1986 National Assessment of Educational Progress. *The Science Report Card: Elements of Risk and Recovery* (1988).

[8]The most recent report is from the International Association for the Evaluation of Educational Achievement, *Science Achievement in Seventeen Countries* (Pergamon Press 1988).

[9]*Educating Americans, supra*, note 41 at 19, and sources cited.

[10]*A Nation Prepared*, supra, note 40, at 15-20. The Carnegie Task Force on Teaching as a Profession goes on to describe in greater detail and with considerable eloquence what it means by "complex, nonroutine intellectual tasks".

[11]*Id.* at 13.

[12]*Id.* at 21.

them educationally effective and ones that will give kids "hands on" experience with science.

3. Expanded use of computers, interactive video, and other new technologies in the classroom.

All three of these also will require continuing research and experimentation to determine how kids learn and what science and math is most important for them to learn.

NSF programs should have a comparative advantage in inducing top scientists and mathematicians to help take on these problems. Such programs should be getting the scientists and mathematicians together with teachers, school administrators, curriculum publishers, and vendors of computer hardware and software or other new technologies to develop materials and methods that will take account of all the realities of classrooms, school systems, and school markets.

Without having conducted any exhaustive inquiry — which would be the province of another National Science Board Committee — we understand the NSF has made a good start at all of these things. They are appropriate for continued NSF focus.

We RECOMMEND:

The NSF's own programs at the elementary and secondary levels should give high priority to expanded use of new technologies in the classroom, to developing improved science and math curricula and materials, to training teachers of science and math, and to research and experimentation on learning of math and science.

E. "Pipeline" and "pool"

The NSF is inevitably concerned with the "pipeline" of youngsters that eventually yields the next generation of scientists and engineers. At a time when the projected need for scientists and engineers and other technical professionals has been rising rapidly (though not as fast as in most competitor nations) and is projected to continue rising, that pipeline is not full.

First, demographic trends are reducing the pool from which the pipeline draws. The pool of college-age Americans peaked in the early 1980s, is falling by around a million a year, and will fall for most of the remaining years of this century. We will have advanced several years into the 21st century before cohorts at Ph.D. ages begin to increase again.[13]

One would hope that the consequent shortfall could be offset by increases at all levels in the numbers of students getting sufficient background in math, science, and technology to remain in the pipeline. Unfortunately, that is not yet happening. A quarter of American kids still are dropping out before they finish high school — a much higher rate than in other advanced countries.[14] A big share of those who do go to college are so poorly prepared in math and science that technical degrees and careers are virtually precluded for them. In recent years the proportion of undergraduates working toward degrees in natural science and engineering, already lower than in almost any other industrialized nation, has leveled. And we have already described the distressingly small numbers of American citizens who are obtaining graduate degrees in these fields, leading to our insecure dependency on foreign graduate students.

Many of the things that need to be done to refill the pipeline and rebuild competitive strength in our technical and managerial workforce were covered earlier in this chapter. But an especially important further step will be to extend the pool from which the pipeline draws by bringing into it more women, more racial minorities, and more of those who have not participated because of economic, social, and educational disadvantage.

The urgency of doing so is evident from demographic realities and projections. A quarter of our schoolchildren today are black or hispanic; by the turn of the century almost half are likely to be.[15] By then 80% of new entrants to our labor force will be women, minorities, or immigrants.[16] Thus not only is providing a better grounding in math and science for all citizens a matter of making good on the American promise of equal opportunity. It is a pragmatic necessity if we are to maintain our economic competitiveness.

Real progress has been made recently in improving the participation of women. In 1986 women earned 30% more bachelor's degrees in science and engineering than they had in 1976, with a fourteen-fold gain in computer science and a twelve-fold gain in engineering. In 1986 women earned 38% of science and engineering baccalaureates, up from 33% a decade earlier.[17] Women also earned 62% more science and engineering doctorates in 1987 than they had in 1977, increasing their share of such doctorates from 18% to 26% over that period.[18]

For women the challenge is to sustain progress, as signs have appeared that the number of women entering graduate and undergraduate science and engineering education is leveling off, and the number entering the physical sciences and engineering is still low. (Women are concentrated in the biological, behavioral, and social sciences.) We need to keep providing encouragement, role models, and reassurance that science and engineering is indeed open for women. We need also to ensure that women who become scientists or engineers do not find their career paths blocked by discrimination and that adjustments are

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[13] See *Personnel in Natural Science and Engineering*, a monograph produced by the NSF Division of Policy Research and Analysis (Working Draft, June 1988), Figure 2 at 2 and accompanying text.

[14] *The Condition of Education, 1988*, US Department of Education, National Center for Education Statistics (1988), at 28.

[15] *Changing America: The New Face of Science and Engineering*, Interim Report of the Task Force on Women, Minorities, and the Handicapped in Science and Technology (Washington, DC 1988), at p. 9.

[16] Bureau of Labor Statistics, US Department of Labor.

[17] National Science Foundation, Division of Science Resources Studies. See also *Women and Minorities in Science and Engineering* (National Science Foundation 1988), Appendix table 47 at 197-199.

[18] *Early Release of Summary Statistics on Science and Engineering Doctorates, 1987*, National Science Foundation, Division of Science Resources Studies, Table 1 (1988).

made in traditional career paths to account for the demands that children place disproportionately on women.

For blacks, Hispanics, and native Americans progress in science and engineering has hardly been evident. In 1985 blacks earned only 5% of bachelors' degrees and 3% of Ph.D. degrees in science and engineering. Similarly, in 1985 hispanics earned only 3% of bachelors' degrees and 2% of Ph.D. degrees in science and engineering. In both cases there has been no improvement since 1979. These groups, who constitute the fastest-growing contingents in our school-age population, still drop out of high-school and skip college at much higher rates than whites or Asians.[19]

Discrimination, and certainly the legacy of discrimination, still contributes to this. Conceivably also minority communities harbor preferences that militate against technical schooling and careers. For the most part, however, the failure of blacks and hispanics to move in proportionate numbers into the mainstream of American science and engineering clearly derives from economic, social, and educational disadvantage — which affects them disproportionately, but not uniquely.

Disadvantaged students often start with a strike against them because of poor family backgrounds. They attend schools that usually fall far below the standards of schools for more affluent students from more supportive family backgrounds. They achieve less and drop out more at all levels of education. Such realities not only mock the American dream, but threaten to leave millions of Americans persistently unable to compete with workers abroad at American wages. No educational problem more urgently calls for public and NSF attention.

The NSF has maintained programs focussed on women and minorities for some time. In recent years these have received increased funding priority. The Board and the Director have devoted much management attention to the problems of women and minorities and have encouraged efforts across the NSF to redress those problems.

We RECOMMEND:

From the perspective of economic competitiveness (as well as other perspectives) NSF programs and management efforts designed to help bring women, minorities, and the economically, socially, and educationally disadvantaged into the mainstream of science and engineering deserve continued focus.

[19]Unpublished tabulations, National Science Foundation, Division of Science Resources Studies.

IV. ENGINEERING AND OTHER TECHNOLOGY-ORIENTED FIELDS

Obviously engineering relates especially directly to economic performance and competitiveness. It is practicing engineers who directly manage and implement the "chain of innovation" — drawing upon the scientific and technical knowledge built up from research and translating it into new products, processes, and services. Moreover, engineering research generates knowledge relevant with special immediacy to technology and economic production. The role of the National Science Foundation in engineering has for several years been a focus of policy deliberations in the National Science Board and in Congress, the Administration, NSF management, and the engineering community. The evolution of the NSF role continues.

A. Nature and history

Engineering is different from science. "Science is concerned with learning things; engineering is concerned with making things." In other words synthesis, not analysis, is the aim of engineering, and the defining activity in engineering is design. In those respects engineering practice is like many other fields — architecture and literature, for instance — but unlike science.

Engineering does, on the other hand, extensively employ analysis and science — both science from other fields and "engineering science" generated internally. But it employs them as means to the end of producing something new. (Science in return resorts to design of experiments and engineering of experimental apparatus as means to the end of *learning* something new.) Moreover, engineering cannot abstract as science does from the complexities and uncertainties of the real world, but must reckon with them very directly. Thus the science it employs tends to involve multiple disciplines and probabilistic calculations.

Indeed, engineering not only integrates analysis with synthesis, but must do so within constraints of time and money (budgets and deadlines); must reckon with other concerns such as health, safety, and environmental impact; and must take account generally of the political and social setting within which it operates.

Before World War II practicing engineers mostly worked from accumulated experience, rules of thumb, and established scientific laws. Naturally those were also the focus of engineering education. But wartime experience exposed deficiencies in this approach. Scientists outdid engineers on what were really engineering tasks — for example, developing radar and nuclear weapons. After the war, therefore, science came to be emphasized in engineering practice, engineering research, and engineering education. Though in many respects a considerable advance, this emphasis tended to submerge the synthetic and integrative functions that are the special province of engineering. Those functions languished — partly, at least, for lack of tools and techniques to put them on an equivalently rigorous basis.

With the focus on analysis, the attitude also grew that the best and brightest minds, in engineering as supposedly in science, should be concerned with reductionist theory, not messy reality — notwithstanding that the confrontation with reality, in all its complexity and uncertainty, is of the essence in engineering. This attitude combined with limited funding for equipment and facilities to constrict the confrontation of academic engineers and their students with the real world. Hands-on experience and experimentation — the testing of theory by making and trying things — also languished, as did concern with construction and optimization of systems.

Along with these trends came an emphasis on product design over production engineering. US engineers have been the world's most innovative in designing new products that draw on the latest scientific developments, but the US has put much less technical effort and sophistication into production, process, assembly, and manufacturing. Technical careers in production engineering have been relegated to lower prestige and pay. Our best engineers, not surprisingly, have not chosen or been selected for such careers. This is one reason why our international competitors have been outdoing us, as described earlier, in management of production and in introduction of incremental innovations on the production floor.

In recent years the recognition has been growing among US industrial and academic leaders that these things must change if the US is to regain industrial competitiveness. At the same time, fortunately, new tools and techniques have been emerging that make possible a new level of rigor and sophistication in the synthetic and integrative functions of engineering generally, and in production engineering particularly. Many of these tools and techniques have been made possible by modern computer power, abetted by increasingly refined quantitative characterization of materials and processes and by new statistical and computational methods.

Today there is much talk of new Federal programs to improve US "technology", and there is room for such. We ought to recognize, however, that when we talk of "technology" (particularly in the context of research and education) we are really talking largely of "engineering". "Technology" refers to the application of science to industrial, commercial, military, and other practical ends — the task primarily of engineering. Not entirely, of course, for some technology is developed by people involved in production or marketing who are not professional engineers, and many sciences contribute also to the application of science to practical ends.

Indeed, the practical distinctions between engineering and some fields of science are not so clear as we may thus far have made out. Just as analytical research that fully deserves to be called science is performed by engineers, much synthetic work aimed at application for industrial, commercial, and other practical ends is performed by scientists in such fields as the computer sciences, chemistry, materials science, and the biosciences. Much of what we have said and will be saying about engineering has pertinence for those fields as well.

B. The NSF role

Engineering has had a place at NSF from the beginning. For quite some time, though, engineering at NSF was regarded as part of science. Thus support for the field was lodged within one of the science directorates. But NSF's role in engineering has emerged very rapidly in the 1980s.

A separate Directorate for Engineering was founded in 1981. Though it started from a relatively small base and still accounts for only 12% of the NSF appropriation for Research and Related Activities, it has grown faster than other directorates. Its role and responsibilities have also been expanding. In 1983 the National Science Board issued a "Statement on the Engineering Mission of the NSF" calling for NSF to play a larger role in both engineering research and engineering education, with "support for new areas of engineering science; for research and education in areas of generic [synthesis] such as engineering design and manufacturing engineering; for increasing the use of computers and computation capabilities in engineering; and for activities relating to [engineering education]."[1]

The Board's policy statement has been implemented and extended by subsequent developments. In 1985 the NSF, with strong Administration and Congressional support, began establishing Engineering Research Centers that bring engineers from multiple disciplinary backgrounds to focus on important technologies, notably for manufacturing and production; that help researchers and students alike to learn skills of synthesis and integration relevant to engineering realities in industry; and that actively involve industry with funding, research, and application of the research results. In the same year, Congress amended the National Science Foundation Act to add the word "engineering" wherever "science" or one of its cognates appeared in the Act[2], thus emphasizing that engineering is different from science, but is equally part of NSF's responsibility.

What then, is the proper scope of that responsibility? In general, those whom NSF supports should not be doing engineering development, but, as in science, building the base of knowledge and trained people to be drawn on by those who later develop products and processes via the normal "chain of innovation". It is entirely proper that researchers supported by NSF should be building the base with emphasis on the distinctive synthetic and integrative aspects of engineering. Among other things, this emphasis should encompass the scientific basis for the process of design; revolutionary new designs of all types; systems operation and optimization; and the processes of production, manufacturing, assembly, and construction. Of course, NSF should continue to support analytic "engineering science" too, as it always has.

Similarly, it is entirely proper that NSF programs in the computer sciences, chemistry, materials science, the biosciences, and other fields with potential for contributing to new technology should recognize and support synthesis-oriented work which builds the science and technology base that practicing technologists will later use in developing industrial and commercial technology.

We RECOMMEND:

The Board should confirm as appropriate the NSF's recent expansion of attention to engineering and to fundamental work on design, manufacturing, process, systems, and related "synthesis" activities, both in engineering and in other technology-related fields.

C. Research — how far "downstream"?

We have said that in engineering and other technology-related work the NSF should be involved in building the science and technology base, not in doing engineering development of specific products and processes for the market. This is the right principle. The elements of the science and technology base are shared property of widespread usefulness and have many of the characteristics of "public goods". Generally they involve knowledge or training that an individual industrial firm could not effectively exclude other firms from using, or where, if it could, the exclusion would either greatly restrict potential applications of the knowledge or require other firms to needlessly reproduce it in order to avoid that result.[3]

This does not mean that in these areas NSF-supported research should ignore potential for downstream commercial payoff. On the contrary, one of four primary criteria the Board has long since adopted for selection of research projects addresses the "utility or relevance of the research" and is "used to assess the likelihood that the research can . . . serve as the basis for new or improved technology or assist in the solution of societal problems".[4] Thus we reconfirm the existing criterion and also

RECOMMEND:

Where appropriate, NSF long-range plans and budget presentations should directly identify the potential areas of application for each field.

In these fields no dichotomy need be or should be drawn between "basic" and "applied" research. Virtually all such research is "basic" in that it is prompted by gaps in the store of scientific and technical knowledge, earlier identified as a major element of the science and technology base, and strives to add to that store. Virtually all such research is also "applied" in that it is undertaken with the expectation or hope that it will ultimately be drawn upon for practical technical applications, at least the general nature of which can be identified at the time the research is done.[5]

On the other hand, not every research project that may add to the store of scientific and technical knowledge and hence to our science and technology base will be appropriate for Federal, or especially for NSF, support. Government should not be funding what industry can and will do for itself. Where the value of research depends on production and marketing realities, more-

[1]Statement on the Engineering Mission of the NSF Over the Next Decade, *NSB-83-250* (August 19, 1983).

[2]National Science Foundation Authorization Act for FY 1986, section 110-11, 99 Stat. 887, 890-93 (1985).

[3]See C.H. Herz, *Research: Framework for a Federal Role* (work in preparation).

[4]Criteria for the Selection of Research Projects by the National Science Foundation, *NSB-81-488* (August 1981).

[5]See C.H. Herz, *supra* note 3.

over, industry is better positioned to judge that value and is subject to salutary market discipline.

Indeed, in these technology-related areas a choice of either Government or industry support for research may often be unnecessary and undesirable. NSF has recently obtained, or even required, industry contribution, matching, or "leveraging" in research centers and projects that NSF supports. The closer the research to specific markets and particular industries, the more reasonable and even necessary that becomes. Moreover, in these areas NSF should be putting effort into finding the best scientists and engineers in industry and using them as peer reviewers and advisory panelists.

Even where a Federal role is appropriate in principle, NSF need not fund what other agencies can and should fund. NSF should be concentrating on longer-term base-building and on what other agencies do not do. A good rule of thumb is that NSF should be funding work of high quality and economic potential where it can say "if we don't do this, no one will".

D. Research funding — how much is enough?

The private economy will underinvest in research unless Government provides or subsidizes additional investment. But to a considerable extent Government already does. How much is enough? That cannot be precisely calculated, but we will confidently assert that the United States still invests in research related to economic performance and competitiveness well below the optimal level. We do not know where the top of the hill is, but we are surely still headed uphill.

We base this conclusion on four primary considerations:

> First, opportunities for productive employment of resources in science and engineering are now exceptionally high. Seasoned observers in almost every field of science and engineering report with palpable excitement that discoveries, theoretical understanding, and research techniques are advancing at unprecedented and accelerating pace.
>
> Second, the extent to which uncertainties and inappropriability of benefits will lead the private economy to underinvest in research is great.
>
> Third, though innovation accounts for a very large share of our economic growth, the R&D that in our time is the primary wellspring of such innovation still consumes less than two percent of our gross national product.
>
> Fourth, the US is not matching its principal competitors in the share of its GNP devoted to R&D. Japan and Germany, which have been conspicuously outstripping the United States in productivity growth and international competitiveness, have also been conspicuously and consistently investing a larger share of their national incomes in nondefense R&D.

The United States should therefore be significantly increasing both the level and share of Government investment in research which contributes to our economic performance and competitiveness. For reasons described earlier, that makes sense even — perhaps especially — while we are fighting Federal budget deficits.

E. Engineering education

The NSF needs to give special attention to engineering education. The previous chapter of this report singled out education as the prime determinant of US competitiveness. Because of the central role of engineers in the innovative process, engineering education has a particularly pivotal role. Multiple recent reports have drawn attention to significant deficiencies in current engineering education, which takes place predominantly at the undergraduate level. Sweeping revision of curriculum and methods in undergraduate engineering is being widely urged and has the support of engineering leaders in both academia and industry. NSF has responded as best it can within limited resources, with programs in undergraduate engineering education that emphasize design, manufacturing, multidisciplinary problem-solving experience, and hands-on experience with modern equipment.

A common theme of the reports and inputs the NSF and the Board have been receiving is that the undergraduate engineering curriculum, while continuing to acquaint students with the sciences that underlie engineering analysis, needs to reintroduce and reemphasize synthesis as the engineer's characteristic task. The curriculum should also reemphasize the way in which an engineer must integrate analysis and synthesis with constraints of time and money and wider social and environmental concerns.

Indeed, one notion is that the very earliest undergraduate engineering courses should bring out all these elements, introducing students headed for engineering majors to the core elements of the profession they are choosing. Non-engineering majors could gain from the same kind of course a concrete understanding of how technology is developed and how it fits within a broader social and political context — an increasingly appropriate element in a liberal education.

Another pressing problem in engineering education is the obsolescence of laboratory equipment and facilities, which have fallen far behind modern technology and engineering practice in industry. Students need to be introduced to modern computer-aided design and manufacturing, systems simulation, and information management and in general to get a more realistic preparation for the application of engineering principles in industry.

Finally, we need to address the particularly severe shortage of American engineering students who are going on to graduate school and entering engineering faculties. We have become dangerously dependent on foreign students to fill our graduate schools of engineering and to teach our engineering undergraduates.

Redressing these and related problems is an integral aspect of our recommendations both on education and on continued NSF focus in engineering.

V. INFRASTRUCTURE AND INTERNATIONAL

A. Knowledge transfer

The pace of innovation, of scientific advance, and of progress between research and applications is accelerating. Hence success in international economic competition increasingly depends on "shifting leads in close technological races".[1] The speed and efficiency with which scientists, engineers, and technologists obtain from each other and from the store of scientific and technical knowledge information that helps them perform their functions therefore assumes unprecedented importance.

The National Science Foundation, as befits its statutory charge to "foster the interchange of scientific and engineering information"[2], can claim a useful past in building the resources and channels for transfer and diffusion of knowledge. Years back its "science information" programs fostered the growth of US scientific journals and financed early reference databases like Chemical Abstracts that have since grown into major national assets. Further, NSF's early financing of computer facilities at universities opened new information resources for scientists and engineers. More recently the NSF took a lead in making supercomputers available for scientists and engineers — a lead that was soon widely followed — and has been helping to build and tie together computer networks for scientists and engineers, plus means to use the networks for transmission of complex scientific and technical documents. All along NSF-supported research in information science has been contributing theoretical underpinnings and new or improved techniques and tools for information storage and retrieval.

However, Federal support for activities in knowledge transfer has recently been low and declining. The NSF itself no longer has any separately budgeted program or organizational champion for such activities, which are dispersed to the individual directorates.

We RECOMMEND:

The Board should ask the Director to assess whether the programs of the Foundation are well organized to address continually the needs of the country in knowledge transfer, and to make recommendations based on his assessment.

A number of thoughtful leaders in the science community and especially in the engineering community have expressed concerns about availability of data needed by scientists, engineers, and technologists in the course of their work. The focus of those concerns has not been disciplinary literature; nor computerized access to existing scientific and technical information, which is available through excellent commercial or professional-society services; but the evaluation, integration, and packaging of reference data so that it will be trustworthy, complete, and comprehensible to users.

Having considered these legitimate concerns, the Committee concludes that they are not ones the NSF is well qualified, equipped, or funded to address. The National Institute of Technology and Standards (the former Bureau of Standards) has responsibilities and experience in the area of standard data, and we would support expansion of NBS programs to meet high-priority needs in this area.

B. "Connections"

Contacts, collaborations, and movements among people are the best means for diffusing scientific and technical knowledge and knowhow. People are themselves repositories of knowledge. They can also guide others to information resources in their fields that otherwise would remain unknown, buried, or forbidding. Furthermore, people "know more than they can say"[3], and possess skills as well as knowledge. The only way to communicate such "tacit" knowledge and knowhow from one institution or one part of the innovation process to another is for people to learn from each other, to move from one locus to another, and to work with each other across organizational and institutional lines.

The worst impediments to such connections lie in human attitudes. Rigid preconceptions and narrow role definitions are chief culprits, as are disinterest and prejudice toward ideas or technologies "not invented here". A Government administrator in a defense or space program may not or will not fund anything called "research" (though research is just what he needs to solve his problem), because research is not in his program description or budget category. An industrial engineer makes no attempt to learn new technique or use new technology developed in a Government or university laboratory, let alone a Japanese one. A university professor synthesizes a substance that could lead to a better fuel cell, but disdains pursuing "applied research" to realize its potential.

We RECOMMEND:

NSF should recognize and respond to activities in the research community that foster connections in research and innovation across sectoral, institutional, R&D-spectrum, and disciplinary lines.

University-industry connections in particular are a long-standing US strength. Students move into industry, professors consult with industry, and both bring along ideas and techniques from frontier work at universities. New enterprises spin off from universities, not infrequently spawning major centers of high-tech industry like Silicon Valley in California and Route 128 in Massachusetts. Recently universities and industries have expanded direct collaborations, from individual joint research projects to research centers with multiple industry associates.

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[1]Krugman, ed., *Strategic Trade Policy and the New International Economics* (MIT Press 1987) at 8.

[2]National Science Foundation Act of 1950, section 3(a)(3), 42 U.S.C. 1862(a)(3).

[3]See M. Polanyi, *The Tacit Dimension* (Doubleday 1966).

NSF programs for Industry-University Cooperative Research and for Industry-University Research Centers helped to get this trend rolling. NSF Engineering Research Centers, Biotechnology and Plant Sciences Centers, and Science and Technology Centers are building further on the same theme.

These programs, and particularly the newest centers programs, are also interdisciplinary and substantially focussed on the transition from basic science and engineering to commercial applications. Thus, they have the further virtue of building individual and institutional connections in those dimensions as well. The intent of our recommendation is that such connection-building should be continue to be fostered in these programs and welcomed in other programs as well.

C. International

What we mean by a "global economy" is that trade, people, money, and information move with growing ease all over the world; a growing share of all economic transactions cross national borders; and a growing share of world economic activity is accounted for by firms with operations in more than one country. Yet the world is still bounded politically into individual nation states. The premise of even this report is that those nation states are in competition with one another.

In such a situation technology protectionism is a clear and present danger. Much value could be lost and much tension created if nations set out to compete in science and technology by protecting national markets for high-technology industries and by setting up national or regional technology programs that exclude nationals and firms of other nations.

More can be gained from international openness and cooperation in science and technology. All nations can profit from the economic and technical strength of other nations — as consumers of their products, sellers to their markets, and beneficiaries from their political stability and economic security. All can benefit from the stimulus that wider markets and vigorous competition provide for development of innovative technology. Mutual openness with research results and within the research programs and educational institutions that create and transmit new scientific and technical information can permit wider extension and application and hence greater value from such information. By jointly funding major facilities and projects that any one nation would struggle to afford nations together can advance science and technology further and faster.

Though international cooperation can therefore lead to an expanding international pie, international competition will inevitably determine how the pie will be divided. We do need to look after our own interests in international competition, in science and technology as in other fields. We can and should demand fair sharing of costs for research that yields results usable worldwide, fair recognition of our contribution in educating students from elsewhere in the world, and fair reciprocity in science and technology flows.

However, we are in a poor position to complain much about lack of reciprocity when reciprocity is being offered, but we lack capacity or willingness to accept it because of inadequate language training, limited international experience and exposure, and parochial attitudes in our own scientific and technical communities. The contrast with Japan's global full-court press to acquire technology from abroad could scarcely be stronger.

The US scientific and technical communities should be assigning high priority to building our ability to compete in other countries and to draw technology from them. This will require language training, translation of foreign literature, and increased international experience and exposure for US scientists and engineers. It will require improved intelligence on science and technology developments in other countries. Above all it will require numbers of US scientists and engineers who know the science and engineering systems of other countries, particularly their major research centers and unique sites or facilities.

We RECOMMEND:

> **Programs that inspire and encourage US scientists and engineers to become more actively involved with scientists and engineers in other countries, and that otherwise build US capacity to absorb science and technology from and compete in other countries, are appropriate for continued NSF focus.**

Moreover, pressuring others to provide reciprocity and to take their fair share of the research and education burden, or complaining about their failure to do so, can too easily take the place of getting our own house in order. Our recent difficulties in international competition do not result in any large degree from failure of reciprocity or burden sharing by Japan or other nations. They result from our own weaknesses in savings and investment, in education, in civilian research and development, and in managing production and implementing technology.

The era of the global economy offers all nations, and all the world's people, an unprecedented opportunity to obtain a global grasp of our collective destiny. Neither science and technology nor economic performance are ends in themselves. Together the nations can employ advancing technology and the expanding productivity it yields, not to build an ever more extensive and elaborate, but also ever more precarious cantilever out over a widening abyss, but to secure sustainable prosperity and opportunity for all the world's people. Economic competitiveness is a game in which all can win.

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