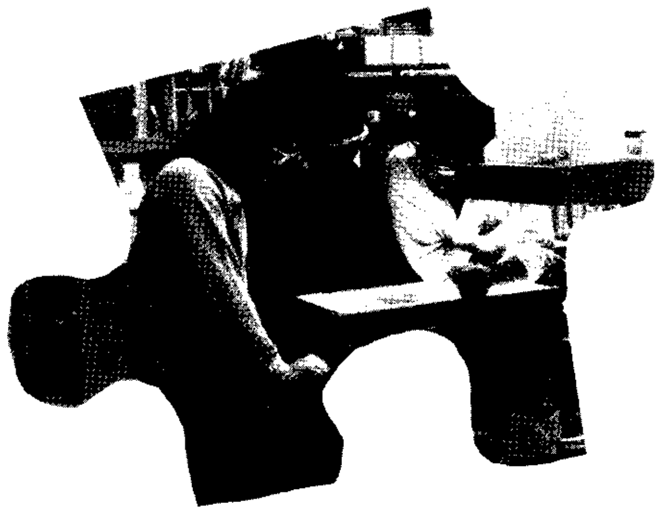
CHAPTER 1

summary and Issues for congress



Contents

Boxes

Figures

Tables

CHAPTER 1

Summary and Issues for Congress

Introduction

Research provides extraordinary benefits to society through the creation of new knowledge and the training of scientists and engineers. The research and higher education system in the United States is the envy of the world, and has a long history of advancing the state of scientific knowledge. This is known as "scientific progress": ". . . not the mere accumulation of data and information, but rather the advancement of our codified understanding of the natural universe and of human behavior, social and individual."[1] These advances have addressed such goals as enhancing the Nation's public health, military security, prestige, educational achievement, work force, technological development, environmental quality, and economic competitiveness.

To say only that research contributes to national goals, however, simplifies and understates a complex system. Research is no longer a remote, scientist- or engineer-defined activity resulting in new knowledge for society. Perhaps it never was. "Deeply held political values of democratic accountability and public scrutiny have naturally and inevitably impinged on science policy. Demands for observable benefits from public investment in science increase. ' Such demands have led to claims that scientitic research has a signficant and direct impact on the economy, and that an investment in knowledge is a downpayment on the products and processes that fuel U.S. economic growth and productivity.[3] Economists admit, however, that the "difficulties in measuring the benefits of research . . . are hard to exaggerate. ' The Nation now expects that in addition to knowledge, science and engineering will contribute to U.S. prestige and competitiveness abroad, create new centers of research excellence on a broad geographic basis, continue to provide unparalleled opportunities for education and training, and nurture a more diverse research work force.

Photo credit: Research Triangle Institute

Scientists at the Research Triangle Institute, NC, synthesize chemicals for cancer research. Scientific research takes place in many settings in the United States.

Thus, the Federal Government funds research to achieve more than specific national goals. By doing so, it invests in knowledge-and the people who produce it—not only for its intrinsic worth (which can be considerable), but also for the value knowledge acquires as it is applied.

Scientific research is typically split into two categories, "basic" and "applied." Basic research pursues fundamental concepts and knowledge (theories, methods, and findings), while applied research focuses on the problems in utilizing these concepts and forms of knowledge. OTA does not generally

[1]Harvey Brooks, "Knowledge and Action: The Dilemma of Science Policy in the 70s," *Daedalus*, vol. 102, spring 1973, p. 125. Unless otherwise stated, 'science' in this report includes the social and behavioral sciences as well as the natural sciences and engineering. "Research" refers to a creative activity ongoing in all of these fields.

[2]Kenneth Prewitt, "The Public and Science Policy," *Science, Technology, & Human Values, vol. 7, spring 1982,* p. 13.

[3]See Edwin Mansfield, "The Social Rate of Return From Academic Research," *Research Policy*, forthcoming 1991; and James D. Adams, "Fundamental Stocks of Knowledge and Productivity Growth,'' *Journal of Political Economy,* vol. *98, No. 4, 1990,* pp. 673-702.

'Quoted in Eugene Garfield, "Assessing the Benefits of Science in Terms of Dollars and Sense,"*The Scientist,* vol. 4, No. 22, Nov. 12,1990, p. 14. The source is Nathan Rosenberg and David C. Mowery, *Technology and the Pursuit of Economic Growth (New* York, NY: Cambridge University Press, 1989).

distinguish between these categories in this report, because policymakers, especially Congress, make very few decisions in which the two are separate. In particular, research agency program managers rarely allocate monies on the basis of a project's basic or applied classification, and divisions of research funding into these categories are often unreliable.[5]

This Report and Its Origins

In December 1989, the House Committee on Science, Space, and Technology requested that OTA assist it in understanding the state of the federally funded research system—its goals, research choices, policies, and outcomes—and the challenges that it will face in the 1990s. By requesting a study of the state of the Nation's research system and of alternative approaches the Federal Government could take in funding research, the Committee sought information on the nature and distribution of research funding and decisionmaking. Direct congressional involvement in research decisionmaking is growing, and annual agency appropriations seem more closely tied to specific goals-and tough choices among them-than ever before.[6] As one member put it:

> . . . the payoffs for the Nation are so great that increased investments in science and technology are only prudent. However, even if we could double the science budget tomorrow, we would not escape the need to establish priorities. ...7

The Federal Government has sustained an illustrious history of support for research. Underlying this relationship between government and the scientific community was a social contract or ''trusteeship,' developed after the scientific breakthroughs spurred by World War II, that delegated much judgment on Federal research choices to scientific experts.[8] Perhaps the epitome of the trusteeship was the research grant, which created a new relationship between the Federal Government and the research performer, especially the principal investigator in universities.[9] This social contract implied that in return for the privilege of receiving Federal support, the researcher was obligated to produce and share knowledge freely to benefit—in mostly unspecified and long-term ways—the public good.[10]

Since the 1960s, Federal funding for research (both basic and applied) has increased from roughly $8 billion in 1960 (1990 dollars) to over $21 billion in 1990 (see figure l-l). Funding increased quickly in the early 1960s during the "golden years' for research, after the launch of the Sputnik satellite, the escalation of the Cold War, and the Presidential commitment to land men on the Moon. Once these challenges had been met, research funding decreased

5A quarter-century ago it was noted that: "The precise partitioning of all basic research into components is, of course, largely arbitrary. Basic research can be classified in terms of its motivation-as culture, as an adjunct to education, as a means to accomplish nonscientific goals of the society; of its *sources of support*—whether mission-oriented agency or science-oriented agency; of its *performers*—whether university, government laboratory, or private industry; or of its *character*—whether 'little science' or 'big science. ' Any one of these classifications, if applied consistently, cover all basic science, but none is wholly satisfactory. ., ." See National Academy of Sciences, Committee on Science and Public Policy, *Basic Research and National Goals*, A Report to the Committee on Science and Astronautics, U.S. House of Representatives (Washington DC: March 1965), p. 9, italics added. This was independently confirmed by extensive OTA interviews with research agency personnel, spring-summer 1990. Today, research is also sometimes labeled 'strategic, " "targeted,' or ''precompetitive,'' for example. For an update and discussion see Harvey Averch, ' 'The Political Economy of R&D Taxonomies,'' *Research Policy,* forthcoming 1991.

6See National Academy of Sciences, *Federal Science and Technology Budget Priorities: New Perspectives and Procedures* (Washington, DC: National Academy Press, 1989); and U.S. Congress, House Committee on Science, Space, and Technology, Subcommittee on Science, Research, and Technology, *The Hearings inadequacy, Direction and Priorities for the American Science and Technology Effort,* 101st Cong., Feb. 28-Mar. 1, 1989 (Washington, DC: U.S. Government Printing Office, 1989).

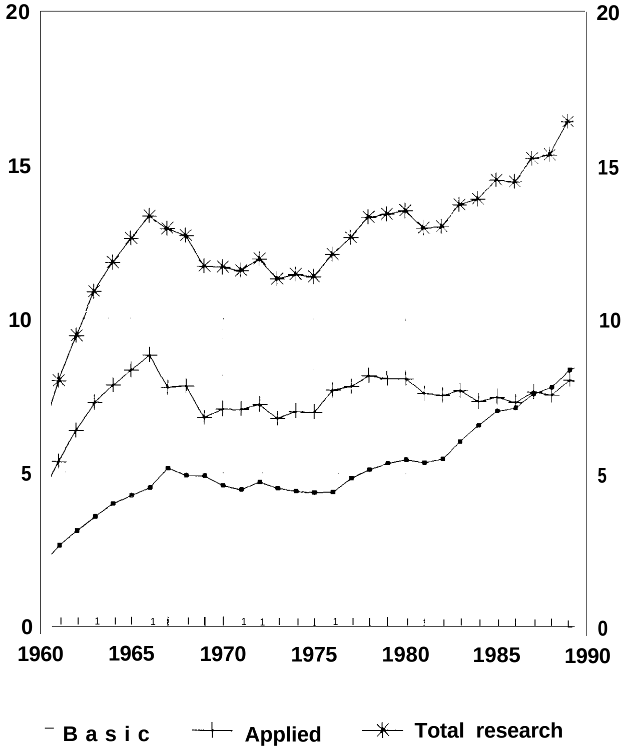
7Doug Walgren, Chairman of the House Subcommittee on Science, Research, and Technology, in House Committee on Science, Space, and Technology, op. cit., footnote 6, pp. 1-2.

8Research as a planned activity of the Federal Govement can be traced to two landmark volumes: Vannevar Bush's 1945 ' 'A Report to the President on a Program for Postwar Scientific Research" (subsequently known as *Science; The Endless Frontier)*, which instigated the creation of an agency-the National Science Foundation-whose dual mission was the promotion of research and science education, and *Science and Public Policy,* or the 1947 Steelman Report, which championed a crosscutting policy role for managing federally funded research. For interpretations, see Merton England, *A Patron for Pure Science: The National Science Foundation' s Formative Years, 1945-57 (Washington* DC: National Science Foundation, 1982); and Deborah Shapley and Rustum Roy, Lost *at the Frontier* (Philadelphia, PA: 1S1 Press, 1985).

9See U.S. Congress, House Committee on Science and Technology, Task Force on Science Policy, *A History of Science Policy in the United States, 1940-1985,* 99th Cong., September 1986 (Washington DC: U.S. Government Printing Office, September 1986), pp. 19-20. Also see Rodney W. Nichols, "Mission-Oriented R&D," Science, vol. 172, Apr. 2, 1971, pp. 29-37.

10For examinations, see Bruce L.R. Smith, *American Science Policy Since World War II* (Washington DC: The Brookings Institution, 1990), especially chs. 1 and 3; Gene M. Lyons, *The Uneasy Partnership: Social Science and the Federal Government in the Twentieth Century (New* York, NY: Russell Sage Foundation 1969); and U.S. Congress, Office of Technology Assessment, *The Regulatory Environment for Science,* OTA-TM-SET-34 (Washington, DC: U.S. Government Printing Office, February 1986), pp. 15-16.

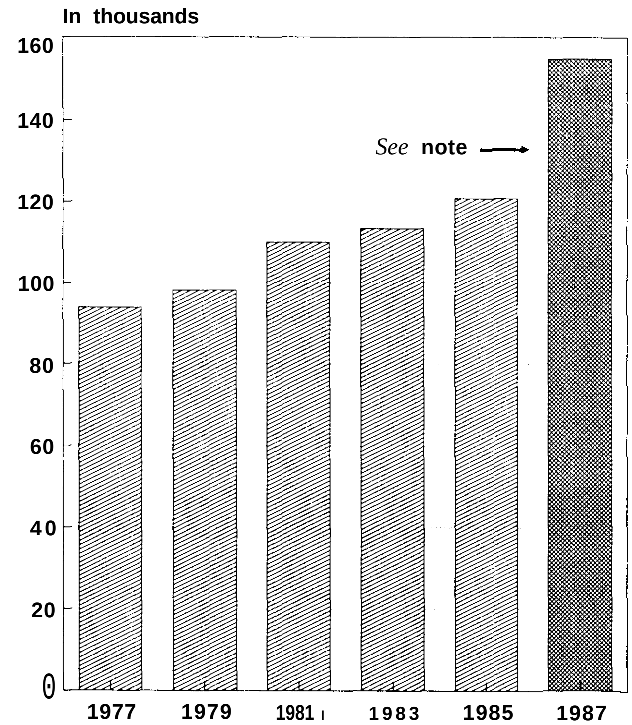
Figure 1-1—Federally Funded Research (Basic and Applied): Fiscal Years 1960-90
(in billions of 1982 dollars)



NOTE: Figures were converted into constant 1982 dollars using the GNP Implicit Price Deflator. For 1990 (current dollars), basic research = $11.3 billion, applied research= $10.3 billion, and total research= $21.7 billion. 1990 figures are estimates.

SOURCE: National Science Foundation, *Federal Funds for Research and Development, Detailed Historical Tables: Fiscal Years 1955-7990* (Washington, DC: 1990), table A; and National Science Foundation, *Selected Data on Federal Funds for Research and Development: Fiscal Years 1989, 1990 and 1991* (Washington, DC: December 1990), table 1.

Figure 1-2—Doctoral Scientists and Engineers in Academic R&D: 1977-87



NOTE: There was a change in the wording of the National Science Foundation survey questionnaire of academic Ph.D.s in 1987: respondents were asked to identify whether "research" was their *primary or secondary work* activity. This change may have resulted in an artificially large increase from 1985 to 1987 in "academic researchers." Prior to 1987, Ph.D.s in academia were only asked to identify their primary work activity.

SOURCE: National Science Board, *Science & Engineering Indicators-7989,* NSB 89-1 (Washington, DC: U.S. Government Printing Office, 1989), appendix table 5-17 and p. 115.

slightly and leveled off from the late 1960s until the mid-1970s. From 1975 onward, however, Federal research funding again increased, due in large part to the expansion in health and life sciences research.[11]

Along with this increase in research funding, the number of academic researchers grew steadily, perhaps by as much as 60 percent from 1977 to 1987 (see figure 1-2).[12] More generally, from 1980 to 1988, scientists and engineers in the work force grew by an average of 7.8 percent per year, four times the annual rate for total employment.[13] Not surprisingly, the competition for research funds among these scientists and engineers also intensified. By the late

[11] See National Science Foundation, *Federal Funds for Research and Development-Detailed Historical Tables: Fiscal Years 1955-1990* (Washington, DC: 1990). For discussions, see William D. Carey, "R&D in the Federal Budget: 1976- 1990," *Science and Technology and the Changing World Order,* Colloquium Proceedings, Apr. 12-13, 1990, S.D. Sauer (cd.) (Washington, DC: American Association for the Advancement of Science, 1990), pp. 43-51; and Genevieve J. Knezo, "Defense Basic Research Priorities: Funding and Policy Issues," *CRS Report for Congress* (Washington DC: Oct. 24, 1990).

[12] Note, however, that there was a change in the wording of the National Science Foundation Survey questionnaire, which may have resulted in an artificially large increase from 1985 to 1987 in those that identify "research" as their primary or secondary work activity. Prior to 1987, Ph.D.s in academia were only asked to identify their primary work activity. This probably underestimated the number of academic Ph.D. researchers in the United States. See National Science Board, *Science & Engineering indicator.+-1989,* NSB 89-1 (Washington, DC: Congressional Research Service, 1989), app. table 5-17.

[13] Ibid., p. 67.

1980s, researchers supported by the Federal Government had become increasingly restive over funding. Today, many say that their lives as researchers have become more stressful and laden with the paperwork of proposal applications and accountability for awarded finds, inhibiting the creativity and joy of the research process.[14] They cite the declining fraction of meritorious proposals that are funded, new investigators lacking the support to set up independent research groups, and the fear that U.S. students will turn their careers away from academic science and engineering.[15]

Today, because the scientific community has the capability to undertake far more research than the Federal Government supports, policymakers and sponsors of research must continuously choose between competing "goods." (The tensions underlying these choices are summarized in table l-l.) Controversies over the support of younger scientists and established researchers, "have" and "have-not" institutions, and tradeoffs among fields are all manifestations of the consequences of choices perceived by various segments of the "scientific community." [16] Scientific community, as used here, refers to apolitical entity. Like other sectors, science contributes to national goals and competes for Federal resources. At a more practical level, *the* scientific community invoked by Congress and the Presidential Science Advisor refers to a heterogeneity of professional associations, lobby activities, and actual research performers. (These disciplinary or subject-specific divisions and interest groups more accurately correspond to what OTA calls ''research communities.

Additional funding for science and engineering research would certainly be a good investment of Federal resources. There is much that could be done, and many willing and able people and institutions to do it. The focus of this report, however, is not on the level of investment, but on the "Federal research system." As the sum of the research programs and efforts that involve the support of the Federal Government, the "system" is best characterized as the conglomeration of many separate systems, each with constituencies inside and outside of science.[17] How these participants compete, cooperate, and interact in processes of Federal decisionmaking determines *which* research is funded by the agencies and performed by scientists and engineers.

If large increases in the budget were to materialize, it would not necessarily relieve system stresses for long. Additional research funding would certainly allow the pursuit of more scientific opportunities and yield fruitful gains, but it would also enlarge the system and increase the number of deserving competitors for Federal support. Thus, such stresses must be addressed with other policies. In the short term, the government faces a rising budget deficit. Congress has set targets to reduce the deficit and eventually to balance the budget.[18] In this fiscal climate, the research system may not be able to maintain the growth in Federal funding of research that it experienced in the 1980s. Regardless of funding levels, however, issues of management, tiding, and personnel remain.

Given the extraordinary strength of the U.S. research system and the character of scientific research, there will always be more opportunities

[14] *Science: The End of the Frontier?* A report from Leon M. Lederman, President-Elect to the Board of Directors of the American Association fOr the Advancement of Science (Washington, DC: American Association for the Advancement of Science, Jan. 31, 1991).

[15] These were the prominent issues, for example, at the National Academy of Sciences/Institute of Medicine, ''Forum on Supporting Biomedical Research: Near-Term Problems and Options for Action,'' Washington DC, June 27, 1990. Recent discussion has paradoxically focused on the broad field of the life sciences where Federal funding increases have been most generous for the last 15 years. In its initial effort to document change and stress in the Federal research system created by an abundance of research applications, OTA found that an increasing proportion could not be funded by various research agencies due to budget limitations, rather than to deficiencies of quality. U.S. Congress, Office of Technology Assessment, "proposal Pressure in the 1980s: An Indicator of Stress on the Federal Research System,'' staff paper of the Science, Education, and Transportation Program, April 1990.

[16] See Institute of Medicine, *Funding Health Sciences Research: A Strategy to Restore Balance (Washington* DC: National Academy Press, November 1990). For insight into the contentiousness that greeted the Institute of Medicine report, see Peter G. Gosselin, "A Clash of Scientific Titans: Key Groups Battle Over Funds for Medical Projects," *The Washington Post*, Dec. 18/25, 1990, Health section, p. 6.

[17] As one political scientist writes: ". . . because the Federal R&D system is comprised of so many independent actors, each of whom tend to view science and engineering from a relatively narrow perspective, the Federal R&D system proceeds virtually without pl arming and coordination. If it moves , . . it does so . . . oozing slowly and incrementally in several directions at once, with constantly changing boundaries and shape. ' Joseph G. Morone, "Federal R&D Structure: The Need for Change," *The Bridge,* vol. 19, fall 1989, p. 6.

[18] The debt held by the Federal Government recently topped $3.1 trillion, and payments on the debt exceeded $255 billion in fiscal year 1990. These figures are expected to rise significantly in 1991 and 1992, with the costs of the war in the Persian Gulf and the bailouts of the Nation's financial system. For an explanation of the Budget Enforcement Act of 1990, see Lawrence J. Haas, ''New Rules of the Game," *National Journal, vol. 22, No. 46, Nov. 17, 1990, pp. 2793-2797.*

Table I-I—Tensions in the Federal Research System

Centralization of Federal research planning	←→	Pluralistic, decentralized agencies
Concentrated excellence	←→	Regional and institutional development (to enlarge capacity)
“Market” forces to determine the shape of the system	←→	Political intervention (targeted by goal, agency, program, institution)
Continuity in funding of senior investigators	←→	Provisions for young investigators
Peer review-based allocation	←→	Other funding decision mechanisms (agency manager discretion, congressional ear-marking)
Set-aside programs	←→	Mainstreaming criteria in addition to scientific merit (e.g., race/ethnicity, gender, principal investigator age, geographic region)
Conservatism in funding allocation	←→	Risk-taking
Perception of a “total research budget”	←→	Reality of disaggregate funding decisions
Dollars for facilities or training	←→	Dollars for research projects
Large-scale, multiyear, capital-intensive, high-cost, per-investigator initiatives	←→	Individual investigator and small-team, 1-5 year projects
Training more researchers and creating more competition for funds	←→	Training fewer researchers and easing competition for funds
Emulating mentors’ career paths	←→	Encouraging a diversity of career paths
Relying on historic methods to build the research work force	←→	Broadening the participation of traditionally underrepresented groups

SOURCE: Office of Technology Assessment, 1991.

than can be funded, more researchers competing than can be sustained, and more institutions seeking to expand than the prime sponsor—the Federal Government-can fund. The objective, then, is to ensure that the best research continues to be funded, that a full portfolio of research is maintained, and that there is a sufficient research work force of the highest caliber to do the job. This report is designed to support Congress in achieving these goals.

Trends in Federal Research Funding

The research system has shown itself to be remarkably robust over at least the last 30 years, and it has done well with the resources it has received. To develop multiple perspectives on the system, Federal funding can be examined by agency, broad field, and category of recipient.

Figure 1-3 displays Federal funding trends for the six largest research agencies.[19] Since 1973, the Department of Health and Human Services (HHS, largely through the National Institutes of Health—NIH) has supported more research than any other Federal research agency. In fiscal year 1989, HHS supplied nearly twice the research funds of the next largest research agency, the Department of Defense (DOD). HHS and DOD were followed by the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), the National Science Foundation (NSF), and the Department of Agriculture (USDA) .20

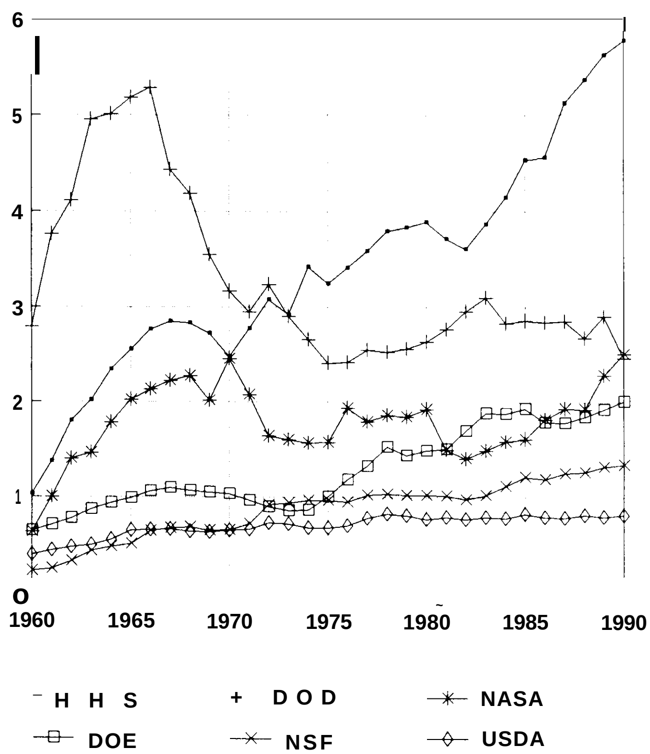
Reflecting the division of research funds by agency and broad field, a 20-year time series is shown in figure 1-4. Life sciences continues its steady growth relative to other broad fields. In fiscal year 1990, life sciences dominated Federal funding at $8.9 billion (in 1990 dollars). Engineering was funded at slightly less than one-half the level of support given to the life sciences ($4.4 billion), as were the physical sciences (roughly $4 billion). Environmental and mathematics/computer sciences were funded at $2.1 and $0.7 billion respectively, and the social sciences together gathered $0.6 billion.

Turning to research performance, universities and colleges in the aggregate are the largest recipients of federally funded research (basic and applied, see

[19]Congress is most interested in comparing research expenditures to other elements of the Federal budget. Thus, a deflator that represents expenditures on products and services that are often bought throughout the United States-a “constant dollar” in the most general sense--is often the most useful for congressional policy analysis. Given the problems with research-specific deflators and the advantage of a general-GNP deflator to compare expenditures across the economy, all constant dollar graphs and tables in this report were calculated with the GNP Implicit Price Deflator for 1982 dollars (see ch. 2).

[20]Note that the order of these agencies would be changed if research and development or basic research were used to rank them. The remaining agencies, not included in the top six, together fund less than 5 percent of the research supported by the Federal Government.

Figure 1-3—Federally Funded Research in the Major Research Agencies: Fiscal Years 1960-90
(in billions of 1982 dollars)

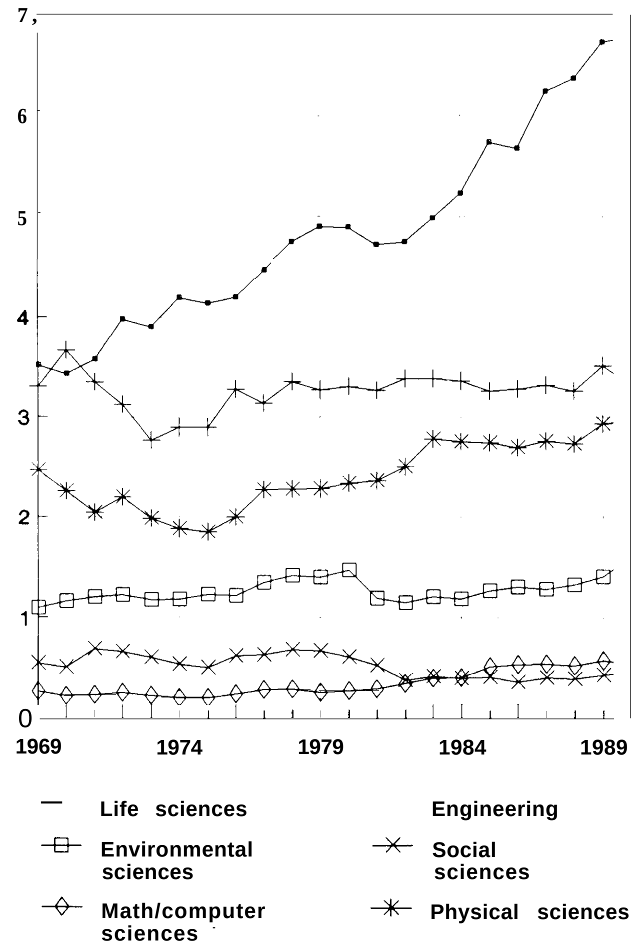


KEY: HHS=U.S. Department of Health and Human Services; DOD=U.S. Department of Defense; NASA= National Aeronautics and Space Administration; DOE=U.S. Department of Energy; NSF= National Science Foundation; USDA=U.S. Department of Agriculture.

NOTE: Research includes both basic and applied. Figures were converted to constant 1982 dollars using the GNP Implicit Price Deflator. 1990 figures are estimates.

SOURCE: National Science Foundation, *Federal Funds for Research and Development, Detailed Historical Tables: Fiscal Years 1955-7990* (Washington, DC: 1990), table A; and National Science Foundation, *Selected Data on Federal Funds for Research and Development: Fiscal Years 1989, 7990 and 1991* (Washington, DC: December 1990), tables 4 and 5.

Figure 1-4-Federally Funded Research by Broad Field: Fiscal Years 1960-90 **(in billions of 1982 dollars)**



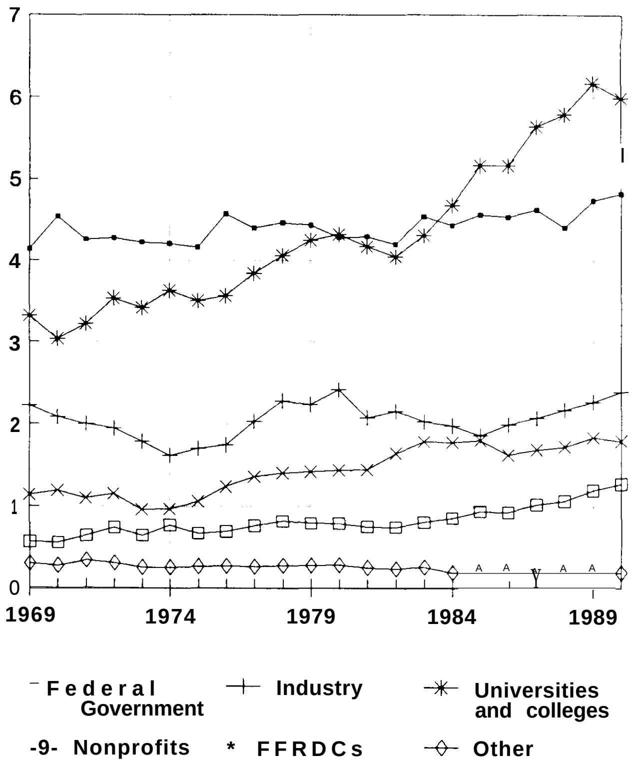
NOTE: Research includes both basic and applied. Fields not included in this figure collectively accounted for $l.1 billion (4.9 percent) of all federally funded research in 1990. Figures were converted to constant 1982 dollars using the GNP Implicit Price Deflator. 1990 figures are estimates.

SOURCE: National Science Foundation, *Federal Funds for Research and Development, Detailed Historical Tables: Fiscal Years 1955-7990* (Washington, DC: 1990), table 25; and National Science Foundation, *Selected Data on Federal Funds for Research and Development: Fiscal Years 1989, 1990 and 1991* (Washington, DC: December 1990), table 1.

figure 1-5). From 1969 to 1990, Federal funding for research at universities and colleges grew from over $4 billion to nearly $8 billion (in constant 1990 dollars). In 1990, performance of research by industry (at over $3 billion) and the Federal laboratories (at over $6 billion) are funded at lower levels. For basic research alone (not shown), universities and colleges are even more clearly the dominant research performer at over $5 billion when compared with Federal laboratories, the next largest basic research performer, at slightly over $2 billion.

The distribution of Federal research and development (R&D) funds has long been a contentious issue—both in Congress and in the scientific community. As shown in figure 1-6, if these funds are aggregated by the State of the recipient institution or laboratory, then five States received 53 percent of the R&D funds in fiscal year 1990 (California,

Figure 1-5—Federally Funded Research by Performer: Fiscal Years 1969-90 (in billions of 1982 dollars)

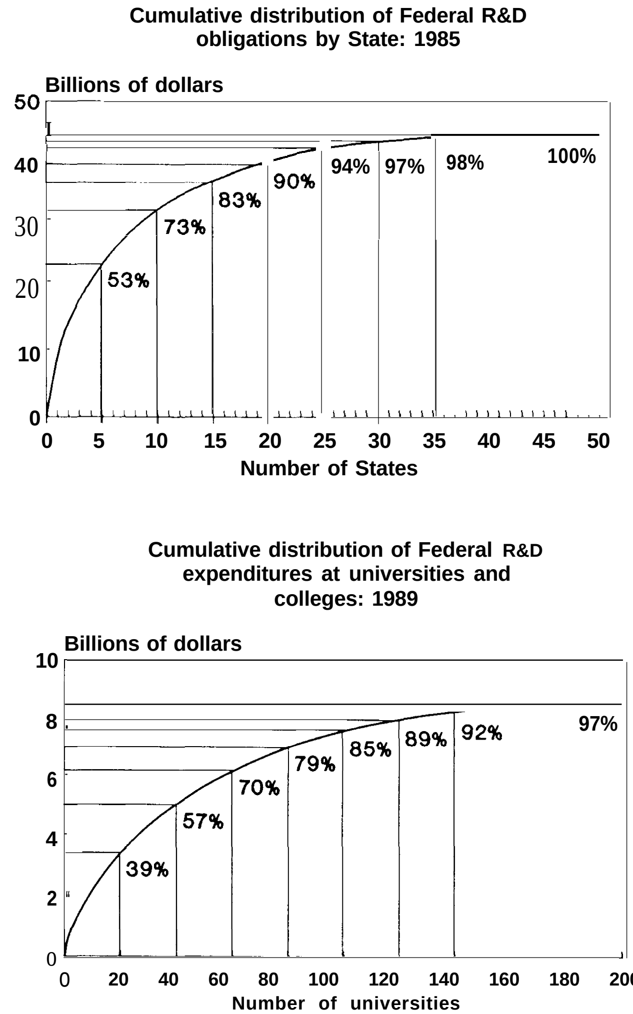


KEY: FFRDCs include all Federally Funded Research and Development Centers that are not administered by the Federal Government. Other includes Federal funds distributed to State and local governments and foreign performers.

NOTE: Research includes both basic and applied. Figures were converted to constant 1982 dollars using the GNP Implicit Price Deflator. 1990 figures are estimates.

SOURCE: National Science Foundation, Federal *Funds for Research and Development, Detailed Historical Tables: Fiscal Years 1955-1990* (Washington, DC: 1990), table 17; and National Science Foundation, *Selected Data on Federal Funds for Research and Development: Fiscal* Years 1989, 1990 and 1991 (Washington, DC: December 1990), table 1.

Figure 1-6—Federal R&D Obligations by State (1985) and at Universities and Colleges (1989)



SOURCE: National Science Foundation, *Geographic Patterns: R&D in the* United *States,* Final Report, NSF 90-316 (Washington, DC: 1990), table B-5; and National Science Foundation, *Se/acted Data on Academic Sdenca/Engineering R&D Expenditures,* Fiscal *Year 1989,* NSF 90-321 (Washington, DC: October 1990), table B-35 and CASPAR database.

Maryland, Massachusetts, New York, and Virginia).[21] (Research institutions are also not randomly dispersed across America; rather, they are concentrated on the two coasts and the upper midwest.) At the other end of the distribution, 15 States together received less than 2 percent of the funds. At the institutional level, 10 universities receive 25 percent of the Federal research funding,

[21] These figures are presented for research and development because figures for research alone are not available. Based on 1984 data, the General Accounting Office found various patterns of concentration among performers: researchers in 10 States submitted over one-half of the proposals to the National Science Foundation and the National Institutes of Health, supplied almost 60 percent of the proposal reviewers, and won over 60 percent of the awards. See U.S. General Accounting Office, *University Funding: Patterns of Distribution of Federal Research Funds to Universities* (Washington, DC: February 1987), p. 43. These figures, however, ignore other relevant factors in judging the "fair" distribution of Federal research funds, such as the total population of a State and the number of scientists and engineers living in it. No matter how fair the competitive process, the outcomes may still be seen as "unfair." Also see William C. Boesman and Christine Matthews Rose, "Equity, Excellence, and the Distribution of Federal Research and Development Funds, " *CRS Report for Congress* (Washington, DC: Congressional Research Service, Apr. 25, 1989).

and only 30 universities account for 50 percent. Funding is concentrated in 100 research universities in 38 States. This reflects their importance to the Nation's research enterprise.

These data on the distribution of resources bear a critical message: research capabilities-institutions and people—take time to grow. It is not *simply a* matter of ''they who have, get. '' The reputation, talent, and infrastructure of research universities attract researchers and graduate students.[22] Some universities become assets not only in the production of fundamental knowledge, but also in bridging science and technology to other goals such as State and regional economic development.

Federally Funded Research in the 1990s

Snapshots of federally funded research, comparing fiscal years 1980 and 1991, are provided in table 1-2. Research is a small portion of the total Federal budget. Although the distribution of research funds by agency sponsor, category of performer, and stratum of academic institution has hardly changed during this period, the activity has never been in greater demand.

However, questions such as "Does the Nation need more science?' and "How much research should the Federal Government support?' have no ready answers. Measures of distress and conflicts over resource allocation within the scientific community do not address whether the Nation needs more science. Other problems in the Federal research system do not derive from, but are exacerbated by, such stress. They include sparse participation by women and ethnic minorities in science, indications that other nations are better able to capitalize on the results of U.S. research than American industry, and management problems that have plagued many Federal research agencies. Only some of these problems can be addressed solely by the Federal Government, and long-term solutions may not be found in adjusting Federal funding levels. Rather, they reflect problems in the organization and management of research and competing values within the scientific community .23

"How much is enough" depends on the goals of the research system (see box l-A). The system by definition takes on new goals, each of which can be evaluated. But in the aggregate how these goals are assimilated-by add-on or substitution-is not easily predicted. The challenge is not to determine what fraction of the Federal budget would constitute appropriate funding for scientific research. Rather, OTA finds that under almost any plausible scenario for the level of research funding in the 1990s, there are issues of planning, management, and progress toward national goals to address.

Because the reach of science is now great, decisions about the funding of research are intertwined with many Federal activities. Congress and the executive branch, which make these decisions in our form of government, will continue to wrestle with scientific and other national priorities, especially those that help prepare for tomorrow's science—renewing human resources throughout the educational pipeline and building regional and institutional capacity. History cautions against the expectation that the scientific community will set priorities across fields and research areas. Congress must instead weigh the arguments made within each area against desired national outcomes.

In the 1990s, the Federal research system will face many challenges. OTA has organized them here under four interrelated issues: 1) setting priorities for the support of research; 2) understanding research expenditures; 3) adapting education and human resources to meet the changing needs of the research work force; and 4) refining data collection, analysis, and interpretation to improve Federal decisionmaking. (For a summary of issues and possible congressional responses, see table 1-3.) To craft public policies for guiding the system, each issue is outlined in the following discussion.

[22] Institutions, like the faculty researchers employed by them, accumulate ''tivmmge. '' Among the many factors that influence Federal research funding, institutional reputation is part of a cycle of credibility that gives investigators an edge in competition for scarce resources-the very resources that strengthen the institution as a productive research performer, which builds more credibility, and so on. See Robert K. Merton, "The Matthew Effect in Science, II: Cumulative Advantage and the Symbolism of Intellectual Property," *Isis*, vol. 79, No. 299, 1988, pp. 606-623.

[23] See Joshua Lederberg, ''Does Scientific Progress Come From Projects or People?' *Current Contents*, vol. 29, Nov. 27,1989, pp. 4-12. In this report, OTA concentrates on Federal, especially agency, perspectives on research. Performer (researcher and institutional) responses to changes in Federal policies and programs were included to broaden understanding of the Federal rolvis-a-vis *academic* research, since universities are the primary site for research performance and most data are collected on universities. However, national laboratories and industry play targeted roles and figure prominently in research funding decisions.

Table 1-2—Federally Funded Research in the 1980s and 1990s (in percent)

		Fiscal year 1980	Fiscal year 1991 (est.)
R&D as percent of total Federal budget		5.0	4.7
Total research as percent of Federal R&D		38.9	36.3
Basic researches percent of Federal R&D		15.7	19.1
Basic researches percent of total Federal budget		0.8	0.9
	Agency	**Fiscal year 1980**	**Fiscal year 1991 (est.)**
Percent of total (basic) research funds distributed, by agency	HHS/NiH	29/24(38/35)	34/29(40/37)
	DOD	20(12)	15(8)
	NASA	14(12)	16(15)
	DOE	11(11)	12(14)
	NSF	8(17)	9(15)
	USDA	6(6)	5(5)
	Other	7(4)	lo(4)
	Performer	**Fiscal year 1980**	**Fiscal year 1991 (est.)**
Percent of total (basic) research funds, by performer	Universities	32 (50)	36 (47)
	Federal	32 (25)	30 (23)
	industry	18 (7)	15 (9)
	Nonprofits	6 (6)	8 (9)
	FFRDCs[a]	11 (11)	11 (12)
	Ranking	**Fiscal year 1980**	**Fiscal year 1988**
Percent distribution of Federal R&D funds at academic institutions	Top 10	25	25
	Top 20	40	39
	Top 50	68	65
	Top 100	84	85

KEY: DOD=U.S. Department of Defense; DOE=U.S. Department of Energy; FFRDC=Federally Funded Research and Development Center; USDA=U.S. Department of Agriculture; NSF-National Science Foundation; HHS/NIH=U.S. Department of Health and Human Services/National Institutes of Health; NASA= National Aeronautics and Space Administration

aThe category of FFRDCs includes all Federally Funded Research and Development Centers that are not administered by the Federal Government.

NOTE: R& D data are based on Federal obligations; calculations involving the total Federal budget are based on outlays. Columns may not sum to 100 percent due to rounding.

SOURCES: Office of Technology Assessment, 1991, based on National Science Foundation data; U.S. General Accounting Office data; Economic *Report of the President* (Washington, DC: U.S. Government Printing Office, 1991); and *Budget of the United States Government: Fiscal Year 7992* (Washington, DC: U.S. Government Printing Office, 1991).

Issues and Options for Congress

ISSUE 1: Setting Priorities in the Support of Research

Summary

Priorities are **set** throughout the Federal Government at many levels. At the highest level, research priorities are compared to conscience and nonengineering needs. At the next level, priorities are set across research fields, such as biomedicine and mathematics. Within fields, agency programs reflect research opportunities in subfields and relevance to national needs. Finally, research projects are compared, ranked, and awarded Federal funds.

Although priority setting occurs throughout the Federal Government, it falls short in three ways. First, criteria used in selecting various areas of research and megaprojects are not made explicit and vary widely from area to area. This is particularly true, and particularly a problem, at the highest levels of priority setting, e.g., in the President's budget and the congressional decision process. Second, there is currently no mechanism for evaluating the total research portfolio of the Federal Government in terms of progress toward many national objectives, although recent efforts by the Office of Science and Technology Policy have lead to some cross-agency planning, budgeting, and evaluation. Third, the principal criteria for selection, scientific merit and mission relevance, are in practice coarse filters. Con-

Box I-A—How Much is Enough?

''How much is enough money for research?' is a question that can only be asked if it is clear what scientific and engineering research in the United States is attempting to accomplish: research for what?

1. Is the primary goal of the Federal research system to fund the projects of all deserving investigators of natural and social phenomena?
   If so, then there will always be a call for more money, because research opportunities will always outstrip the capacity to pursue them.
2. Is it to educate the research work force, or the larger science and engineering work force, needed to supply the U.S. economy with skilled labor?
   If so, then support levels can be gauged by the need for more technically skilled workers. Preparing students throughout the educational pipeline will assure an adequate supply and diversity of talent.
3. Is it to promote economic activity and build research capacity throughout the United States economy by supplying new ideas for industry and other entrepreneurial interests?
   If so, then the support should be targeted in line with our efforts to pursue applied research, development, and technology transfer.
4. Is it all of the above and other goals besides?
   If so, then some combination of these needs must be considered in allocating Federal support.

Indicators of stress and competition in the research system do not address the question of whether science needs more funding to do more science. Rather, they speak to the organization and processes of science and to the competitive foundation on which the system is built and that sustains its vigor.

Education, economic activity, and other national goals have long been confronted by Congress and the executive branch, Although the relative importance of these needs varies over time with new developments and crises, their absolute importance has not been set. Thus, allocating resources to these needs has always been a tradeoff, within a limited budget, against other national goals and the programs that embody them.

Because of its intrinsic merit and importance to the Nation, research has consistently been awarded funding increases. But these do not compare to what some claim would be an appropriate level of funding for research to pursue a full agenda of opportunities. Deciding if the Nation is pursuing enough research opportunities or if the Nation needs more science is thus a complicated question, which requires that other decisions about the nature of the research system and its goals be settled first. Table 1A-1 reports the costs of some potential science initiatives as estimated in the late 1980s.

Table 1A-1—Sample Requests From the Research Community for Increased Funding

Field or agency	Report or intiative	Additional funds requested[a]
NSF	Initiative to double the NSF budget	$2.1 billion
NASA space science	Towards a New Era in Space: Realigning U.S. Policies to New Realities[b]	Over $1 billion
Neuroscience	1990s Decade of the Brain Initiatlve[c]	Over $1 billion
USDA research grants	Investing in Research[d]	$0.5 billion
Behavioral and social sciences	The Behavioral and Social Sciences: Achievements and Opportunities[e]	$0.26 billion
Mathematical sciences	Renewing U.S. Mathematics[f]	$0.12 billion
All academic research	Science: The End of the Frontier?[g]	Over $10 billion

KEY: NSF-National Science Foundation; NASA-National Aeronautics and Space Administration; USDA-U.S. Department of Agriculture

[a]Adjustd to 1990 dollars using the 1982 GNP Implicit Price Deflator.

[b]National Academy of Sciences/National Academy of Engineering, Committee on Space Policy, "Towards a New Era in Space: Realigning U.S. Policies to New Realities," *Space Policy*, vol. 5, August 1989, pp. 237-255.

[c]"Brain Decade' Neuroscientists Court Support," *The Scientist*, vol. 4, No. 21, Oct. 29, 1990, p. 8.

[d]National Research Council, *Investing in Research* (Washington, DC: National Academy Press, 1989).

[e]National Research Council, *The Behavioral and Social Sciences: Achievements and Opportunities* (Washington, DC: National Academy Press, 1988).

[f]National Research Council, *Renewing U.S. Mathematics: A Plan for the 1990s* (Washington, DC: National Academy Press, 1990).

[g]*Science: The End of the Frontier?* a report from Leon M. Lederman, President-Elect to the Board of Directors of the American Association for the Advancement of science (Washington, DC: American Association for the Advancement of Science, Jan. 31, 1991).

SOURCE: Office of Technology Assessment, 1991.

Table 1-3--Summary of Issues and Possible Congressional Responses

Issue	Possible congressional responses
Setting priorities for research	Hearings on crosscutting priorities and congressional designation of a body of the Federal Government to evaluate priority setting. Application of criteria to: a) promote education and human resources, b) build regional and institutional capacity in merit-based research decisionmaking, and c) balance little science and megaproject initiatives. Oversight of agency research programs that focuses on strategies to fulfill the above criteria, and on responses to priority setting.
Coping with changing expenditures for research	Encouragement of greater rest-accountability by the research agencies and research performers (especially for indirect costs, megaprojects, and other multiyear initiatives). Allowance for the agencies to pursue direct cost containment measures for specific items of research budgets and to evaluate the effectiveness of each measure.
Adapting education and human resources to meet future needs	Programs that focus investment on the educational pipeline at the K-1 2 and undergraduate levels. Attention to diversity in the human resource base for research, especially to the contributions of underparticipating groups. Incentives for adapting agency programs and proposal requirements to a changing model of research (where teams are larger, more specialized, and share research equipment and facilities).
Refining data collection and analysis to improve research decision making	Funding to: a) augment within-agency data collection and analysis on the Federal research system, and b) increase use of research program evacuation at the research agencies. Encouragement of data presentation and interpretation for use in policymaking, e.g., employing indicators and other techniques that measure outcomes and progress toward stated objectives.

SOURCE: Office of Technology Assessment, 1991.

cerns for developing human resources and building regional and institutional capacity must also be considered; these criteria strengthen future research capability. While not every project or agency will factor these criteria equally, the total Federal research portfolio must address these concerns.

Priority-setting mechanisms that cut across research fields and agencies, and that make selection criteria more transparent, must be strengthened in both Congress and the executive branch. Congressional oversight must evaluate the total Federal research portfolio based on national objectives, research goals, and agency missions. In the executive branch, Congress should insist, at a minimum, on iterative planning that results in: a) setting priorities among research goals, and b) applying (after scientific merit and program relevance) other criteria to research decisionmaking that reflect planning for the future. In addition, since megaproject costs affect the ability of other disciplines to start new, large projects, megaprojects are candidates for crosscutting priority setting.

Discussion

Priority setting can help to allocate Federal resources both when they are plentiful, as they were in the 1960s, and when they are scarce, as expected through the early 1990s.[24] Governance requires that choices be made to increase the benefits and decrease the risks to the Nation. Priority setting occurs throughout the Federal Government at many levels. At the highest level, research priorities are compared to conscience and nonengineering needs. At the next level, priorities are set across research fields, such as biomedicine and mathematics. Within fields, agency research programs reflect research opportunities in subfields and relevance to national needs. Finally, research projects are compared, ranked, and awarded Federal funds.

[24] Congress recognized the importance of priority setting in the National Science and Technology Policy, Organization and Priorities Act of 1976 (Public Law 94-282), May 11, 1976. For an elucidation of the dilemmas inherent in priority setting, especially comparisons between "social merit" and ''scientific merit, ' see A.M. Weinberg, *Rejections on Big Science* (Cambridge, MA: MIT Press, 1966). Also see Stephen P. Strickland, *Research and the Health of Americans* (Lexington, MA Lexington Books, 1978).

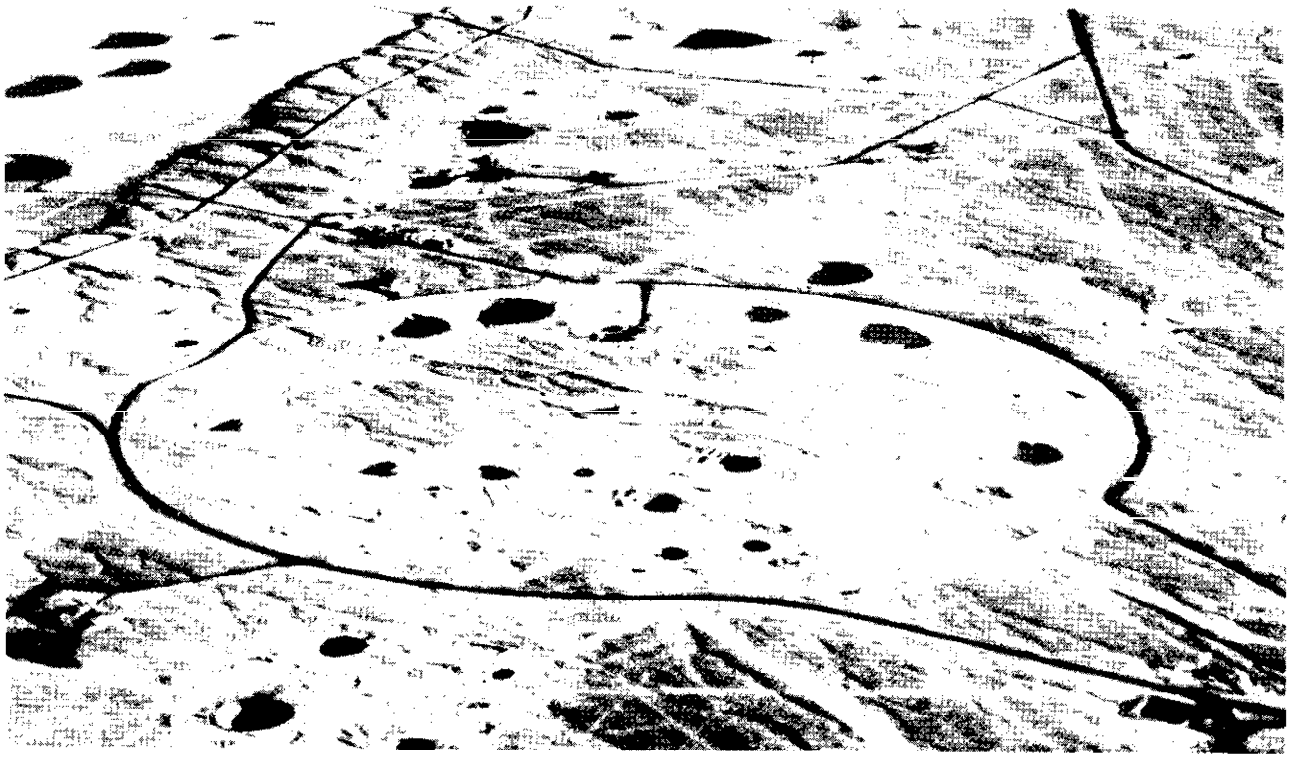


Photo credit: Department of Energy

Underground nuclear test craters dot Yucca Flat at the Nevada Test Site (NTS). In addition to nuclear testing, researchers at NTS explore other scientific phenomena such as geologic and seismic problems.

Toward More Explicit Priority Setting

There are three problems with priority setting as it is currently practiced in the Federal Government. First, criteria used in selecting various areas of research and megaprojects are not made explicit, and vary widely from area to area. This is particularly true, and particularly a problem, at the highest levels of priority setting+. g., in the President's budget and the congressional decision process. The best developed priority-setting mechanisms are within the research agencies and at the agency program level.

Second, there is currently no mechanism for evaluating the total research portfolio of the Federal Government in terms of progress toward many national objectives. Research priorities must be considered across the Federal research system, and in particular, across the Federal agencies. What the Federal Government values more or less in research can be inferred in part from the Federal budget, but there is no "research budget." Federal support is distributed across many executive agencies and falls under the jurisdiction of a number of congressional committees and subcommittees (see table 1-4). Therefore, once allocations have been made to agencies (by the Office of Management and Budget-OMB) or to appropriations subcommittees (by full appropriations committees), decisions are made independently within narrow components of what is after-the-fact called the research budget. This hampers the implementation of crosscutting comparisons by Congress.

During the 1980s, OMB was a surrogate for a crosscutting agent, with Congress adding its own priorities through budget negotiations.[25] Recent efforts by the Office of Science and Technology Policy (OSTP) have lead to cross-agency planning, budgeting, and evaluation in certain research and education areas. President Bush has invested more power in OSTP to participate with OMB in delibera-tions over research spending, especially in targeted

[25]For an overview, see Elizabeth Baldwin and Christopher T. Hill, "The Budget Process and Large-Scale Science Funding," *CRS Review*, February 1988, pp. 13-16.

Table 1-4-Congressional Authorization Committees and Appropriations Subcommittees With Significant Legislative Authority Over R&D

Jurisdictions of authorization committees: [a]	Agency
House:	
Agriculture	USDA
Armed Services	DOD, DOE
Energy and Commerce	DOE, ADAMHA, NIH, CDC, DOT
Interior and Insular Affairs	DOI
Science, Space, and Technology	NASA, NSF, DOE, EPA, NOAA, DOT NIST DOI
Public Works and Transportation	NOAA, DOT
Merchant Marine and Fisheries	USDA, NOAA, DOT
Veterans' Affairs	VA
Foreign Affairs	A.I.D.
Senate:	
Agriculture, Nutrition, and Forestry	USDA
Armed Services	DOD, DOE
Commerce, Science, and Transportation	NSF, NASA, DOT NOAA, NIST
Energy and Natural Resources	DOE, DOI
Labor and Human Resources	NIH, ADAMHA, CDC, NSF
Environment and Public Works	EPA
Veterans' Affairs	VA
Foreign Relations	A.I.D.

Jurisdictions of appropriations committees: [a]	Agency
Labor, Health and Human Services, Education and Related Agencies	NIH, ADAMHA, CDC
HUD and Independent Agencies	NASA, NSF, EPA, VA
Energy and Water Development	DOE
Interior and Related Agencies	DOE, USDA, DOI
Agriculture, Rural Development, and Related Agencies[b]	USDA
Commerce, Justice, State, the Judiciary, and Related Agencies	NOAA, NIST
Transportation and Related Agencies	DOT
Foreign Operations	A.I.D.
Defense	DOD

KEY: ADAMHA=Alcohol, Drug Abuse, and Mental Health Administration; A.I.D.=Agency for International Development; CDC=Centers for Disease Control; DOD=U.S. Department of Defense; DOE=U.S. Department of Energy; DOI=U.S. Department of the Interior; DOT=U.S. Department of Transportation; EPA=U.S. Environmental Protection Agency; HUD=U.S. Department of Housing and Urban Development; NASA=National Aeronautics and Space Administration; NIH=National Institutes of Health; NIST=National Institute of Standards and Technology; NOAA=National Oceanographic and Atmospheric Administration; NSF= National Science Foundation; USDA=U.S. Department of Agriculture; VA=U.S. Department of Veterans Affairs.

[a]The jurisdictions of the authorizing committees are not exclusive. For this table, repeated authorization of a number of R&D-related programs was required to establish jurisdiction.

[b]The corresponding subcommittees of the Senate and House Committees on Appropriations have the same name with one exception: the Senate Subcommittee on Agriculture, Rural Development, and Related Agencies and the House Subcommittee on Rural Development, Agriculture, and Related Agencies.

SOURCES: Office of Technology Assessment, 1991; and Elizabeth Baldwin and Christopher T. Hill, "The Budget Process and Large-Scale Science Funding," *CRS Review,* February 1988, p. 15.

Presidential priority areas such as high-performance computing, global environmental change, and mathematics and science education.[26] Since the Administration is moving in the direction of more centralized and coordinated priority setting, it is all the more important for Congress to consider priority-setting mechanisms as well.

Third, although scientific merit and mission relevance must always be the chief criteria used to judge a research area or agency program's potential worth, they cannot always be the sole criteria. In particular, the application of criteria that augment scientific merit-which represent *today's* judgments of quality-would help meet ***tomorrow's***

[26]The clearest public statement of executive branch priorities is contained in "Enhancing Research and Expanding the Human Frontier," *Budget of the United States Government, Fiscal Year* 1992 (Washington, DC: U.S. Government Printing Office, 1991), pp. 35-76. The ground rules for setting crosscutting priorities through the Office of Science and Technology Policy, Federal Coordinating Council on Science, Engineering, and Technology Committee mechanism are detailed in the Office of Management and Budget (OMB) "terms of reference" memoranda (provided to OTA project staff during an interview with Robert E. Grady, Associate Director, Natural Resources, Energy, and Science, and other OMB staff, Feb. 7, 1991.

Box 1-B-Criteria for Research Decisionmaking in Agency Programs

Within agency research programs, research proposals have traditionally been selected for support on the basis of expert peer or program manager judgments of scientific merit and program relevance. Many Federal agencies are now finding that the introduction of other explicit criteria is important for research decisionmaking.[1]

For example, the National Science Board (NSB) established the following criteria for the selection of research projects by the National Science Foundation (NSF): 1) research performer competence, 2) intrinsic merit of the research, and 3) utility or relevance of the research. In addition, NSB included 4) the". . . effect of the research on the infrastructure of science and engineering. This criterion relates to the potential of the proposed research to contribute to better understanding or improvement of the quality, distribution, or effectiveness of the Nation's scientific and engineering research, education, and manpower base. "[2]

Under this fourth criterion, NSF includes:

> . . . questions relating to scientific, engineering, and education personnel, including participation of women, minorities, and disabled individuals; the distribution of resources with respect to institutions and geographical area; stimulation of high quality activities in important but underdeveloped fields; support of research initiation for investigators without previous Federal research support as a Principal Investigator or Co-Principal Investigator and interdisciplinary approaches to research or education in appropriate areas.[3]

In short, this criterion defines the bases for using other criteria in addition to scientific merit in mainstream allocations of research funds, and within set-aside programs, Set-aside programs, at NSF and elsewhere, underscore the continuing need for ''sheltered competitions' for researchers who do not fare well in mainstream disciplinary programs.[4]

As acknowledged by NSB, although scientific merit and program relevance must always be the primary criteria used to judge a research program or project's potential worth, they cannot always be the only criteria. For most of today's research programs, there are many more scientifically meritorious projects than can be funded. Proposal

[1] OTA interviews, Spring -summer 1990.

[2] Quoted in National Science Foundation, *Grants for Research and Education in Science and Engineering: An Application Guide*, NSF 90-77 (Washington, DC: August 1990), pp. 8-9.

[3] Ibid., p. 9.

[4] OTA finds that, in some programs at the National Science Foundation (NSF), the fourth criterion is not strongly heeded relative to the other three criteria in the merit review process (OTA interviews, spring-summer, 1990). NSF faces the impossible task of being all things to all people. The organic act entrusts it with the support of the Nation's basic research and science education. In the academic institutions that form NSF's core clientele these activities are not pursued in the same way or with the same vigor. Every research program at NSF now impacts on human resources for science and engineering. This should remain foremost in mind when weighing policies for research programs.

objectives of research investment. Broadly stated, there are two such criteria: strengthening education and human resources at all stages of study (e.g., increasing the diversity and versatility of participants); and building regional and institutional capacity (including economic development by matching Federal research support with funds from State, corporate, and nonprofit sources).

Education and human resources criteria would weigh research initiatives on their ''production' of new researchers or technically skilled students. Contributions to human resources include increasing participation in the educational pipeline (through degree completion), the research work force, and the larger science and engineering work force. Regional and institutional capacity criteria would weigh research initiatives on their contribution to under-participating regions and institutions. Regional and institutional capacity are important concerns in all Federal finding, and encouraging new institutional participants and development of research centers strengthens the future capacity and diversity of the research system. Some agency programs already incorporate these criteria in *project* selection (see box 1-B).

Can Congress look to the scientific community for guidance on setting priorities? The short answer is ''no. ' Congress wishes—perhaps now more than ever—that the scientific community could offer priorities at a macro level for Federal funding. Science Advisor Bromley and former Science Advisor Press have stated criteria and categories of review could thus bean iterative process. First, a pool of proposals could be identified based on scientific merit and program relevance, and those with exceptional human resources and/or research infrastructure potential so indicated. The program manager, with or without the advice of expert peers, can then pick a balanced subset from the pool. Any of several subsets might be equally meritorious-+.his is where selection criteria and judgment enter the process. The result is a program research portfolio that can be reshaped in succeeding years.

OTA suggests that two broad criteria could be applied to research project selection: strengthening education and human resources, and building regional and institutional capacity. How might these two additional criteria be rated in research proposals?

- Education and human resources criteria would weigh proposals on their future **production** of new researchers or technically skilled students. Outcome measure s would relate to undergraduate education, graduate training, and characteristics of new Ph.D. s--the number and quality of those entering graduate study and the research work force, respectively.

  Contributions to human resources include increasing participation in the educational pipeline (through degree completion), the research work force, and the larger science and engineering work force. **With the** changing character of the student population, tapping the diversity of traditionally underrepresented groups in science and engineering (e.g., women and U.S. minorities) is vital for the long-term health of the research work force.
- *Regional and institutional capacity* criteria would weigh proposals on their contribution to underparticipating regions and institutions. Outcome measures would include the enhanced research competitiveness of funded institutions; State, local, and private participation in the support of the research infrastructure; and an enlarged role in training and employment in targeted sectors, industries, and fields.

  Regional and institutional capacity are important concerns in all Federal finding, reflecting the interests of taxpayers. While the major research universities are exemplary in their production of research, untapped resources could be developed in other types of educational institutions throughout the United States.[5]

Funding research to achieve all of these objectives will remain a prerogative of Congress. But decisions that add tomorrow criteria to May's, especially in the review of project proposals at the research agencies, will expand the capability of the Federal research system.

[5] If the Federal Government wishes to augment the economic health of a particular region, supporting research m that area is one means of achieving it. "Spin-offs" from research centers have traditionally improved local economies by encouraging development of technical industries and local research infrastructures. They also often contribute to local educational efforts and directly provide technical jobs for residents. See U.S. Congress, Office of Technology Assessment, *Higher Education for Science and Engineering*, *OTA-TM-SET-52* (Washington, *DC:* Us. Gov ernment Printing Office, March 1989).

priority that they consider essential for science.[27] Each emphasizes the separation of large projects requiring new infrastructure from ''small science. ' Press further distinguishes human resources from national crises and extraordinary scientific breakthroughs, whereas Bromley places national needs and international security concerns above all else.[28]

While the Press and Bromley formulations appear to provide frameworks for priority setting, they do not address the problem that there are few mechanisms for, and no tradition of, ranking research topics across fields and subfields of inquiry. In addition, priority setting is often resisted by the recipients-of Federal funding because it orders the importance of research investments, which means that some programs do not get funded and some groups within the scientific community complain of lack of support. Consequently, Congress and the executive branch have found that the scientific community cannot make crosscutting priority decisions in science. In particular, the traditional mechanism of peer review is clearly not suited to making judgments across scientific fields. Some research communities do set priorities *within* specific research areas. However, the practice is not universal

[27] See Frank Press, ''The Dilemma of the Golden Age," *Congressional Record, May 26, 1988,* pp. E1738-E1740; and D. Allan Bromley, "Keynote Address," in Sauer, op. cit., footnote 11, p. 11. (This was augmented by "U.S. Technology Policy, " issued by the Executive Office of the President Office of Science and Technology Policy, Sept. 26, 1990).

[28] One effect of these rank-orders is the seeming creation of separate accounts, i.e., that choices could be made within each category and then across categories. Of course, such choices are being made by various participants in the research system simultaneously.

or widespread.[29] Therefore, while recognizing the preferences of researchers, the Federal Government must set priorities at two levels: among scientifically meritorious research areas and megaprojects, and among agency programs.

Megaprojects and the Science Base

Key to the consideration of allocating public funds for science and engineering research is the simultaneous support of little and big science. Little science is the backbone of the scientific enterprise, and a diversity of research programs abounds. Not surprisingly, many investigators and their small teams shudder at the thought of organizing Federal science funding around a principle other than scientific merit-an approach that, in fact, is advocated by no one. They fear that setting priorities would change the criteria by which research funds are awarded. In particular, they seem to hear calls for priority setting as calls to direct ***all*** of research along specified lines, not as a means to assure that balance is achieved. For example, one goal would certainly be the maintenance of funding for a diverse science research base,[30] while other goals would include training for scientists and engineers, and supplying state-of-the-art equipment.

The Federal" Government also seeks to achieve goals at many levels. These goals are likely to differ between programs that pursue specific objectives and those that seek primarily to bolster the science base. For instance, the allocation of additional monies to NIH for AIDS (acquired immunodeficiency syndrome) research, beginning in the late 1980s and continuing today, has been a clear designation of an objective as a priority research area. In addition, to enhance the science base in specific research areas, such as environmental science and high-temperature superconductivity, the Bush Administration has increased funding in certain fields. These increases, however, seem to be dwarfed by the cost of a very few, but visible, megaprojects.

Megaprojects are large, "lumpy," and uncertain in outcomes and cost. Lumpy refers to the discrete nature of a project. Unlike little science projects, there can be almost no information yield from a megaproject until some large-scale investment has occurred. Presumably, a successful science megaproject provides knowledge that is important and unattainable by any other means. Because of the large expenditures and long timeframes, many science megaprojects are supported by large political constituencies extending beyond the science community .31 Future decisions may center on ranking science megaprojects, since not all of them may be supportable without eroding funding of the science base (see figure 1-7).

There are few rules for selecting and funding science megaprojects; the process is largely ad hoc. From a national perspective, megaprojects stand alone in the Federal budget and cannot be subject to priority setting within a single agency. Nor can megaprojects be readily compared. For example, the Superconducting Super Collider (SSC) and the Human Genome Project (HGP) are not big science in the same sense. One involves construction of one large instrument, while the other is a collection of smaller projects .32

An issue raised about some megaprojects is their contribution to science. For instance, the Space Station has little justification on scientific grounds,[33] especially when compared with the SSC, the HGP, or the Earth Observing System, which have explicit scientific rationales. On purely scientific grounds, the benefits that will derive from investing in one project are often incommensurable with those that would be derived from investing in some other.[34]

29For examples, see the National Research Council, *Renewing U.S. Mathematics: A Plan for the 1990s* (Washington, DC: National Academy Press, 1990); and the National Research Council,*The Behavioral and Social Sciences: Achievements and Opportunities* (Washington, DC: National Academy Press, 1988).

30This priority has been preeminent since the Federal support of research began. See House Committee on Science and Technology, op. cit., footnote 9.

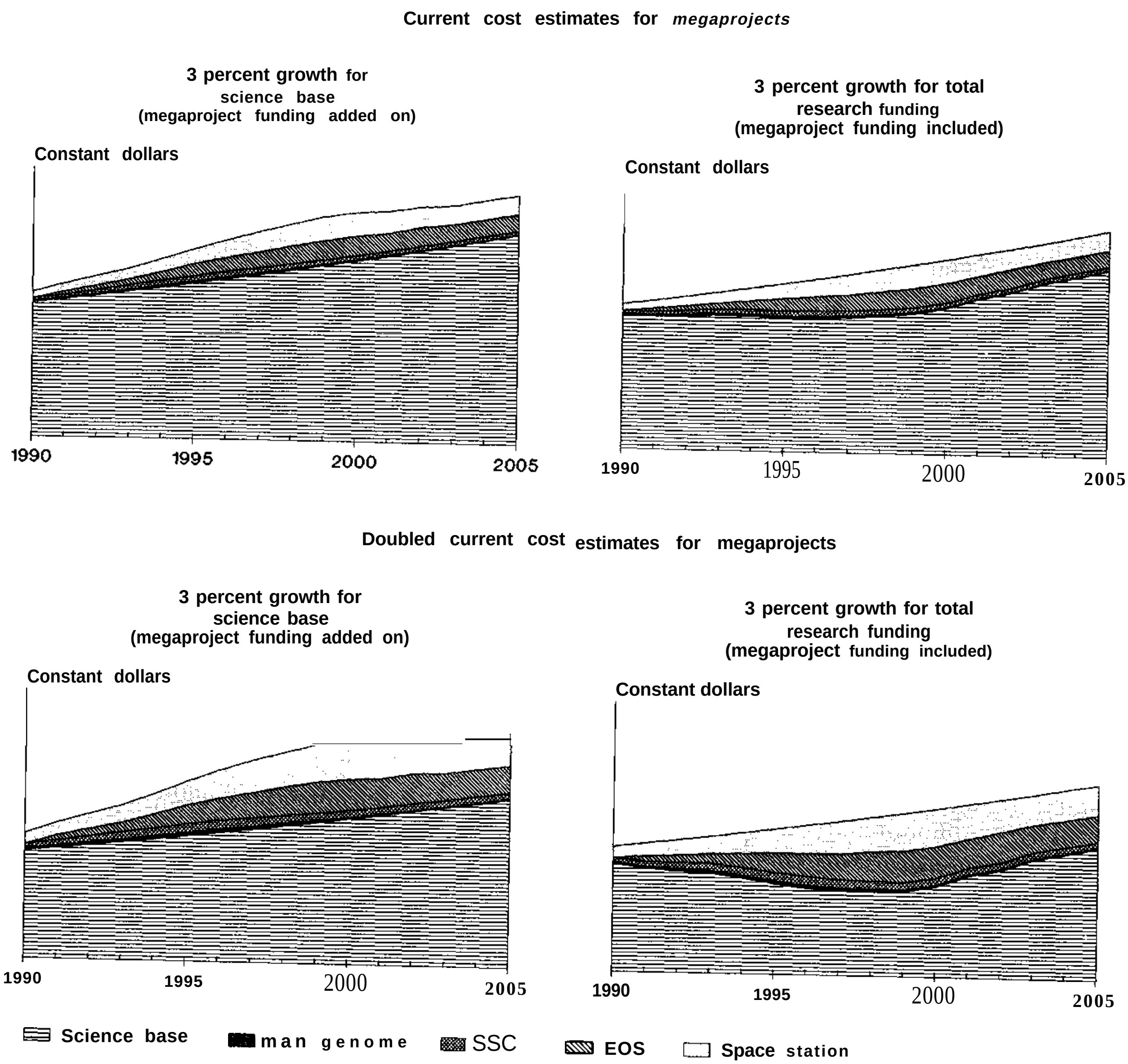
31Phil Kuntz, ''Pie in the Sky: Big Science Is Ready for Blastoff,'' *Congressional Quarterly,* Apr. 28, 1990, pp. 1254-1260.

32The research supported b, the Human Genome Project—HGP—may have some scientific benefits before the project is complete. Thus, HGP may not be big science in the strict sense of thedefinition outlined above. See TomShoop, "Biology's Moon Shot, " *Government Executive,* February 1991, pp. 10-11, 13, 16-17.

33For an early statement of this view, see U.S. Congress, Office of Technology Assessment, *Civilian Space Stations and the U.S. Future in Space,* OTA-STI-241 (Springfield, VA: National Technical Information Service, November 1984).

34This is elaborated in Harvey Averch, ''Analyzing the Costs of Federal Research,'' OTA contractor report, August 1990. Also see J.E. Sigel et al., "Allocating Resources Among AIDS Research Strategies," *Policy Sciences, vol. 23, No.* 1, February 1990, pp. 1-23.

Figure 1-7—Cost Scenarios for the Science Base and Select Megaprojects: Fiscal Years 1990-2005



KEY: SSC=Superconducting Super Collider; EOS=Earth Observing System.

NOTE: These figures are schematic representations of projected costs for science projects. In the figures on the left, the *science base* is projected to *grow* at an annual rate of 3 percent above inflation. In the figures on the right, *total Federal research funding* is projected to grow 3 percent above inflation. The cost estimates for the megaprojects are based on data from "The Outlook in Congress for 7 Major Big Science Projects," *The Chronicle of Higher Education,* Sept. 12, 1990, p. A28, and Genevieve J. Knezo, Congressional Research Service, Science Policy Research Division, "Science Megaprojects: Status and Funding, February 1991," unpublished document, Feb. 21, 1991.

SOURCE: Office of Technology Assessment, 1991.

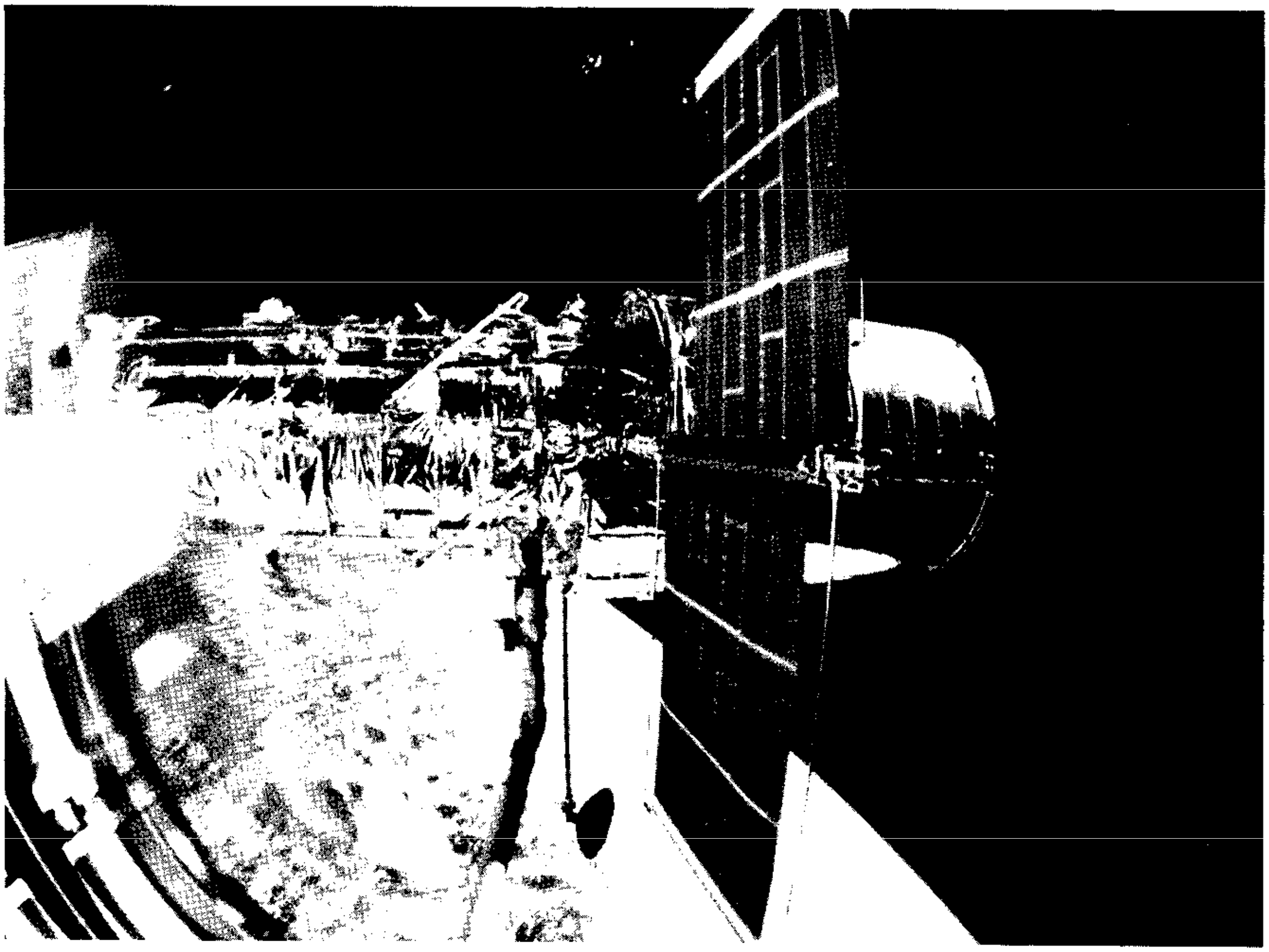


Photo credit: National Aeronautics and Space Administration

The Hubble Space Telescope (HST) is shown, still in the grasp of Space Shuttle Discovery, with only one of two solar panels extended. Earth is some 332 nautical-miles away. HST is an example of a large scientific mission at NASA.

However, because the problem of selecting among science megaprojects has most in common with the selection of complex capital projects, timeliness (why do it now rather than later?) and scientific and social merit must all be considered, as well as economic and labor benefits. At present, for example, the Space Station has considerable momentum as an economic and social project.

Other measures to evaluate and, if necessary, compare megaprojects include the number and diversity of researchers that can be supported, the scientific and technological value of information likely to be derived (i.e., the impact of the megaproject on the research community), and the ultimate utility of the new equipment and/or facility. For instance, if one project will support only a few researchers, while a second of similar cost and scientific merit will support a larger number of researchers, then perhaps the second should be favored. One might also expect preference for megaprojects that can be cost-shared internationally over those that cannot be. (Issues of costs in megaprojects are discussed below.)

Once the context for priority setting is examined, choices take on another dimension. What do U.S. society and the Federal Government expect for their research investment? What does the scientific community promise to deliver? The answers differ among participants and over time. As Robert White, President of the National Academy of Engineering, states: “It may be time that we think about whether our concern for the support of the science and technology enterprise has diverted us from attention to how we can best serve national needs. “3[5]

Congressional Priority Setting

Since progress begets more opportunities for research than can be supported, setting research priorities may be imperative for shaping a successful Federal research portfolio in the 1990s.[36] To improve priority setting at a macro level, Congress should hold biennial hearings specifically on the state of the research system, including cross-field priorities in science and engineering, and the criteria used for decisionmaking within the cognizant research agencies.

For “objective-oriented” science and engineering that may or may not cross agencies, such as high-temperature superconductivity research, Congress should allocate resources based on plans to attain specific goals. In programs that seek primarily to fortify the science base, such as those sustained by NSF, Congress could judge progress toward goals that reflect the research capacity of the scientific community. While objective-oriented programs will contribute to these goals, the burden falls largely on science base programs to meet the goal of maintaining the research community. Congressional oversight of the research agencies could include questions of how their total research activities and specific programs, such as multiyear, capital-intensive megaprojects, contribute to expanding education and human resources, as well as to building regional and institutional capacity.

If Congress determines that more thorough and informed priority setting is required, the executive branch must disclose the criteria on which its priorities were set. OSTP is a candidate for this task. Building on the Federal Coordinating Council for Science, Engineering and Technology (FCCSET) mechanism, which presently considers only certain cross-agency research topics, OSTP could also initiate broader priority setting. In the executive branch, Congress should insist, at a minimum, on iterative planning that results in: a) making tradeoffs among research goals; and b) applying (after scientific merit and program relevance) other criteria to research decisionmaking that reflects planning for the future. In addition, since megaproject costs affect the ability of other disciplines to start new, large projects, megaprojects are candidates for crosscutting priority setting.[37]

Structural improvements to current priority setting, especially those that facilitate the budget process and research planning within and across the agencies, would also make the tradeoffs more explicit and less ad hoc, and the process more transparent. At a minimum, agency crosscutting budgetary analysis[38] and a separate congressional cycle of priority-setting hearings (e.g., biennially) could reduce uncertainty and reveal the relationships among new and continuing projects, the support of new investigators by each agency, and the changing cost and duration estimates that currently bedevil all participants in the Federal research system.

Congress could also initiate specific changes in the executive agencies that would increase their ability to respond to changing priorities. They would include measures that encourage: 1) flexibility, so that programs can be more easily initiated, reoriented, or terminated; 2) risk-taking, so that a balanced portfolio of mainstream and “long-shot” research can be maintained; 3) strategic planning, so that agency initiatives can be implemented as long-term goals; 4) coordination, so that crosscutting priorities can be pursued simultaneously in many agencies; and 5) experimentation with finding allocation methods, so that new criteria can be introduced into project selection and evaluated to ascertain the value added to decisionmaking.

It is symbolic that across the Federal research system, national policymakers, sponsors, and performers alike have acknowledged that the funding process would benefit from careful consideration of

[35]Robert M. White, “Science, Engineering, and the Sorcerer’s Apprentice,” Presidential Address to the National Academy of Engineering, Washington DC, Oct. 2, 1990, p. 12.

[36]Brooks writes, ‘‘Today many of the same negative signals that existed in 1971 are again evident. Will science recover to experience anew era of prosperity as it did beginning in the late seventies, or has the day of reckoning that so many predicted finally arrived?’ Harvey Brooks, “Can Science Survive in the Modern Age? A Revisit After Twenty Years,’ *National Forum,* vol. 71, No. 4, fall 1990, p. 33.

[37]For example, see Alissa Rubin, ‘‘Science Budget: Hill Must Make Hard Choices Among Big-Money Projects,” *congressional Quarterly* ***Weekly Report,*** **vol. 49, Feb. 9, 1991, p. 363.**

[38]This was a principal recommendation proposed in National Academy of Sciences, op. cit., footnote 6.

research priorities, especially at the macro level.[39] Whether their exhortations lead to clearer research agendas (including the suspension or postponement of some activities) remains to be seen, and whether these investments are balanced, well-managed, and yield the desired consequences is hard to judge in real time. But surely the policy process is enriched by drawing a map of the choices, the benefits, and the costs to be incurred by the scientific community and the Nation.

ISSUE 2: Understanding Research Expenditures

Summary

Many in the scientific community claim that the "costs of doing research" are rising quickly, especially that the costs of equipment and facilities outpace increases in Federal research funding. The most reliable data are available from research agencies, and can be analyzed at two levels: 1) total Federal expenditures for research, and 2) individual components of research project budgets. OTA finds that Federal expenditures for research have risen faster than inflation, and more researchers are supported by the Federal Government than ever before. Salaries and indirect costs account for the largest and fastest growing share of these expenditures. However, these findings do not truly address the claims expressed above, because of the numerous and sometimes inconsistent meanings of the costs of doing research.

Most research activities become cheaper to complete with time, as long as the scope of the problem and the standards of measurement do not change. However, advances in technology and knowledge are ''enabling' they allow deeper probing of more complex scientific problems. Experiments are also carried out in an environment driven by competition. While competition is part of the dynamic of a healthy research system, competition drives up demand for tiding, because success in the research environment often correlates highly with the financial resources of research groups.

Direct cost containment by the research agencies may not be an appropriate Federal role, although Congress might direct the agencies to pursue specific measures at their discretion and to evaluate their effectiveness. Instead, greater cost-accountability could be encouraged by the executive branch and Congress. In particular, the Federal Government should seek to eliminate the confusion around allowable indirect costs, and develop better estimates of future expenditures, especially for megaprojects where costs often escalate rapidly.

Discussion

Many researchers state as an overriding problem that the ''costs of doing research" have risen much faster than inflation in the Gross National Product (GNP), and Federal expenditures for research have not kept pace with these rising costs. Included in the costs of research are salaries, benefits, equipment, facilities, indirect costs, and other components of research budgets. Equipment and facilities are typically named as most responsible for increased costs.[40]

However, addressing these claims is difficult, because it is hard to define what is meant by the costs of doing research. Research activities become cheaper to complete with time, as long as the scope of the problem and the standards of measurement do not change. But this is not the way progress is made. Advances in technology and knowledge are "enabling' they allow deeper probing of more complex problems. This is an intrinsic challenge of research.

There is an extrinsic challenge as well. Experiments are carried out in an environment that is driven by competition. Competition is part of the dynamic of a healthy research system. One sign of a

[39] In addition to those cited previously, see Robert M. Rosenzweig, President, Association of American Universities, ''Ad&ess to the President's Opening Session, The Gerontological Society of America, " 43rd annual meeting, Boston, MA, Nov. 16, 1990; John H. Dutton and Lawson Crowe, "Setting Priorities Among Scientific Initiatives, " *American Scientist,* vol. 76, No. 6, November-December 1988, pp. 599-603; Albert H. Teich, ''Scientists and Public Officials Must Pursue Collaboration To Set Research Priorities,' *The Scientist, vol. 4, No. 3,* Feb. 5, 1990, pp. 17; and Tina M. Kaarsberg and Robert L. Park, "Scientists Must Face the Unpleasant Task of Setting Priorities, "*The Chronicle of Higher Education, vol. 37, No. 23,* Feb. 20, 1991, p. A52.

[40] See Janice Long, "Bush's Science Advisor Discusses Declining Value of R&D Dollars," *Chemical & Engineering News, vol. 68, No. 17,* Apr. 23, 1990, pp. 16-17; Science: *The End of the Frontier?,* op. cit., footnote 14; and OTA interviews at the University of Michigan and Stanford University, July-August 1990.

healthy research system is that it can expand to produce more research. "Needs" in the research environment are thus open-ended.

Although competition exists in the research community, it does not necessarily drive down costs, as would be expected in typical "markets." In an earlier era, the chief cost of research was the annual salary of the principal investigator (PI). Today, the PI is often the head of a team with many players and access to the latest research technologies. In the face of inherent uncertainty about the eventual outcomes of research,[41] sponsors must apply various criteria in predicting the likelihood of eventual project success, such as access to sophisticated equipment or the availability of appropriately trained personnel. These criteria are often associated with higher rather than lower costs. Success, therefore, often comes to those who spend the most (especially if research teams are relatively evenly matched). In fact, competitive proposals are often the most expensive and low bids can actually ***decrease*** a proposer's chance of winning a grant. Because additional personnel and sophisticated equipment are seen by sponsors as being instrumental in the conduct of research, costs are ultimately limited by what sponsors are willing to spend.

Products, or ''outputs,'' of scientific research have also traditionally defied measurement.[42] Consequently, the price of research measured in economic terms-the cost per-unit output-is extremely difficult to estimate. Analysis using crude measures of scientific "productivity' suggests that the cost of producing a published paper or performing a given scientific measurement has *decreased: with* less than double the investment per year since 1965, more than double the number of papers are published today in academia, and more than double the number of Ph.D. scientists are employed in the academic sector.[43] By these measures, science has grown more productive (and consequently the cost per-unit output of research has decreased).[44] However, there is no metric to compare a ''unit' of today's research with one in the past.

Thus, 'Are the costs of research going up?' is not a useful question for policy purposes. Research expenditures by the Federal Government are awarded and accounted for on an annual basis. What gets included in these expenditures can be modified by adjusting the scale and pace of scientific research. Especially for basic research, these factors are variable, though the competition for personal and institutional recognition pushes PIs toward larger teams and more sophisticated instrumentation. In mission-oriented science, the rate of research maybe dictated by pressing concerns (e.g., curbing the AIDS epidemic is desired as quickly as possible).

For policy purposes, research costs equal expenditures: if the Federal Government provides more finds, ''costs'' will go up accordingly. A more useful policy question might be: ''Is Federal spending on individual components of research project budgets reasonable?' The Federal Government will tend to have a different point of view on this question from the research performer. OTA has explored both perspectives.

Incomplete and murky data on research expenditures complicate questions on the costs of research. Analysis of Federal expenditures for the conduct of research must factor what Federal agencies are willing to spend for personnel, facilities, and instrumentation, while analysis of expenditures by research performers is confounded by the expenditure accounting schemes that vary from research institu-

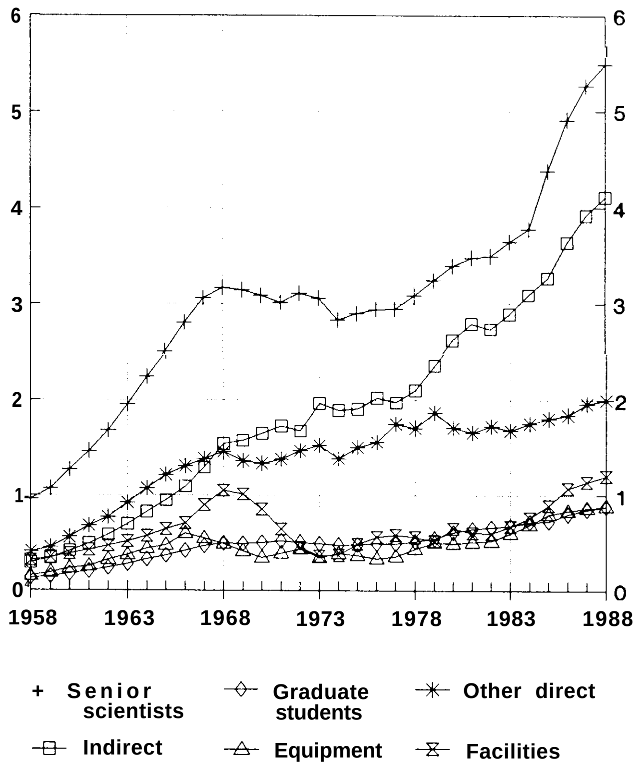
41 See, for example, Richard Nelson, ''The Allocation of Research and Development Resources: Some Problems of Public Policy," *Economics Of Research and Development*, Richard Tybout (cd.) (Columbus, OH: Ohio State University Press, 1965), pp. 288-308. Nelson points out that". . . research and development has economic value because the information permits people to do things better, and sometimes to do things that they did not know how to do before. . . [but] there is no simple way to evaluate the benefits society can expect from the knowledge created by different kinds of R&D. . . ." (pp. 293-294). Also see Mansfield, op. cit., footnote 3.

42 Published papers and patents have been used as proxies, but they cannot be standardized. See Susan E. Cozzens, ''Literature-Based Data in Research Evaluation: A Manager's Guide to Bibliometrics,'' final report to the National Science Foundation Sept. 18, 1989.

43 On the former, see H.D. White and K.W. McCain, ''Bibliometrics, " *Annual Review of Information Science and Technology,* vol. 2A, 1989, pp. 119-186; and on the latter, National Science Board, op. cit., foomote 12, tables 5-17 and 5-30.

44 However, even if one acccepts these definitions of research output, the productivity of research relative to other economic activities might still be stagnant. Economist William Baumol explains that research, due to the price of labor rather than increases in its productivity, has an " . . . inherent tendency to rise in cost and price, persistently and cumulatively, relative to the costs and prices of the economy's other outputs. " He warns that". . . the consequence may be an impediment to adequate funding of R&D activity, that is, to a level of funding consistent with the requirements of economic efficiency and the general economic welfare. " See W.J. Baumol et al., *Productivity and American Leadership: The Long View* (Cambridge, MA: MIT Press, 1989), ch. 6, quotes from pp. 116, 124.

Figure 1-8-Estimated Cost Components of U.S. Academic R&D Budgets: 1958-88 (In billions of 1988 dollars)



SOURCE: Government-University-Industry Research Roundtable, *Science and Technology in the Academic Enterprise: Status, Trends and/Issues,* (Washington, DC: National Academy Press, 1989), figure 2-43.

NOTE: Constant dollars were calculated using the GNP Implicit Price Deflator.

DEFINITION OF TERMS: Estimated personnel costs for *senior scientists* and *graduate students* include salaries and fringe benefits, such as insurance and retirement contributions. *Other direct* costs include such budget items as materials and supplies, travel, subcontractors, computer services, publications, consultants, and participant support costs. *Indirect* costs include general administration, department administration, building operation and maintenance, depredation and use, sponsored-research projects administration, libraries, and student-services administration. *Equipment* costs include: 1) reported expenditures of separately budgeted current funds for the purchase of research equipment, and 2) estimated capital expenditures for fixed or built-in research equipment. *Facilities* costs include estimated capital expenditures for research facilities, including facilities constructed to house scientific apparatus.

DATA: National science Foundation, Division of Policy Research and Analysis. Database: CASPAR. Some of the data within this database are estimates, incorporated where there are discontinuities within data series or gaps in data collection. Primary data source: National science Foundation, Division of Science Resource Studies, "Survey of Scientific and Engineering Expenditures at Universities and Colleges"; National Institutes of Health; American Association of University Professors; National Association of State Universities and Land Grant Colleges.

tion to research institution.[45] In addition, much of the current debate over rising expenditures takes place within a context of agency budget constraints and pressures felt by research performers.

The most reliable data on Federal research expenditures are available from research agencies, and can be analyzed at two levels: 1) total Federal expenditures for research, and 2) individual components of research project budgets. OTA finds that total expenditures on individual components of grants have risen over inflation, but not nearly at the rate for total Federal expenditures for research (see figure 1-8). Instead, growth in the size of the research work force supported by the Federal Government seems to account for the largest increase in Federal research expenditures. Also, the largest component increases of research project budgets are for salaries and indirect costs.

Trends in Components of Total Federal Research Expenditures

Analyzing Federal expenditures for specific line items of research budgets reveals interesting trends (again see figure 1-8). First, reimbursements for indirect costs are the fastest growing portion of Federal research expenditures. Indirect costs is a term that stands for expenses that research institutions can claim from the Federal Government for costs that cannot be directly attributed to a single research project, i.e., they are distributed over many investigators who share research infrastructure and administrative support. Federal support for indirect costs has increased since the 1960s, with the largest increases in the late 1960s and the 1980s. In 1958, indirect cost billings comprised 10 to 15 percent of Federal academic R&D funding. By 1988, that share had risen to roughly 25 percent.[46] In addition, some agencies allow more than other agencies in indirect costs. For example, in 1988, the indirect cost as a percent of the total R&D expenditures allowed at

[45] For an attempt to compare expenditures at two public and two private universities associated with the performance Of National Science Foundation-funded research, see G.W. Baughman, ' 'Impact of Inflation on Research Expenditures of Selected Academic Disciplines 1%7-1983," report to the National Science Foundation and the National Center for Educational *Statistics,* NSF/PLN 8017815, Nov. 8, 1985. Also see Daniel E. Koshland, "The Underside of overhead,' *Science,* vol. 249, May 11, 1990, p. 3; and 'The Overhead Question,'' letters in response to Koshland's editorial, Science, vol. 249, July 6, 1990, pp. 10-13.

[46] National Science Foundation, *The State of Academic Science and Engineering* (Washington, DC: 1990), p. 121.

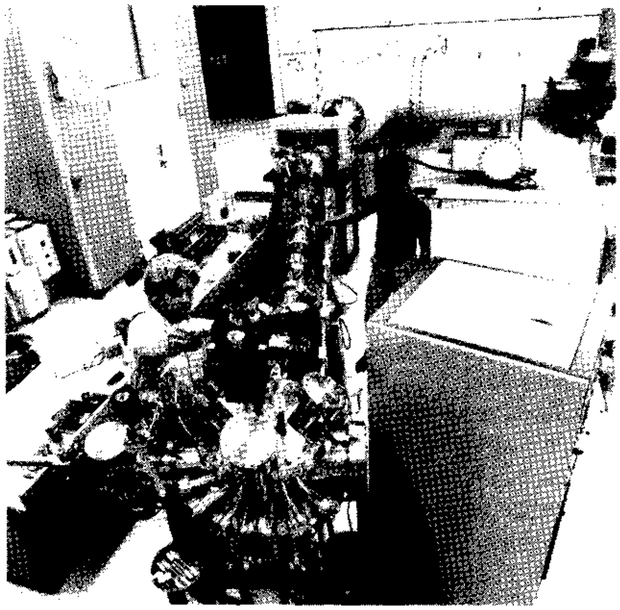


Photo credit: Bob Kalmbach, University of Michigan

These scientists are in an ion beam laboratory at the University of Michigan. Research often requires state-of-the-art equipment.

NIH was 30 percent, whereas it was less than 24 percent for NSF (a proportion unchanged since the mid- 1980s).[47]

Second, increasing numbers of investigators and rising salaries (and the benefits that go with them) have driven up the price of the personnel component of direct costs. University personnel speak of the increased competition for faculty with other sectors of the economy, and note that faculty salaries have been rising significantly over inflation during the last decade. The average total compensation (salaries and benefits) for academic Ph.D,s in the natural sciences and engineering increased from $59,000 (1988 dollars) in 1981 to more than $70,000 in 1988. In the same period, the number of full-time equivalent scientists and engineers employed in academic settings rose steadily from about 275,000 to almost 340,000.4

Third, Federal support for *academic* research equipment alone increased from $0.5 billion in 1968 (1988 dollars) to $0.9 billion in 1988. Despite pronounced increases and improvements in equipment stocks in the 1980s, 36 percent of department heads still describe their equipment as inadequate (to conduct state-of-the-art research). This is in part due to the reduction in the obsolescence time of equipment and instrumentation use since the late 1970s.[49]

Finally, the Federal share of all capital expenditures for *academic* facilities (which include both research and teaching facilities) has never topped one-third. Now it is less than 10 percent.[50] For university *research* facilities alone, the Federal Government provided an estimated 11 and 16 percent, respectively, of private and public university capital expenditures in 1988-89. The government also supports research facilities through depreciation, operation, and maintenance charges accounted for in the indirect cost rate. In 1988, the Federal Government supplied nearly $1 billion to support university infrastructure. Almost 20 percent was for facilities depreciation, while the rest was recovered for operation and maintenance costs.[51]

Academic administrators claim that with growing frequency, aging laboratories and classroom buildings falter and break down,[52] and many claim that facility reinvestment has not kept pace with growing needs. However, the. picture is not clear. For example, when asked by NSF, a majority of the research administrators and deans at the top 50

[47] Ibid., p. 142; and Association of American Universities, *Indirect Costs Associated With Federal Support of Research on University Campuses: Some Suggestions for Change* (Washington, DC: December 1988).

[48] Government-University-Industry Research Roundtable, *Science and Technology in the Academic Enterprise: Status, Trends, and Issues* Washington DC: National Academy Press, October 1989), pp. 2-34 and 2-47, based on National Science Foundation data.

[49] National Science Foundation, *Academic Research Equipment in Selected science/Engineering Fields: 1982-83 to 1985-86*, SRS 88-D1 Washington, DC: June 1988).

[50] For public universities, 50t060percent of the facilities funds come from the States, and 30 percent from bond issues. For private universities, roughly one-third comes from the Federal Government, while another one-third is from donations. See Michael Davey, *Bricks and Mortar: A Summary and Analysis of Proposals to Meet Research Facilities Needs on College Campuses* (Washington, *DC: Congressional* Research Service, 1987).

[51] Over the period 1982 to 1988, the Federal support of university infrastructure grew by over 70 percent in real terms. These figures are presented in "Enhancing Research and Expanding the Human Frontier," op. cit., footnote 26, pp. 61-62. The document further states that: "Each academic institution must provide a certification that its research facilities are adequate (to perform the research proposed) as a condition of accepting research grants." The . . . $12 billion of needed, but unfunded capital projects. . . ." reported in the National Science Foundation surveys of universities . . has not had an apparent effect on the ability of universities to accept Federal research funds. '

[52] Karen Grassmuck, "Colleges Scramble for Money to Reduce Huge Maintenance Backlog, Estimated to Exceed $70 Billion; New Federal Help Seen Unlikely," *The Chronicle of Higher Education, vol. 37, No. 6,* Oct. 10, 1990, pp. Al, A34.

research universities replied that their facilities were "good to excellent," whereas a majority of the research administrators and deans in the schools below the top 50 estimated that their facilities were ''fair to poor.' '[53]

The crux of the facilities problem is that research and academic centers can always use new or renovated buildings, but how much is enough? Even though "need" may not be quantified in the different sectors of the research enterprise, a demand certainly exists. For example, when NSF solicited proposals for a $20 million program in 1989 to address facilities needs, it received over 400 proposals totaling $300 million in requests.[54]

Federal Policy Responses to Increased Demand

Many Federal agencies have experimented with grant-reducing measures, such as the salary caps required by Congress and temporarily imposed by NSF and NIH, the ceilings on indirect costs currently in place at USDA, the elimination of cost-blind reviews of proposals in some research programs at NIH, the limitation of funds supplied in new grants to researchers with multiple Federal grants at the National Institute of General Medical Sciences, and the institution of freed-price grants in some NSF programs.[55] Congress could pursue permanent grant-reducing measures to slow or limit increases in research expenditures on individual research grants. However, it may not be an appropriate Federal role to dictate specific allowable costs in research projects. In general, allowing market forces to determine costs has been a tradition in Federal policy.

Instead, greater cost-accountability could be encouraged. One benefit of cost-accountability could be incentives for performers to spend less than what was targeted in project budgets, and greater flexibility in expenditures for performers (e.g., researchers could be encouraged to use the money saved one year in the next year, a so-called no-cost extension). Within such cost-accountability measures, Congress might also direct the agencies to experiment with cost-containment schemes and to evaluate their effectiveness.

Greater cost-acountability is especially important in the calculation of indirect cost rates. At present, the guidelines for calculating costs are detailed in conjunction with OMB Circular A-21 and have been in force since 1979. Every major research university has an indirect rate established for the current fiscal year for recovery of costs associated with sponsored research. These rates have evolved over many years as a result of direct interaction and negotiation with the cognizant Federal agency. There is a wide range of indirect costs rates among universities, with most noticeable differences between public and private institutions (rates tend to be higher at private institutions). Rates vary because of: 1) significant differences in facilities-related expenditures, 2) underrecovery by some universities, 3) imposition of limits by some government agencies in the negotiation process, and 4) diversity in assigning component expenditures as direct or indirect.[56]

However, confusion around what is contained in the indirect cost rate is getting worse, not better. This reflects, in part, the difficulty of separating expenditures along lines of research, instruction, and other functions.[57] Recent investigations by the Office of Naval Research and the House Committee on Energy and Commerce have also uncovered significant variation in the accounting of indirect costs by the cognizant Federal agencies and research universities.[58] These differences should be sorted out, and more explicit and understandable guidelines devised.

[53] National Science Foundation, *Scientific and Engineering Research Facilities at Universities and Colleges: 1988,* NSF *88-320* (Washington, DC: September 1988), p. 26.

[54] See Jeffrey Mervis, "Institutions Respond in Large Numbers to Tiny Facilities Program aNIH, NSF," *The Scientist,* vol. 4, No. 8, Apr. 16,1990, p. 2.

[55] For a discussion of various options, see Barbara J. Culliton, ''NIH Readies Plan for Cost Containment,'' *Science*, vol. 250, Nov. 30, 1990, pp. 1198-1 199; and Colleen Cordes, "Universities Fear That U.S. Will Limit Payments for Overhead Costs Incurred by Researchers," *The Chronicle of Higher Education, vol. 37, No. 3, Nov. 21,* 1990, pp. A19, A21.

subassociation of American Universities, op. Cit., footnote 47.

[57] Eleanor C. Thomas and Leonard L. Lederman, National Science Foundation, Directorate for Scientific, Technological, and International Affairs, "Indirect Costs of Federally Funded Academic Research,'' unpublished paper, Aug. 3, 1984, p. 1.

[58] See Marcia Barinaga, ''Stanford Sails Into a Storm,'' Science, vol. 250, Dec. 21, 1990, p. 1651; "Government Inquiry,'' *Stanford Observer,* November-December 1990, pp. 1, 13; Colleen Cordes, ''Conceding 'Shortcomings,' Stanford To Forgo $500,000 in Overhead on U.S. Contracts," *The Chronicle of Higher Education,* Jan. *30, 1991,* vol. *37, No. 20,* pp. A19, A22; and Colleen Cordes, ''Stanford U. Embroiled in Angry Controversy on Overhead Charges, ' *The Chronical of Higher Education,* Feb. 6, 1991, vol. 37, No. 21, pp. Al, A20-A21.

It is also important to stress accuracy in developing estimates of costs for megaprojects. When the Federal Government ''buys'' a megaproject, the initial investment seems to represent a point of no return. Once the go, no-go decision has been made at the national level, the commitment is expected to be honored. However, criteria for consideration in the funding of a science megaproject could conceivably include: startup and maintenance costs, cost of unanticipated delay, cost of users' experiments, and likely changes in the overall cost of the project from initial estimate to completion. Some estimates for science megaprojects double before the construction is even begun, and costs of operating a big science facility once it is completed are sometimes not considered.[59]

Megaprojects will always be selected through a political process because of their scale, lumpiness, and incommensurability. Since their costs, especially in following years, affect other disciplines' abilities to start new, large projects, megaprojects could well be considered as candidates for crosscutting, priority-setting analysis *before the* practical point of no return. As the National Academy of Sciences' report on budget priorities reminds: "... it is necessary to specify the institutions, individuals, and organizations that will be served; [and] the costs . . . of the program."[60] The cost of investment for the Federal Government is an important criterion to apply to all scientific research, including megaprojects.

Performer Expectations

Not all problems in research costs can be addressed by the Federal Government. Many researchers point to higher expectations, which require more spending, and competition in the university environment. In the academic environment, researchers are asked today to publish more papers, shepherd more graduate students, and bring in more Federal funding than their predecessors.[61] If they do not meet these expectations, some report a sense of failure.[62] This is true even if they have succeeded, but not by as much or as quickly as they had hoped.

To boost research productivity and to compete with other research teams, faculty attempt to leverage their time with the help of postdoctoral fellows, nontenure track researchers, and graduate students who are paid lesser salaries. Due to the shortage of faculty positions for the numbers of graduate students produced, young Ph.D.s have been willing to take these positions in order to remain active researchers. This availability of ''cheap labor" is seen by many senior researchers and their institutions as the only way they can make ends meet in competing for grants.[63] This is a trend toward an ''industrial model, ' where project teams are larger and responsibilities are more distinct within the group.[64] While the expenditures charged to an *individual* grant may be less (since more grants may be required to support the diverse work of the group), the overall cost of supporting a PI and the larger group are greater.[65]

Some experiments have been attempted on U.S. campuses to temper the drive for more research publications (as a measure of productivity). For example, at Harvard Medical School, faculty are allowed to list only five publications for consideration in tenure reviews, with similar numbers set for

59For example, see K*@ op. cit., footnote 31; and David P. Hamilton, ''The SSC Takes on a Life of Its Own,'' *Science*, vol. 249, Aug. 17, 1990, pp. 371-372.

60National Academy of Sciences, op. cit., footnote 6, p. 11.

61This is especially true in entrepreneurial research areas such as biotechnology. See Henry Etzkowitz, ''Entrepreneurial Scientists and Entrepreneurial Universities in American Academic Science," *Minerva*, vol. 21, summer-autumn 1983, pp. 198-233.

62*Science: The End of the Frontier? Op. Cit.*, footnote 14.

63Labor economist Alan Fechter, Executive Director, Office of Scientific and Engineering Personnel, National Research Council, writes: ''... personnel costs constitute roughly 45 percent of total costs and . . . this percentage has remained reasonably stable over time. Given that salaries of faculty (i.e., principal investigators) have been rising during the 1980s, this suggests that the staffing pattern of research projects has been changing, with the input of PIs decreasing relative to . . . other, less expensive resources. There is some evidence to support this hypothesis in the report of GUIRR [Government-University-Industry Research Roundtable] . . . [that] finds in academia an increasing ratio of nonfaculty to faculty," personal communication, Nov. 15, 1990. See Government-University-Industry Research Roundtable, op. cit., footnote 48.

64Elsewhere this has been called the ''industrialization' of science, Or ''~. . a new *collectivized* form in which characteristics of both the academic and industrialized modes are intermingled. ' See John Ziman, *An Introduction to Science Studies* (Cambridge, England: Cambridge University Press, 1984), p. 132 (elaborated below).

65Noted at OTA Workshop on the Costs of Research and Federal Decisionmaking, July 19, 1990.

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other promotions.[66] Thus, the quality and 'importance of the candidate's selected set of papers is stressed, though measuring these characteristics remains controversial.[67] However, strong incentives militate against reducing research volume. Most overhead is brought into the university by a small number of research professors. (At Stanford, 5 percent of the faculty bring in over one-half of the indirect cost dollars.) Any measure that would reduce grant awards and publications produced by these investigators would deprive the university of revenues. In fact, many universities in tight financial straits try to ***maximize the*** level of research volume.[68]

The Federal Government must seek to understand better the trends in expenditures in the research environment-specially variations across institutional settings-and craft government policies to allocate resources effectively. Reliable analyses of research expenditures at all of the Federal agencies are not available. Future studies of expenditures should look not only at the economic forces that increase (and decrease) research expenditures, but also at the sociology of research organizations, including the demography of research teams and institutional policies for sponsored projects.[69]

Federal agencies clearly must understand increasing demands to fund research, as research universities and laboratories are an invaluable resource for the United States. Devising mechanisms for coping with research expenditures is one of the central challenges to the Federal system for funding research in the 1990s.

ISSUE 3: Adapting Education and Human Resources To Meet Changing Needs

Summary

Three issues are central to education and human resources for the research work force:

1. Recent projections of shortages of Ph.D. researchers in the mid-1990s have spurred urgent calls to augment Ph.D. production in the United States. OTA believes **that the likeli**hood of these projections being realized is overstated, and that these projections alone are poor grounds on which to base public policy. For instance, they assume continued growth in demand in both academic and industrial sectors, independent of the level of Federal funding. In both this and previous OTA work, however, OTA has indicated the value to the Nation—regardless of employment opportunities in the research sector-of expanding the number and diversity of students in the educational pipeline (IS-12 and undergraduate) for science and engineering, preparing graduate students for career paths in or outside of research, and, if necessary, providing retraining grants for researchers to move more easily between research fields.

2. Total participation in science and engineering can be increased if the opportunities and motivation of presently underparticipating groups (e.g., women, minorities, and researchers in some geographic locations) are addressed. Federal legislation has historically played an important role in recruiting and retaining these groups. Also, "set-aside" programs (which offer competitive research grants to targeted groups) and mainstream disciplinary programs are tools that can enlarge, sustain, and manage the diversity of people and institutions in the research system.

3. Research in many fields of science and engineering is moving toward a larger, more ''industrial' model, with specialized responsibilities and the sharing of infrastructure. In response, the Federal Government may wish to acknowledge changes in the composition of research groups and to enhance the opportunities and rewards for postdoctorates, nontenure track researchers, and others.

[66] The National Science Foundation also **now limits the number of publications it will consider, as evidence of an applicant's track record in** reviewing **grant proposals. See David P. Hamilton, "Publishing By—and For?-the Numbers,"** ***Science,*** **vol. 250, Dec. 7, 1990, pp. 1331-1332.**

[67] See N.L. Geller et al., **''Lifetime Citation Rates to Compare Scientists** Work,'' ***Social Science Research,*** **vol. 7, No. 4, 1978, pp. 345-365; and A.L. Porter et** al., **"Citations and Scientific Progress: Comparing** Bibliometric **Measures With Scientist Judgments,"** ***Scientometrics,*** vol. ***13, 1988,*** **pp. 103-124.**

[68] OTA **interviews at Stanford University, Aug. 2-3, 1990.**

[69] See **Susan E.** Cozzens et al. (eds.), *The Research System* **in** *Transition,* Proceedings **of a NAT()** Advanced Study Institute, Il Ciocco, Italy, **Oct. 1-13, 1989** (Dordrecht, **Holland: K**luwer, **1990).**

Discussion

The graduate science and engineering (s/e) education system in the United States, especially at the doctoral level, is the envy of the world. Foreign nationals continue to seek graduate degrees from U.S. institutions at an ever-growing rate.[70] From 1977 to 1988, the number of Ph.D.s awarded in s/e by U.S. universities increased by nearly 50 percent[71] (for a breakdown by field and decade, see figure 1-9). This exemplary production of Ph.D.s continues a noble tradition abetted by Federal research and education legislation.

With passage of the National Defense Education Act of 1958 (Public Law 85-864) in the wake of the Sputnik launch, the Federal Government became a pivotal supporter of pre- and postdoctoral science, engineering, and indeed, non-s/e students.[72] Additional programs were soon established by NSF, NASA, NIH, and other Federal agencies. This period of growth in Federal programs offering *fellowships* (portable grants awarded directly to students for graduate study) and *traineeships* (grants awarded to institutions to build training capacity) was followed by decreases in the 1970s.[73] In s/e, this decline was offset by the rise in the number of *research assistantships (RAs)* for students awarded on Federal research grants to their mentors.

During the 1980s, RAs became the principal mechanism of graduate s/e student support, increasing at 5 percent per annum since 1980, except in agricultural sciences where RAs have actually declined. (A comparison of the types of graduate student Federal support, 1969 and 1988, is presented in figure 1-10.)[74] This trend is consistent with the growing "research intensiveness" of the Nation's universities: more faculty report research as their primary or secondary work activity, an estimated total in 1987 of 155,000 in academic settings.[75]

Thus, the Federal Government has historically played both a direct and indirect role in the production and employment of s/e Ph.D.s. Both as the primary supporter of graduate student stipends and tuition, and as a patron, mainly through research grants, the Federal Government has effectively intervened in the doctorate labor market and helped shape the research work force.

Supplying the Research Work Force

The U.S. graduate research and education system trains new researchers and skilled personnel for all sectors of the Nation's work force (and arguably for some countries abroad). Since 1980, NSF estimates that the *total s/e* work force (all degrees) has grown at 7.8 percent per year, which is four times the annual rate of growth in total employment. Scientists and engineers represented 2.4 percent of the U.S. work force in 1976 and 4.1 percent in 1988.[76]

While new s/e Ph.D.s have traditionally been prepared for faculty positions in academia-almost 80 percent were employed in this sector in 1987[77]—in broad fields such as engineering and disciplines such as computer science the demand for technical labor outside of academia is great. Other fields, like chemistry, benefit from having a large set of potential academic and industrial employment opportunities. This diversity makes any labor market

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[70] See National Science Board, op. cit., footnote 12, p. 55; and National Research Council, *Foreign and Foreign-Born Engineers in the United States* (Washington, DC: National Academy Press, 1988). Although OTA uses the shorthand "scientists and engineers," it recognizes the range of fields represented by the term. They are encompassed by the degree-granting categories in the National Science Foundation's Science Resources Studies reports: engineering, physical sciences, environmental sciences, mathematical sciences, computer/information sciences, life (biological/agricultural) sciences, psychology, and social sciences.

[71] National Science Foundation, Science *and Engineering Doctorates:* 1960-89, *NSF* 90-320 (Washington, DC: 1990), table 1.

[72] For details, see U.S. Congress, Office of Technology Assessment, *Demographic Trends and the Scientific and Engineering Work Force,* OTA-TM-SET-35 (Washington DC: U.S. Government Printing Office, December 1985), pp. 44-49.

[73] Association of American Universities, *The Ph.D. Shortage: The Federal Role* (Washington, DC: Jan. 11, 1990), pp. 15-16.

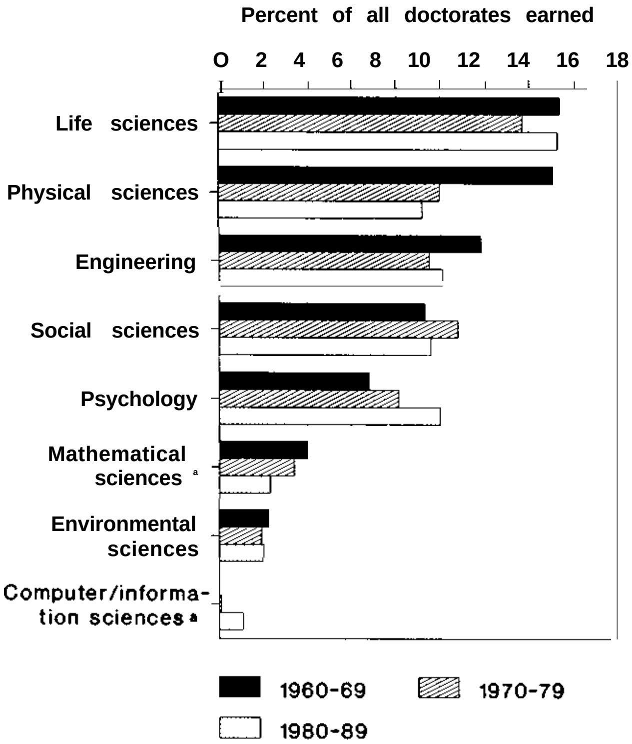
[74] If plotted by gender, this figure would look quite different. Traditionally, women have not received as many fellowships and traineeships as men or foreign students on temporary visas, are more dependent on personal or family resources during graduate study, and suffer higher attrition before completing the Ph.D. See U.S. Congress, Office of Technology Assessment, *Educating Scientists and Engineers: Grade School to Grad School,* OTA-SET-377 (Washington, DC: U.S. Government Printing Office, June 1988), pp. 79-80; and National Science Foundation, *Women and Minorities in Science and Engineering,* NSF 90-301 (Washington, DC: January 1990), pp. 23-24.

[75] National Science Board, op. cit., footnote 12, pp. 46,57. These 155,000 represented 37 percent of the doctorate scientists and engineers employed in the United States in 1987.

[76] Ibid., p. 67. Among Ph.D.s, the ratio of employed scientists to engineers is 5 to 1.

[77] Ibid., app. table 5-19.

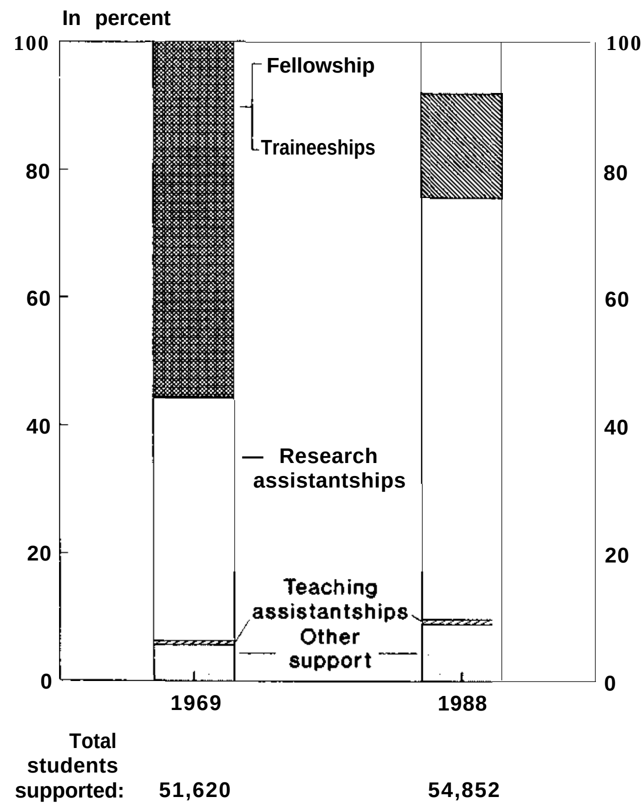
Figure 1-9—Percentage Distribution of Doctorates by Science and Engineering Field: 1960-89 (by decade)



a Degrees in computer science were not awarded until the late-1970s; before then, computer science was counted with mathematical sciences.

SOURCE: National Science Foundation, *Science and Engineering Doctorates: 1960-89*, NSF 90-320 (Washington, DC: 1990), detailed statistical tables, table 1.

Figure I-l O-Federal Support of Science and Engineering Graduate Students, 1969 and 1988 (by type of support)



NOTE: Fellowships and traineeships were not reported separately in 1969.

SOURCE: National Science Board, Science *and Engineering /ndicators-7989,* NSB 89-1 (Washington, DC: U.S. Government Printing Office, 1989), appendix table 2-18; and National Science Foundation, *Graduate Student Support and Manpower Resources in Graduate Science Education, Fall 1969,* NSF 70-40 (Washington DC: 1970), table C-1 la.

fluid and its forecasting difficult, but the major components can be analyzed.[78]

Based on changing demographics and historical trends in baccalaureate degrees, some studies have projected that the scientific community will face a severe shortage in its Ph.D. research work force during the 1990s.[79] However, there are pitfalls in the methodologies employed in these projections of Ph.D. employment demand.[80] Predicting the demand for academic researchers must also account for enrollment and immigration trends, anticipated career shifts and retirements, and the intentions of new entrants, as well as shifting Federal priorities and available research funding. All of these are subject to change, and may vary by institution, field, and region of the country .81 In addition, OTA questions

[78]For examples, see Eileen L. Collins, "Meeting the Scientific and Technical Staffing Requirements of the American Economy," Science *and Public Policy*, vol. 15, No. 5, October 1988, pp. 335-342; and National Research Council, *The Effects on Quality of Adjustments in Engineering Labor Markets* (Washington, DC: National Academy Press, 1988).

[79]See Richard C. Atkinson, "Supply and Demand for Scientists and Engineers: A National Crisis in the Making, " *Science*, vol. 246, Apr. 27, 1990, pp. 425-432.

[80]Indeed, shortages may not be the biggest concern. Changes in demographic composition and quality of graduates may be more problematic. For a discussion, see Howard P. Tuckman, "Supply, Human Capital, and the Average Quality Level of the Science and Engineering Labor Force, " *Economics of Education Review, vol. 7, No. 4, 1988,* pp. 405-421.

[81]For example, see Ted I.K. Youn, "Studies of Academic Markets and Careers: An Historical Review, " *Academic Labor Markets and Careers,* D.W. Breneman and Ted I.K. Youn (eds.) (Philadelphia, PA: The Falmer Press, 1988), pp. 8-27.

the ability of statistical analyses to predict future demand for s/e Ph.D.s, especially as responses to market signals and other societal influences are known to adjust both interest and opportunities. Even without the prospect of a slackening economy in the 1990s, such projections would be unreliable. Given the track record of these forecasting tools, they are poor grounds alone on which to base public policy.[82]

Noting the uncertainty of projections, OTA finds that concentration on the preparedness of the pipeline to produce Ph.D.s (i.e., increasing the number of undergraduates earning baccalaureates in s/e) by introducing flexibility into the system is the most robust policy. If shortages begin to occur in a particular field, not only should graduate students be encouraged to complete their degrees (i.e., reducing attrition), but prepared undergraduates should be induced, through various proven Federal support mechanisms, to pursue a Ph.D.[83] Those scientists who would have otherwise left the field might stay longer, those who had already left might return, and graduate students in nearby fields could migrate to the field experiencing a shortage. If shortages do not materialize, then the Nation's work force would be enhanced by the availability of additional highly skilled workers.

OTA believes there are initiatives that maintain the readiness of the educational pipeline to respond to changing demands for researchers and that enhance the diversity of career opportunities—sectors and roles—for graduates with s/e Ph.D.s.[84] Congress could urge NSF and the other research agencies to intensify their efforts to maintain a robust educational pipeline for scientific researchers (and to let the labor market adjust Ph.D. employment). Funding could be provided for undergraduate recruitment and retention programs, for grants to induce dedicated faculty to teach undergraduates, and for the provision of faculty retraining grants.[88]

Expanding Diversity and Research Capacity

Trends in the award of s/e degrees attest to 20 years of steady growth in human resources (see figure 1-11). These data are a sustained record of scientific education at the Ph.D. level. However, the benefits of this education do not accrue equally to all groups, and therefore to the Nation. Women and U.S. racial and ethnic minorities, despite gains in Ph.D. awards through the 1970s and 1980s, lag the participation of white males. Relative to their numbers in both the general and the undergraduate populations, women and minorities (and the physically disabled) are underparticipating in the research work force.[86] Meanwhile, foreign nationals on temporary visas are a growing proportion of s/e Ph.D. recipients (and about one-half are estimated to remain in the United States) .87

82OTA reached this conclusion after examining the performance of various models of academic and industrial labor markets. See Office of Technology Assessment, op. cit., footnote 72, especially chs. 3 and 4. Recent independent confirmation of this conclusion appears in Alan Fechter, "Engineering Shortages and Shortfalls: Myths and Realities, " ***The Bridge,*** **fall 1990, vol.** ***20,*** **pp. 16-20,**

83See Office of Technology Assessment, op. Cit., footnote 74.

84See two reports: U.S. Congress, office of Technology Assessment ***Elementary and Secondary Education for Science and Engineering*****, OTA-TM-SET-41 (Washington, DC: U.S. Government Printing Office, December 1988); and** ***Higher Education for Science and Engineering,*** **OTA-TM-SET-52 (Washington, DC: U.S. Government Printing Office, March 1989).**

85The National Science Foundation, as prescribed in their enabling legislation, is equally responsible for science education and the support Of the Nation's basic research. It has gradually expanded its programs, long focused on the graduate end of the pipeline, to address issues in undergraduate and K-12 education. For example, see National Science Foundation, ***Research on Key Issues in Science and Engineering Education: Targeted Program Solicitation,*** **NSF 90-149 (Washington, DC: 1990). Perhaps faculty retraining programs, both to highlight changes in educational strategies and developments in research, should be considered. Retraining has been acknowledged as important for maintaining the engineering work force, and retraining grants have been provided in some programs within the Department of Defense and other agencies. Additional research refraining grants could certainly be financed by the research agencies and perhaps administered through the Federal laboratories. Retraining for teaching would fall primarily to universities that wish to improve the classroom (i.e., undergraduate) teaching of its faculty. See National Research Council, op. cit., footnote** ***78;*** **and Neal Lane, ''Educational Challenges and Opportunities,'** ***Human Resources in Science and Technology: Improving U.S. Competitiveness, Proceedings*** **of a Policy Symposium for Government, Academia, and Industry, Mar. 15-16, 1990, Washington, DC, Betty Vetter and Eleanor Babco (eds.) (Washington, DC: Commission on Professional in Science and Technology, July 1990), pp. 92-99.**

86Degrees alone tell an incomplete story offuture supply of scientists and engineers. For example, college attendance rates of 18- to 21-year-olds vary by gender and race. Since 1972, 35 to 40 percent of whites of both sexes in the cohort have attended college with Black rates in the 25 to 30 percent range. By 1988, female attendance exceeded that of males and was rising, whereas male attendance of both races peaked in 1986-87 and declined thereafter. See National Science Board, op. cit., footnote 12, p. 50, figure 2-2.

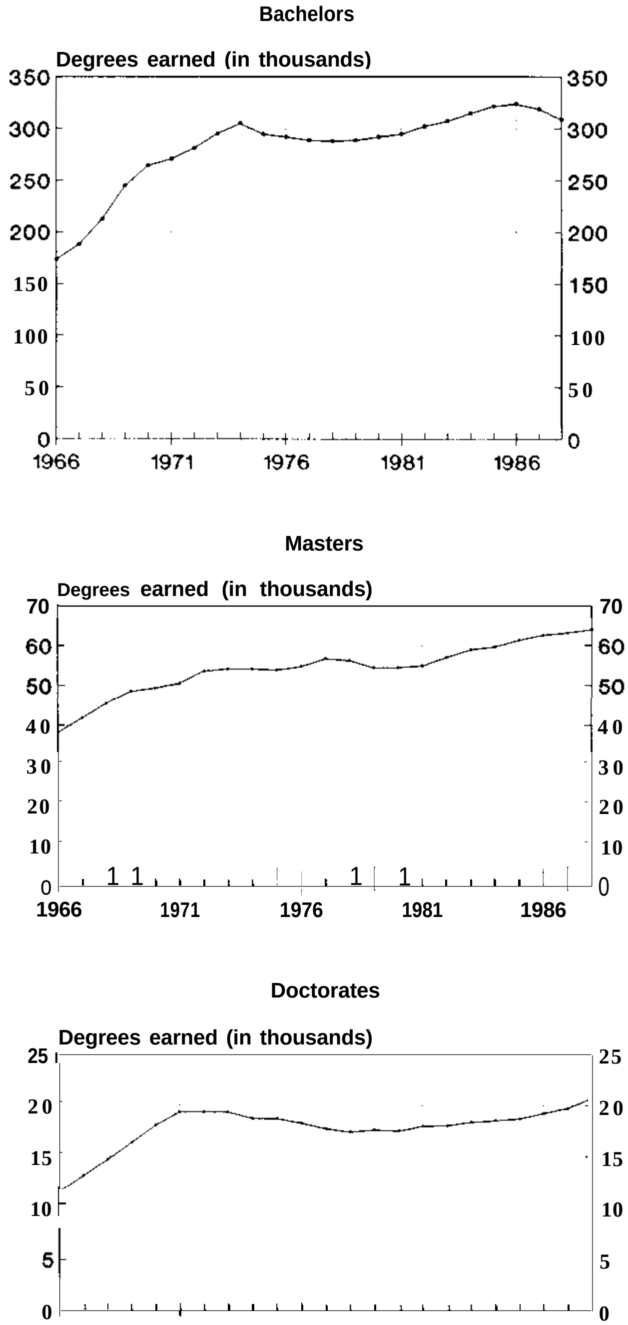
87For an overview, se Commission on Professionals in Science and Technology, ***Measuring National Needs for Scientists to the Year 2000*****, Report of a Workshop, Nov. 30-Dec. 1, 1988 (Washington DC: July 1989), pp. 20-24. For more on graduate engineering education, see Elinor Barber et al.,** ***Choosing Futures: U.S. and Foreign Student Views of Graduate Engineerin gEducation (New*** **York, NY: Institute of International Education, 1990).**

Photo credit: Bob Kalmbach, (Universityof Michigan

These students are in a laboratory at the University of Michigan. Laboratory classes are a crucial part of undergraduate education in the physical sciences.

Increasing the participation at all educational levels in s/e by traditionally underrepresented groups is a challenge to the human resources goals of the Federal research system. Enhancing the participation of targeted groups at the Ph.D. level will be particularly difficult, as the research work force adjusts to changing fiscal conditions and funding of research. As OTA found in an earlier study, ". . . equal opportunity for participation in higher education and in research for all groups is a long-term social goal that will be achieved only with steady national commitment and investments. ' '[88] Congress could amend the Higher Education Act (reauthorization is scheduled for the 102d Congress) and the Science and Engineering Equal Opportunities Act to add provisions that address diversity in research and science education funding, and emphasize undergraduate teaching opportunities at certain categories of institutions such as historically Black colleges and universities (HBCUs).[89] Programs targeted to U.S. minorities, women, and the physically disabled could help to expand the pool of potential scientists and engineers. It is clear that in

Figure 1-1 I--Science and Engineering Degrees: 1966-88 (by level)



SOURCE: National Science Foundation, *Science* and *Engineering Degrees:* 7966-88, *A Source Book,* NSF 90-312 (Washington, DC: 1990), detailed statistical tables, table 1.

[88] Office of Technology Assessment, op. cit., footnote 74, p. 101.

[89] For the scope of current provisions, see Margot A. Schenet, Congressional Research Service, "Higher Education: Reauthorization of the Higher Educational" Issue Brief, May 15, 1990; and Public Law 96-516,94 Stat, 3010, Section II, Science and Engineering Equal Opportunities Act, Part B, as amended by Public Law 99-159, 1982.

this particular realm of human resources, market forces alone will not increase the participation of these groups. Policy intervention is required and Congress is empowered to intervene.

The capacity of the research system could also be augmented by encouraging ''have-not" institutions to concentrate excellence in select research programs (departments and centers) and build from there. Attempting to enter the top ranks of federally funded research-intensive universities through across-the-board enhancement of all research programs may lead to each program being unable to garner enough support to improve research capability. Various programs that address geographical diversity, such as the NSF Experimental Program to Stimulate Competitive Research (EPSCoR), or greater consideration of geography in funding allocation within the portfolios of mainstream scientific merit-based programs, could build research capacity that benefits States and regions as well as the Nation as a whole.

Research and Education in Flux

Calls for the reform of higher education in the 21st century are now emanating from many presidents of research universities.[90] These calls center on improved undergraduate education and abetter balance between research and teaching. Many see a need to change the reward system of the university, since asking universities to augment the teaching of undergraduates may be misplaced if faculty continue to view this as a drain on time that would be better spent doing research.[91]

The tension between research and teaching is perpetuated by the provision of funds meant to improve both the institution's research performance and teaching capability. A common perception during the 1960s was that Federal dollars that supported research also benefited undergraduate teaching because these top researchers would communicate their excitement about developments ''at the laboratory bench" to undergraduate and graduate students alike. In the 1980s, with the separation between research and undergraduate education becoming more pronounced, the connection between research progress and the cultivation of human resources grew more tenuous.[92] These calls for increased undergraduate teaching by faculty seek to alter an academic research and teaching model in the United States that is already under strain.

The predominant mode of academic research in the natural sciences and engineering begins with a research group that includes a PI (most often a faculty member), a number of graduate students, one or several postdoctoral scientists, technicians, and perhaps an additional nonfaculty Ph.D. researcher. While this group may be working on a single problem funded by one or two grants, subsets of the group may work on different but related problems funded simultaneously by multiple project grants. (In the social sciences, the groups tend to be smaller, often numbering only the faculty member and one to two graduate students.)

In addition, the dominant model to launch a career as a young scientist is movement from one research university to another with an assistant professorship, the attainment of a first Federal research grant, and the re-creation of the mentor's professional lifestyle (e.g., independent laboratory, graduate students, postdoctorates). For an institution to subscribe to this model tends to shift much of the actual responsibility for awarding tenure from the department faculty to the Federal Government. While university officials say there is ". . . no fried time in which researchers are expected to become self-sufficient through outside grants . . . researchers who have failed to win such grants are less likely to

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90 Prominent among them are the two institutions that OTA studied as part of this assessment, Stanford and Michigan. See Karen Grassmuck, "Some Research Universities Contemplate Sweeping Changes, Ranging From Management and Tenure to Teaching Methods," *The Chronicle of Higher Education, vol. 37, No. 2,* Sept. 12, 1990, pp. Al, A29-31.

91 This would include nothing less than a redefinition of faculty scholarship that includes teaching. See Ernest L. Boyer *Scholarship Reconsidered: Priorities of the Professoriate* (Princeton, NJ: The Carnegie Foundation for the Advancement of Teaching, 1990). Also see Alliance for Undergraduate Education, *The Freshman Year in Science and Engineering: Old Problems, New Perspectives for Research Universities* (University Park, PA: 1990).

92 See Anthony B. Maddox and Renee P. Smith-Maddox, ''Developing Graduate School Awareness for Engineering and Science: A Model,' *Journal of Negro Education, vol.* 59, No. 3, 1990, pp. 479-490. This connection was also highlighted when institutions of higher education receiving Federal assistance were required to provide certain information on graduation rates, reported by program and field of study. See Public Law 101-542, Title I—Student Right-To-Know, Stat. 2381-2384, Nov. 8, 1990, p. 104.

Photo credit: Jay Mangum Photography

Seventh graders observe research in a "cleanroom." Seeing science at work is important for all age groups.

earn tenure than their colleagues who have found such support'[93]

There is doubtless a role for universities to play in the diversification of research careers of recent Ph.D.s. New Ph.D.s find it difficult to entertain alternative opportunities if they have no experience with them. Thus, programs that offer a summer in a corporate laboratory or part of an academic year at a 4-year liberal arts college can help advanced graduate students visualize working in settings other than the university. Arrangements that link an HBCU or liberal arts college to a research university or national laboratory stretch the resources and experience of both participating institutions.[94]

New Models: University and Federal

Other models of education could be encouraged that feature a greater sharing of resources (e.g., equipment and space) and people (e.g., doctoral students, nonfaculty researchers, and technicians). Models that stress research in units other than academic departments, research in *nonacademic* sectors, and *nonresearch* roles in academia could be entertained. Some Federal research agencies already

[93]See Debra E. Blum, "Yowger Scientists Feel Big Pressure in Battle for Grants," *The Chronicle of Higher Education*, vol. 37, No. 4, Sept. 26,1990, p. A16. As one researcher puts it: "Leading universities should make their own decisions about who their faculty are going to be, and not leave it to the study sections of ND-I." Quoted in David Wheeler, "Biomedical Researchers Seek New Sources of Aid for Young Scientists," *The Chronicle of Higher Education, vol. 36, No. 42,* July 5, 1990, p. A23.

[94]To date, such arrangements have been most common in undergraduate engineering. One coalition, spearheaded by a 5-year $15 million National Science Foundation grant, will establish a communications network for information dissemination, faculty exchange, workshops, and outreach to elementary, secondary, and community college students. The participating universities are City College of New York, Howard, Maryland, Massachusetts Institute of Technology, Morgan State, Pennsylvania State, and Washington. See "NSF Announces Multi-Million Dollar Grants to Form Engineering Education Coalitions," *NSF* News, Oct. 9, 1990.

recognize the development of this form of teamwork in their finding programs and support of the research infrastructure. For example, these models are institutionalized in the centers programs sponsored by NSF. Centers, which support individual researchers (as faculty and mentors) as well, may represent a new way of doing business for NSF. Centers are also featured at NIH intra- and extramurally; at the laboratories affiliated with DOD, DOE, and NASA; and at the agricultural experiments stations funded through block grants by USDA.[95]

Research in general is becoming increasingly interdisciplinary, i.e., it requires the meshing of different specializations to advance a research area.[96] Academic departments house specialists by discipline whose research will be performed in units-enters, institutes, programs-that cut across the traditional departmental organization on campus. Such organized research units have a history on U.S. university campuses, but not as dominant structures.[97] However, as outlined above, in many fields there is movement toward an industrial model of research, characterized by larger research teams and a PI who spends more time gathering funds to support junior researchers who in turn devote their full time to research. For many of today's research activities, this model seems to enhance productivity and allow more complex research problems to be tackled, by specializing responsibilities within the research team and sharing infrastructure.[98]

The expanding size and complexity of research teams under the responsibility of entrepreneurial PIs and "lab chiefs' fosters financial and organizational strains. To help ease the strains caused by a transition in some parts of the research community to an industrial model, the Federal research agencies could encourage alternative models of education-in-research that feature a greater sharing of resources and people. While it is not the role of the Federal Government to dictate university research or education policies, it can provide the impetus for examining and experimenting with those policies through grant support.

Mainstream agency programs have always awarded research funds to advance the state of knowledge in their programmatic areas mainly on the core criterion of "scientific merit. " Though difficult to define precisely, this is generally taken as a necessary condition for funding. Recognition that discipline-based agency programs favor investigator track record in proposal review, but that other factors reflect important objectives of research funding, led to the creation of set-aside programs. These programs, originating both in Congress and within agencies, restrict the competition for scarce funds according to some characteristic of the investigator or the proposal. Set-aside programs thus evaluate proposals first and foremost on scientific merit, but redefine the playing field by reducing the number of competitors. (Examples discussed in the full report include NIH's Minority Biomedical Research Support Program; NSF's aforementioned EPSCoR, Presidential Young Investigator, and Small Grants for Experimental Research programs; and the Small Business Innovation Research programs conducted by various Federal agencies.)

Taken together, such programs address the competitive disadvantage faced by young, minority, or small business research performers; by researchers and institutions in certain regions of the Nation; and by ideas deemed 'high-risk' by expert peers or that do not fit with traditional disciplinary emphases. The proliferation of such programs over the last 20 years has been a response to the desire to enlarge

[95]In 1990, the National Science Foundation supported 19 Engineering Research Centers and 11 Science and Technology Research Centers (STCs) at $48 million and $27 million, respectively. Thus, together they account for less than 10 percent of the National Science Foundation's budget, while providing a long-term funding base (5 to 11 years) for interdisciplinary and high-risk projects oriented to the applied, development, and commercial-use end of the research continuum. See Joseph Palca and Eliot Marshall, "Bloch Leaves NSF in Mainstream," Science, vol. 249, Aug. 24, 1990, p. 850. In the block-grant, multi-investigator approach embodied bySTCs: "NSF has rolled the dice on an experiment in science, and it will take some time to know whether it has come up with a winner."See Joseph Palca, "NSF Centers Rise Above the Storm," *Science,* vol. 251, Jan. 4, 1991, pp. 19-22, quote from p. 22.

[96]For example, see A.L. Porter and D.E. Chubin, "An Indicator of Cross-Disciplinary Research," *Scientometrics*, vol. 8, 1985, pp. 161-176; and Don E. Kash, "Crossing the Boundaries of Disciplines," *Engineering Education,* vol. 78, No. 10, November 1988, pp. 93-98.

[97]D.I. Phillips and B.P.S. Shen (eds.), *Research in the Age @~& Steady-State University* (Boulder, CO: Westview Press, 1982). Three models Of organized research units (which me common in industry and the Federal laboratories) have taken root on campus—agricultural experiment stations, water resources research centers, and engineering research centers, See Robert S. Friedman and Renee C. Friedman, "Science American Style: Three Cases in Academe," *Policy Studies Journal, vol. 17,* fall 1988, pp. 43-61.

[98]See Ziman, op. cit., footnote 64, pp. 132-139, In other words, the traditional academic model of faculty-mentor plus graduate student is today accompanied by production units that demand more teamwork and sharing-what has long been common, for example, in astronomy, fusion, and high-energy physics research.

both the participation in, and the capacity of, the Federal research system. But because the annual finding for each program remains modest (typically in the $10 million range), program impact is limited.

Without set-asides, the Federal Government would have little confidence that once scientific merit has been demonstrated, other differentiating criteria would be applied to the funding of researchers. However, **to a** research system already strapped for resources, the finding of such "tangential" concerns is seen by some as diverting precious dollars away from the core need to advance knowledge.[99]

Human resources are perhaps the most important component of the research system. Through support of scientists and engineers, graduate students, and the educational pipeline, the Federal Government is instrumental in the creation of a strong research work force, which has been expanding under this support since the 1950s. In the 1990s, however, the research work force-in its myriad forms of organization and scale of effort-has reached such a size that it feels strain under the Federal Government's present approach to supporting the conduct of research. In addition, accommodating to an expanding research work force, and to the changing ethnic and racial composition of students in the educational pipeline for science and engineering, poses challenges to the Federal research system. Human resources issues have implications not only for the number of participants in the research work force, but also for the character of the research that new entrants automatically bring to the Nation's research enterprise.

ISSUE 4: **Refining Data Collection and Analysis To Improve Research Decisionmaking**

Summary

Data collected on the health of the Federal research system--dollars spent for research, enrollments, and academic degrees awarded in specific fields, and outcome measures such as publications and citations—are extensive. In other areas, however, data are scarce. For instance, almost no consistent information exists on the size and composition of the *research* work force (as opposed to the total science and engineering work force), or what proportion is supported by Federal funds (across agencies).

Most research agencies, with the exception of NSF and NIH, devote few resources to internal data collection. Consequently, most analyses must rely on NSF and NIH data and indicators alone, potentially generalizing results and trends that might not apply to other agencies. Furthermore, it is not clear how agency data are used to inform research decisionmaking, as some challenge current policy assumptions and others are reported at inappropriate levels of aggregation.

OTA suggests additional information that could be collected for different levels of decisionmaking, concentrating in areas of policy relevance for Congress and the executive branch. However, better information may not be cost-flee. The idea is not merely to *add* to data collection and analysis, but to substitute for current activities not used for internal agency decisionmaking or external accountability. Refried inhouse and extramural data collection, analysis, and interpretation would be instructive for decisionmaking and managing research performance in the 1990s.

Discussion

Many organizations collect and analyze data on the research system. First and foremost is NSF, with its numerous surveys, reports, and electronic data systems that are publicly available. Certainly the most visible compendium of data on the research system is the biennial report, *Science & Engineering Indicators* (SEI), issued since 1973 by the National Science Board, the governing body of NSF.[100] Other sources include the other Federal research agencies; the National Research Council; the Congressional Research Service; professional societies, especially the American Association for the Advancement of

[99]Change comes incrementally and at the margins of the enterprise. But if one were constructing the system from scratch, mainstreaming criteria to reflect the multiple objectives of research funding would be a key element to consider.

[100]See Susan E. Cozzens, "Science Indicators: Description or Prescription?" OTA contractor report, September 1990. Note that Science & *Engineering Indicators* (SEI) was named Science *Indicators* until 1987. SEI builds on data collected, published, and issued in many other reports by the Science Resources Studies Division of the National Science Foundation.

Science; and other public and special interest groups.[101]

Together these databases and analyses provide a wealth of information: time series on the funding of research and development (R&D); expenditures by R&D performer (e.g., universities and colleges, industry, Federal laboratories), by source of funding, and by type (basic, applied, or development); numbers of students who enroll in and graduate with degrees in s/e; characteristics of precollege science and mathematics programs and students in the education pipeline; and size, sectors of employment, and activities of the s/e (especially Ph. D.) work force.[102] Detailed analyses of the Federal budget by research agency are available each year, and impacts on specific disciplines and industries can often be found.

These publications provide a basis for understanding the Federal research system. But even with each of these organizations devoting significant resources to the collection of information, better data are needed to guide possible improvements in the system.[103] With its establishment, NSF was legislatively authorized as the Federal agency data liaison and monitor for science and technology.[104] Data can be used to monitor, evaluate, anticipate, and generally inform decisionmakers-both within agencies and within Congress. Although many data are already collected, they are rarely matched to policy questions. Other (or more) data could improve decisionmaking.

Information for Research Decisionmaking

OTA defines four categories of data that could be useful in decisionmaking: 1) research monies—how they are allocated and spent; 2) personnel— characteristics of the research work force; 3) the research process-how researchers spend their time and their needs (e.g., equipment and communication) for research performance; and 4) outcomes—the results of research. Besides the considerable gaps and uncertainties in measures of these components, the most detailed analyses are done almost exclusively at NSF and NIH, and not at the other major research agencies.[105] These analyses may not generalize across the Federal research system. Comparable data from all of the agencies would be very useful to gain a more well-rounded view of federally supported research.

Perhaps the most fundamental pieces of information on the research system are the size, composition, and distribution of the *research* work force, and how much is federally funded. Varying definitions pose problems for data collection and interpretation (for an example, see box l-C). These data are important to understand the health and capacity of the research system and its Federal components. In addition, there is evidence that research teams are changing in size and composition. This trend is also important to measure since it affects the form and distribution of Federal funding.

Second, information is needed on expenditures (e.g., salaries, equipment, and indirect costs) in research budgets; for all research performers-academia, Federal laboratories, and industry; and by subfield of science and engineering. Data on how Federal agencies allocate monies within project budgets could also be compiled, and would illuminate how funding decisions are made within the research agency and would help to clarify funding levels in specific categories of expenditures. Better cost accounting and forecasting for megaprojects is

[101] For example, see National Research Council, Surveying *the Nation's Scientists and Engineers: A Data System for the 1990s* (Washington, DC: National Academy Press, 1990). Under multiagency support, the National Research Council is well known for collecting, analyzing, and disseminating information on Ph.D. recipients. For a statement of its crosscutting role, see National Academy of Sciences, *The National Research Council: A Unique Institution* (Washington, *DC:* National Academy Press, 1990). For a summary of major databases on science and engineering (individuals and institutions), see National Research Council, *Engineering Personnel Data Needs for the 1990s* (Washington, *DC:* National Academy Press, 1988), app. A-2.

[102] For example, the Government-University-Industry Research Roundtable of the National Academy of Sciences, with data compiled by the National Science Foundation's Policy Research and Analysis Division, provided much useful analysis on the state of academic R&D and changes since the early 1960s. Government-Industry-University Research Roundtable, op. cit., footnote 48.

[103] These efforts must also be seen in the context of the massive Federal data system. The components most relevant to research are the data series compiled and reported by the Census Bureau, the Bureau of Economic Analysis, the Bureau of Labor Statistics, and the National Center for Education Statistics.

[104] For the scope of these data collection and analysis responsibilities, see England, op. cit., footnote 8, app. 1.

[105] For example, the National Institutes of Health sets aside 1 percent of its research budget for research evaluation and internal analysis of the investigators and programs it supports. The Department of Energy, the National Aeronautics and Space Administration the Office of Naval Research, and the National Science Foundation have all conducted ad hoc inhouse evaluations of the research they support and the efficiency of the operations needed to select and manage various research portfolios.

Box I-C—How Many "Scientists" Are There?

How one defines a "scientist," "engineer," researcher," or "postdoctorate" is in the eye of the beholder. Depending on what data collection method is used, counting scientists and engineers (WE's) can result in radically different estimates.[1]

Definition	*Number*
S/E's in the U.S. work force (defined by job held)..	5,300,000
S/E's in academia (defined by responses to surveys in academic institutions)	712,000
S/E Ph.D.s in *basic* research--all sectors (defined by responses to surveys of Ph. D.s)..	187,000
S/E Ph.D.s in academia, where research is either their primaryor secondary work activity (defined by responses to surveys of Ph.D.s)	155,000
S/E Ph.D.s in *basic* research in academia (defined by reponses to surveys of Ph.D.s)	66,000
Full-time equivalent S/E investigators in Ph.D. institutlons (e.g., two researchers who each spend half-the on research would be counted as one full-time equivalent S/E investigator)	63,000

None of these definitions is the 'right' one. Rather, the appropriate definition depends on the purpose for which the number is to be used Throughout this report, **OTA refers to scientists and engineers in many ways: e.g.,** by participation in the U.S. work force, by sector of employment, by work activity, by field, by highest degree earned. The reader should keep in mind **that the** numbers can change by tenfold or more **depending on who is counted as a scientist or engineer.**

[1]Most of the following numbers are taken from the National Science Board, *Science & Engineering Indicators—1989*, NSB 89-1 (Washington, DC: 1989), and are 1987 or 1988 estimates by the National Science Board's Science Resources Studies Division. The number of full-time equivalent investigators is based on analysis by the National Science Foundation 's Policy Research and Analysis Division, as reported in Government-University-Industry Research Roundtable, Science and *Technology in the Academic Enterprise: Status, Trends, and Issues* (Washington, DC: National Academy Press, October 1989), p. 2-51.

surely needed. Continuous upward revisions of cost estimates for megaprojects disrupt decisions about their future funding priority.

Third, data on the research process could be improved in amount and kind. One trend (mentioned above) that OTA has noted, mostly with anecdotal evidence and inferences from analyses of expenditures, is the increasing size of research groups, both within the university structure and through Federal support of centers. This trend has policy implications for the cost of research, its interdisciplinary capabilities, the changing demographics of the work force, and the aspirations of young researchers. It also reflects how researchers may spend their time. More data on ' 'production units" in research, and their dependence on Federal finding relative to other sources, would augment enrollment, Ph.D. award, and work activity data. Changes in the structure of production units have also influenced the research process and the volume---and perhaps the character----of outcomes.[106] Information on the research process would yield a firmer foundation on which to base funding allocation decisions, specifically: 1) how researchers spend their time, 2) movement of research teams toward a more industrial model in the allocation of responsibilities, 3) changing equipment needs and communications technologies, and 4) requirements and average time to attain promotions in the scientific work force.

Evaluating Research Outcomes

Because of the fundamental and elusive nature of research, measuring its outcomes-in knowledge and education—is very difficult. The most elusive outcome is cultural enrichment-the discovery and growth of scientific knowledge. As OMB Director Richard Darman has said (speaking of the proposed Moon/Mars mission): "No one can put a price on uplifting the Nation. Research has resulted in many benefits and is funded precisely for this reason. This kind of benefit is nearly impossible to measure. However, there are some proxies.

[106] The role of laboratory chief or team leader combines entrepreneurial and administrative/superviso~ tasks. Both are essential to the funding and longevity of the productive research unit. On the emergence of the entrepreneurial role on campus, see Etzkowitz, op. cit., footnote 61.

When looking at research as a contribution to education, numbers of degrees can be tallied and assertions made about skills added to the Nation's work force. When looking at research as creating new knowledge, one tangible ''output'' is papers published by scientific investigators to communicate new information to their scientific peers. Communicating the results of scientific research to colleagues through publication in the open literature is considered to be an important feature of good research practice.[107] perhaps the best approach is to construct workable indicators and include a rigorous treatment of their uncertainties.

One tool that has been vigorously developed for measuring the outcomes of research is bibliometrics-the statistical analysis of scientific publications and their attributes.[108] Intrinsic to scientific publication is the referencing of earlier published work on which the current work is presumably based or has utilized in some way. References are a common feature of the scientific literature, and by counting how often publications are cited, bibliometrics can arrive at a weighted measure of publication impact—not only whether publications have been produced, but also what impact those publications have had on the work of other scientists.[109]

OTA has explored several examples of new data sets that could be compiled using bibliometrics.[110] First, universities can be ranked according to an output or citation measure-the citation rates for papers authored by faculty and others associated with each institution.[111] Instititutions can be ranked by total number of cited papers, the total citations received by all papers associated with each institution, and the ratio of number of citations to the number of publications, namely, the *average citations per cited paper. This* appears to be a more discerning measure than either publication or citation counts alone.

For example, a ranking of institutions by average citation rates can be used in conjunction with the list of top universities, in Federal R&D funding received, to link inputs with outputs. Together, these measures illuminate differences in rank.[112] Not only can publishing entities be analyzed, but so can fields of study. For instance, "hot fields, ' in which the rate of publication and citation increases quickly over a short period of time, can be identified and "related fields,'' in which published papers often cite each other, can be mapped.[113] Because of problems of interpretation in bibliometric analysis, it should be seen as ''value-added" to research decisionmaking, not as stand-alone information. Bibliometrics could be used to help monitor outcomes of research, e.g., publication output and other information from the research system.[114]

Criteria that go beyond bibliometric data could be specified for such evaluations. These criteria could include the originality of research results, the project's efficiency and cost, impacts on education and the research infrastructure, and overall scientific merit. Such research project evaluation could be

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107For example, see Leah A. Lievrouw, "Four Research Programs in Scientific Communication, " Knowledge*in Society,* vol. 1, summer 1988, pp. 6-22; and David L. Hull, *Science as a Process: An Evolutionary Account of the Social and Conceptual Development of Science (Chicago,* IL: University of Chicago Press, 1988).

108Researchers in western Europe have been particularly active during the 1980s. For example, see B.R. Martin and J. Irvine, *Research Foresight* (London, England: Pinter, 1989); and A.F.J. van Raan (cd.), Handbook *of Quantitative Studies of Science and Technology* (Amsterdam, Holland: North-Holland, 1988).

109Interpreting citation patterns remains a subject of contention. For caveats, see D.O. Edge, "Quantitative Measures of Communication in Science: A critical Review," *History of Science,* vol. 17, 1979, pp. 102-134. The definitive overview is contained in Eugene Garfield, *Citation Indexing: Its Theory and Application in Science, Technology and Humanities (New* York, NY: John Wiley & Sons, 1979).

110See Henry Small and David Pendlebury, ''Federal Support of Leading Edge Research: Report on a Method for Identifying Innovative Areas Of Scientific Research and Their Extent of Federal Support,'' OTA contractor report, February 1989; and Henry Small, ''Bibliometrics of Basic Research,'' OTA contractor report, September 1990.

111The analysis below is basal on Institute for Scientific Information databases and Small, op. cit., footnote 110.

112As part of the agenda for future exploration, *institutions* receiving primarily directed funds or block grants (e.g., in agriculture) could be compared with those that are investigator-initiated. This comparison would help to test the claim that targeted appropriations (e.g., earmarking) lead to the production of inferior research. For discussion, see ch. 5 of the full OTA report.

113For example, see Angela Martello, "Governments Led in Funding 1989-90 'Hot Papers' Research, " *The Scientist,* vol. *4, No. 16,* Aug. 20, 1990, pp. 20-23.

114See U.S. Congress, Office of Technology Assessment, Research *Funding as an Investment: Can We Measure the Returns?* OTA-TM-SET-36 (Washington, DC: U.S. Government Printing Office, April 1986); and Ciba Foundation, *The Evaluation of Scientific Research (New* York, NY: John Wiley & Sons, 1989). For evidence on U.S. research performance relative to seven other industrialized countries, see 'No Slippage Yet Seen in Strength of U.S. Science," *Science Watch, vol. 2, No.* 1, January/February 1991, pp. 1-2,

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A Research Triangle Park scientist accesses a computer network. Computers can greatly enhance data collection and presentation.

employed to augment agency decisions on funding and administration of research programs. (Some research agencies already utilize certain aspects of research program evaluation.[115])

Utilizing Data for Research Decisionmaking

In a policy context, information must be presented to those who are in positions to effect change by allocating or redirecting resources. In the diverse structure of the Federal research system, research decisions are made at many levels. For example, an agency program manager requires data specific to the purview of his/her program, while OMB and OSTP must be aware of trends in science that span broad fields, institutions, and agencies, as well as those that apply only to specific fields, performers, and research sponsors.

Drawing on NSF expertise as the possible coordinating "agency, information could be collected at each agency on proposal submissions and awards, research expenditures by line items in the budget, and the size and distribution of the research work force that is supported (including the funding that this work force receives from other sources). Information must be available to decisionmakers for evaluation as well as to illuminate significant trends. Often data can be presented in the form of *indicators, e.g.,* comparisons between variables, to suggest patterns not otherwise discernible. NSF has pioneered and sustained the 'creation of indicators for science policy and has recently suggested monitoring several new indicators (e.g., indicators of proposal success rates, PI success rates, and continuity Of NSF support).[116]

OTA agrees that new indicators could be very useful, and also suggests elaborating them. These could include measures of the active research community (which would calibrate the number of researchers actively engaged in research), and production units (which would track trends in the composition of research teams by broad field and subfield).

The combination of such indicators would give a more precise estimate of the changing parameters of the Federal research system.[117] This information would be invaluable to policymakers concerned about the health of certain sectors of the system. To produce such information, as part of ongoing agency data collection and NSF responsibilities for collation and presentation, extra resources would be needed (at least in the near term). Over time, plans could be developed to streamline NSF data and analysis activities, such as a reduction in the number of nonmandated reports issued annually, or expansion of its inhouse and extramural ''research on research. The idea is not merely to *add* **to** data collection and analysis, but to substitute for current activities that are not used for internal agency

[115]For example, see U.S. Department of Energy, Office of Program Analysis, Office of Energy Research, *An Assessment of the Basic Energy Sciences Program,* DOE/ER-0123 (Washington, DC: 1982). For a review of other evaluations, see National Academy of Sciences, Committee on Science, Engineering, and Public Policy, The *Quality of Research in Science* (Washington, *DC:* National Academy Press, 1982), app. C.

[116]National Science Foundation, "NSF Vital Signs: Trends in Research Support, Fiscal Years 198089, " draft report, Nov. 13, 1990. Some of the indicators reported here were used for an inhouse National Science Foundation evaluation of ways to streamline the workload of program staff and the external research community. See National Science Foundation, *Report of the MeritReview Task Force,* NSF 90-113 (Washington DC: Aug. 23, 1990).

[117]For example, what would be the indications that growth in research productivity is slowing or that the size of a research community is precariously large or small relative to the resources supporting it? See Colleen Cordes, "Policy Experts Ask a Heretical Question: Has Academic Science Grown Too Big?" *The Chronicle of Higher Education, vol. 37, No. 3, Nov. 21,* 1990, pp. Al, A22.

decisionmaking or external accountability.[118] If there is a premium on timely information for research decisionmaking, it must be declared (and funded as) a Federal priority.

Congress could instruct every research agency to develop a baseline of information, direct NSF to expand its focus and coordinating function for data collection and analysis, and direct OSTP (in conjunction with OMB) to devise a plan to increase the reporting and use of agency data in the budget process, especially crosscutting information in priority research areas. Using the FCCSET mechanism, this has already been done for global change, high-performance computing, and most recently, science and mathematics education.[119] This mechanism seems to work and could be more widely emulated.

In Summary, better data on the Federal research system could be instrumental in the creation or refinement of research policies for the 1990s. (For a summary of data oriented to different users, see table 1-5.) The utility of data, of course, is judged by many participants in the system: the needs of Congress are usually agency- and budget-specific;[120] the agencies, in contrast, worry about the performance of various programs and their constituent research projects. While data collection by NSF and groups outside the Federal Government has been instructive, it could be greatly enhanced. Much information could be collected on the Federal research system that maps trends, at different levels of aggregation and units of analysis, for different users. However, the existence of data does not ensure their utility.

The highest priority in data collection for research policymaking in the 1990s is comparable data from all of the agencies to help Congress maintain a well-rounded view of federally supported research. The second priority is data presented in forms that are instructive at various levels of decisionmaking. New data and indicators, grounded in the tradition of the SEI volumes and extramural research on research, are needed to monitor changes in the Federal research system.[121] Finally, OTA finds that research evaluation techniques, such as bibliometrics and portfolio analysis, cannot replace judgments by peers and decisionmakers, but can enrich them. Ongoing project evaluation could keep agencies alert to changes in research performance and augment program manager judgments about performers and projects. In short, such evaluation could serve to improve overall program effectiveness.

One of the functions of analysis is to raise questions about the information that decisionmakers have at their disposal, to assess its advantages and disadvantages, and to define a richer menu of options.[122] Improving the measurement process could help to quantify existing opportunities and problems, and pinpoint previously uncovered ones, relevant to decisionmaking at all levels of the Federal Government.

Toward Policy Implementation

Since the post-Sputnik era, both the U.S. capacity to perform research and the demand for funds to sustain scientific progress have grown. Federal investments have fostered the research system, managed through a pluralistic agency structure. This structure has supported the largest and most produc-

[118] The National Science Foundation routinely conducts ‘user SurveyS.’ If Science Resources Studies (SRS) knows from questionnaire responses how its various data reports are used--do they influence research or education policies? are they a source for administrators or faculty-researchers -then NSF should have a sense of audience ‘‘consumption’ and ‘ ‘utilization’ patterns. These would suggest *which* reports could be dropped, replaced, and modified. For an example of the SRS inventory of ‘‘intramural publications,’ see National Science Foundation *Publications List: 1977-1987,* NSF 87-312 (Washington, DC: July 1987).

[119] OTA interview with Office of Management and Budget staff, Feb. 7, 1991.

[120] & several National Science Foundation staff have indicated to OTA project staff (personal communications, October-December 1990), the Science Advisor draws heavily on unpublished and newly published Science & *Engineering Indicators* (SEI) *data* in preparing and presenting the Administration’s policy proposals at congressional “posture hearings” early in the annual authorization process. Indeed, the production cycle of SEI is geared to delivery of the volume as an input to this budget process.

[121] Quantitative data will not suffice. Information on the contexts in which research is performed, and characteristics of the performers individually and collectively, will provide clues to how t-he numbers can be interpreted and perhaps acted on. For example, see Daniel T. Layzell, “Most Research on Higher Education Is Stale, Irrelevant, and of Little Use to Policymakers,’ *The Chronicle of Higher Education, vol. 37, No. 8,* Oct. 24, 1990, pp. B1, B3.

[122] This leads OTA to suggest that the research agencies, especially the National Science Foundation and its policy programs, remain in close touch with external analysts of the Federal research system. Keeping abreast of other new measurement techniques and findings related to people, funding, and research activities would be a modest but fruitful investment in extending inhouse capabilities and refining knowledge of federally sponsored research performance.

Table 1-5-Desired Data and Indicators on the Federal Research System

Category	Description	Method	Primary users: Congress	Agencies	OMB	OSTP
Agency funding allocation method	Funding within and across fields and agencies Cross-agency information on proposal submissions and awards, research costs, and the size and distribution of the research work force supported	Agency data collection (and FCCSET)	X		X	X
Research expenditures	Research expenditures in academia, Federal and industrial laboratories, centers, and university/industry collaborations Agency allocations of costs within research project budgets, by field Megaproject expenditures: their components, evolution over time, and construction and operating costs	Agency data collection	X	X	X	
Research work force	Size and how much is federally funded Size and composition of research groups	Lead agency survey	X	X		X
Research process	Time commitments of researchers Patterns of communication among researchers Equipment needs across fields (including the fate of old equipment) Requirements for new hires in research positions	Lead agency survey; onsite studies		X		
Outcome measures	Citation impacts for institutions and sets of institutions International collaborations in research areas Research-technology interface, e.g., university/industry collaboration New production functions and quantitative project selection measures Comparison between earmarked and peer-reviewed project outcomes Evaluation of research projects/programs	Bibliometrics; surveys of industry and academia	X	X		X
Indicators	Proposal success rate, PI success rate, proposal pressure rates, flexibility and continuity of support rates, project award and duration rate, active research community and production unit indices	Agency analysis	X	X		X

KEY: FCCSET=Federal Coordinating Council on Science, Engineering, and Technology; OMB=Office of Management and Budget; OSTP=Office of Science and Technology Policy; PI=principal investigator.

SOURCE: Office of Technology Assessment, 1991.

tive research capability in the world. For many decades, scientific research has contributed in important ways to the cultural, technological, and economic base of the Nation.

In the 1990s, changing funding pattern and various pressures from both outside and within the scientific community will test the Federal research system. In such an environment, the prospects of fashioning a system that is responsive to national needs through selective, yet generous research funding will demand well-informed, coherent policies.[123]

The system will face many challenges, but four are clear: First, new methods of setting priorities and

[123] As Brooks has observed: "The research enterprise is more like an organism than like a collection of objects. ‘he removal of one part may degrade the functioning of the whole organism and not just the particular function ostensibly served by the part removed. " Harvey Brooks, "Models for Science Planning," *Public Administration Review*, vol. 31, May/June 1971, p. 364. Policies must respond to, and in some ways, anticipate, the consequences of funding decisions on the research system. Indeed, this report has tried to warn about extrapolating the past to manage the future of the system.

increased use of existing methods are required at all levels of decisionmaking. Second, Federal expenditures for individual components of research projects have increased faster than inflation. Understanding and coping with these increases is imperative in research decisionmaking. Third, the development of human resources for the science and engineering work force must occur through Federal incentives and institutional programs that act on the educational pipeline (K-12 through graduate study). Finally, gaps and uncertainties in the data used to describe the Federal research system must be reduced, and be replaced by more routine provision of policy-relevant information.

OTA finds that Congress, the executive branch, and research performers must converge on these issues. Potential congressional actions fall into three categories. Congress can: 1) retain primary responsibility for decisions and initiating actions; 2) place some of the responsibility for coordination and decisions on the executive branch; and 3) encourage research performers (especially universities, as well as Federal and industrial laboratories) to address components of these issues. (For a summary of possible actions, see table 1-6.)

At the congressional level, hearings, legislation, and oversight should first address crosscutting and within-agency priority setting at the national level. OTA suggests that one or more committees of Congress routinely (preferably biennially) hold hearings that require the research agencies, OSTP, and OMB to present coordinated budget plans with analyses that cut across scientific disciplines and research areas. Coordination among relevant committees of Congress would make this most productive. These hearings could also focus on crosscutting criteria for research decisionmaking within and across agencies. Emphasis must be placed on criteria to expand the future capabilities of the research system, such as strengthening education and human resources. A second set of congressional actions could explore cost-accountability efforts at the research agencies and throughout the research system. A final set of hearings ought to examine the state of data on the research system and improvements to inform congressional decisionmaking.[124]

Table 1-6-Summary of Possible Congressional, Executive Branch, and Research Performer Actions

Congressional hearings, legislative efforts, and oversight to:	• Set priorities across and within agencies, and develop appropriate agency missions. • Evaluate the total portfolio to see if it fulfills national research goals, human resources needs, scientific infrastructure development, and balance. • Initiate greater cost-accountability throughout the Federal research system. • Expand programs that fortify the educational pipeline for science and engineering, and monitor the combined contributions of agency programs to achieve education and human resources goals. • Augment data and analysis on the Federal research system for congressional decisionmaking.
Executive branch actions to:	• Enhance cross-agency priority setting in the Federal budget and increase research agency flexibility to address new priorities. • Institute better cost-accountability and cost-containment measures by agencies and research performers. • Expand agency programs to promote participation in the educational pipeline for science and engineering, and require agencies to report progress toward these goals. • Monitor and analyze policy-relevant trends on the research system, especially as related to the changing organization and productivity of research groups and institutions.
Research performer actions to:	• Contain and account for research expenditures. • Revise education and research policies as they affect: a) recruitment and retention in the educational pipeline for science and engineering, and b) faculty promotion, tenure, and laboratory practices.

SOURCE: Office of Technology Assessment, 1991.

Hearings could be followed with congressional oversight-on agency progress toward their research missions, implementing the criteria chosen by Congress to enhance research decisionmaking,

[124] There is a role for the congressional support agencies, as well as other sources of expert advice. For other proposals, see Carnegie Commission on Science, Technology, and Government, Science, *Technology, and Congress: Expert Advice and the Decisionmaking Process* (New York, NY: February 1991).

instituting greater cost-accountability, and providing useful data and analysis on an ongoing basis to Congress.

Some of these hearings and oversight efforts already take place in committees of Congress. While they have been very useful, OTA finds that to effect change in the research system, congressional action must be comprehensive and sustained. Posture hearings with the Science Advisor and agency directors will not suffice.

In its role as the prime sponsor of Federal research, the executive branch (especially OSTP, OMB, and the research agencies) could provide more flexibility in response to changing research priorities. For instance, the executive branch could systematically initiate tradeoffs among agency research programs including, with the cooperation of Congress, the *termination* of programs. This would help to create more coordinated research policies. Similarly, the research agencies could institute greater cost-accountability measures, and include costs as explicit factors in decisionmaking at the project level. This would provide a more realistic assessment of future capabilities with respect to projected funding levels. On human resources issues, the executive branch could implement or expand agency programs and reporting requirements to: 1) encourage recruitment and retention of women, U.S. minorities, and other underparticipating groups in the educational pipeline for science and engineering; and 2) monitor the changing structure of research performance, especially forms of research organization, and devise funding allocation methods that accommodate both the needs of the PI and research teams. Finally, each of the research agencies (with NSF as the lead agency) could conduct routine data collection and analysis on policy-relevant aspects of their programmatic contributions to the research system.

Not all problems in the research system, however, can be addressed in Congress or by the executive branch. Universities and laboratories (both Federal and industrial) are key components of the system, and many policies are dictated by the practices within these institutions. Containing research expenditures and expanding the educational pipeline through institutional programs and requirements are examples of policy areas in which research performers must fulfill their role in the social contract implied by the Federal patronage of research. The Federal Government can only encourage universities and laboratories to follow new paths; few direct Federal incentives are available to initiate change. Greater delineation of government and research performer responsibilities would help to sanction congressional and executive branch action on problems in the research system.

Photo credit: Jay Mangum Photography

Communication among scientists and engineers is an essential part-of the research process.

In addition to specifying at which level (congressional, executive branch, or research performer) issues could be appropriately addressed, responses to the four challenges outlined above must also recognize many inherent tensions in the research system. They include the merits of more centralized decisionmaking juxtaposed against the advantages (and realities) of a decentralized Federal research system. Other tensions arise between the funding of mainstream individual investigator programs and set-aside or more specialized programs (see again table 1-1). Inevitably, policies that relieve some tensions will engender others.

In Summary, decisionmaking in the Federal research system concerns many laudable goals, and the options are clearly competing "goods." Thus, the Federal Government must make tough choices, even beyond issues of merit and constricted budgets, in guiding the research system. A quarter-century ago, a chapter on ''Science and the Federal Government' concluded with these words:

As never before in history, the status of science and technology has become an important hallmark of a nation's greatness; and the United States clearly has perceived and acted upon this fact. In the process, the Federal Government has displaced the university, industry, and the private foundation as chief patron and has fashioned a host of institutions to administer vastly increased commitments to scientific and technological excellence.[125]

Sustaining and managing this system is the challenge of the decade ahead.

[125]Cited in Ralph Sanders and Fred R. Brown (eds.), *Science and Technology: Vital National Assets* (Washington, DC: Industrial College of the Armed Forces, 1966), p. 86.