Chapter 1

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The assumption that federally funded scientific research leads to economic benefits for the country has been fundamental to government science policy since the end of World War II. Analysts have abandoned the linear model that sees a simple progression from basic research to applied research to product development, but they still believe that scientific research plays a vital role in technological progress and consequently in economic growth. Economic returns, however, are neither the sole nor the primary purpose for Federal research spending. The advancement of knowledge and specific mission agency goals such as national security, public health, and the exploration of space are all essential parts of the rationale for Federal research spending.

Several trends have combined in recent years to make some policymakers more interested in economic and other quantifiable measures of research success and benefits. Technology is becoming an essential component of economic competitiveness; Federal budget constraints are forcing lawmakers to reevaluate spending and to look for ways to compare the value of widely divergent government programs; quantification of program success offers the hope for an objective measure that could simplify politically contentious decisions about increasingly esoteric and complex scientific research. One approach to simplifying research evaluation is to view Federal research spending as an investment that should produce a measurable economic return.

The Task Force on Science Policy of the House Committee on Science and Technology has raised the issue of whether the metaphor of research funding as an investment can be used as a practical aid to Federal research decisionmaking. "Can Federal funding for science be viewed as an investment and be measured in a way comparable to other forms of economic investment?" the Committee asked in its Report *on a Study of Science Policy.* Specifically, the Committee asked O-J-A to study "the models and other analytical tools developed by economists to judge capital investments, and the applicability and use of these models and tools to government funding of scientific research. "

To carry out this study, OTA conducted a comprehensive search of the literature on the economic returns to investment in scientific research, met with numerous economists and public policy analysts who have studied this issue, conducted interviews with research decisionmakers in industry and in government, and carried out in-depth studies of the quantitative methods available to evaluate the progress of scientific research. This technical memorandum presents the findings of that investigation.

ECONOMIC RETURNS

Economists have shown a strong positive correlation between research and development (R&D) spending and economic growth. They have estimated private returns in excess of 20 percent per year and social returns in excess of 40 percent on private sector R&D expenditures. They have *not* been able to show comparable returns, and at times been unable to show *any* returns, on Federal R&D expenditures, except for some applied research programs in agriculture, aeronautics, and energy designed to improve industrial productivity. These findings are discussed at length in chapter 2.

The economists who have carried out these studies point out a number of reasons why economic return on investment calculations may be inappropriate for evaluating government R&D expenditures. First, the return-on-R&D-investment studies carried out to date measure an average return on a total previous investment. They give little guidance as to the marginal return that can be expected from the next incremental investment in R&D, which is the decision that policymakers must make. Second, most government expenditures, including R&D expenditures, are for so-called "public goods" whose market value is, by definition, extremely difficult to measure in economic terms. Third, despite the success of retrospective studies, there are no reliable formulae to relate future R&D expenditures to productivity improvements or other economic benefits. Predictions of future returns on investment cannot be made without such relationships.

Financial counselors and economists have developed techniques for selecting investments in situations involving risk and uncertainty. These techniques include capital investment methodologies, portfolio analysis, and financial investment' models. All of these techniques have heuristic properties that could guide investment in research and development. For example, spreading the risk among a number of projects is one response economists sometimes recommend in cases involving great uncertainty. However, the formal models themselves are not especially helpful to research decisionmaking. They assume that the decisionmaker can estimate in dollar values the benefits from potential investments and know or estimate the probability of achieving those benefits. Neither of these assumptions is applicable to government-funded research, except in special cases. The principal benefit of research, especially basic research, is new and often unexpected knowledge, which cannot be assigned a direct economic value.

Investment models also assume that the benefits of the investment return to, or are appropriable by, the investor. New knowledge-by contrast—is available to anyone to use. This is one of the reasons basic research is considered a public good, requiring government support.

Research leads to productivity improvements and economic growth primarily through technological innovation. However, the relationship between research and innovation can be long-term, indirect, and unpredictable. Studies of technological innovations have shown them to depend on research results that are decades old and often in seemingly unrelated fields. Moreover, the transformation of research into economically success" ful innovation depends on factors in the economy that are completely outside the research process. These factors include the climate for investment; government tax, regulatory, and patent policy; the degree of competitiveness and entrepreneurialism in industry; the state of the capital markets; foreign competition; and wages, unionization, and other characteristics of the work force. A highly successful basic research effort may never generate technological innovation or economic payoff if other factors in the economy are not conducive to technological change.

Some observer: argue that if economic returns are to be the primary measure of our research effort, we should focus our attention, as a Nation, on the factors that link science to technology and innovation. The United States spends less of its R&D budget than West Germany, France, England, or Japan on research related directly to industrial productivity. Efforts to improve that situation could include an increased emphasis on technology transfer, increased support for generic research related to industrial needs, and adaptation of more focused forecasting and planning for industry-related R&D. (See ch. 5.)

Applied research, whose goal is the solution of practical problems, can be more closely associated with economic activity. However, most of the applied research in the Federal Government is carried out by agencies whose mission objectives—defense, health, space—are not readily quantifiable in dollar terms. Table 1 shows the estimated 1985 Federal basic and applied research budgets by agency. As can be seen, in applied research the Departments of Defense (DOD) and Health and Human Services (DHHS) were the two largest contributors, with the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) third and fourth. All of the DOD and DHHS applied research re-

Table I.—Federal Obligations for Research and Development by Character of Work and R&D Plant: Fiscal Years 1984-85 (thousands of dollars)

			Research			
Fiscal year and agency	Total R&D and R&D plant	Total R&D	Basic research	Applied research	Development	R&D plant
Fiscal ***year*** 1984 ***(estimated):***						
Total, all agencies	46,554,924	44,835,777	6,981,031	8,127,270	29,727,478	1,719,145
Department of Agriculture	925,364	871,942	386,442	455,594	29,906	53,422
Department of Commerce	367.252	360.021	20.522	272,644	66.855	7,231
Department of Defense	27,987,145	27,540,045	816,590	2,168,184	24,555,271	447,100
Department of Energy[a]	5,770,604	4,825,576	841,671	1,231,733	2,752,172	945,028
Department of Health and Human Services[b]	4,921,924	4,864,292	2,793,052	1,705,911	365,329	57,632
Department of the Interior	427,558	421,825	124,667	276,330	20,828	5,731
Department of Transportation	538,429	515,929	600	81,990	433,339	22,500
National Aeronautics and Space Administration .,	3,044,400	2,888,900	689,133	1,012,031	1,187,738	155,500
National Science Foundation	1,247,580	1,238,480	1,172,466	66,014	—	9,100
Veterans Administration	228,100	220,900	15,200	189,700	16,000	7,200
Other agencies	1,096,568	1,087,867	120,688	667,139	300,040	8,701
Fiscal ***year*** 1985 (estimated):						
Total, all agencies	54,072,393	52,253,607	7,637,587	8,396,633	36,219,387	1,818, 786
Department of Agriculture	926,711	898,941	419,727	449,981	29,233	27,770
Department of Commerce	282,357	270,559	18,416	201,187	50,956	11,798
Department of Defense , .	34,510,984	34,142,084	913,195	2,408,204	30,822.685	368,900
Department of Energy[a]	6,146,700	4,962,272	944517	1,268,964	2,748,791	1 184,428
Department of Health and Human Services[b]	4,967,872	4,953,972	2,925,916	1,679,147	348,909	13,900
Department of the Interior	369,209	368,989	102,762	248,556	17,671	220
Department of Transportation	505,704	495,204	400	79,630	415,174	10,500
National Aeronautics and Space Administration	3,499,400	3,339,400	826,721	1.088,063	1 424,616	160,000
National Science Foundation	1,426,567	1,414,017	1,335,809	78.208	—	12550
Veterans Administration	207,600	194,500	15,000	160,000	19,500	13,100
Other aqencies	1,229,289	1,213,669	135,124	736.693	341,852	15,620

[a]Data shown for fiscal years 1956-73 and fiscal years 1974-76 represent obligations of the Atomic Energy Commission (A EC) and the Energy Research and Development Administration, respectively

[b]Data shown for fiscal years 1955-713 represent obligations of the Department of Health, Education, and Welfare

SOURCE: National Science Foundation

lates to national defense and health, two public goods that are not readily measured in economic terms. With the exception of approximately $200 million in aeronautics research, all of NASA's applied research relates to its space activities, which are not primarily designed to produce economic payoffs. Only the DOE, Department of "Agriculture, Department of the Interior, NASA Aeronautics, and Department of Commerce applied research programs have primary objectives related to improving the economic performance of an industry or the economy as a whole. In sum, nearly two-thirds of the Federal applied research budget is related to the production of public goods, whose primary value is not measured in economic terms.

Table 1 reveals another barrier to the use of economic models for research investment in the Federal Government-decentralized planning and decisionmaking. Six Federal agencies have a share of the total Federal research budget in excess of 5 percent: DHHS, DOD, DOE, NASA, the National Science Foundation (NSF), and the Department of Agriculture in descending order. The Office of Management and Budget, which could develop an overall national research budget, is divided into functional directorates that each examine only part of that budget. The Office of Science and Technology Policy does consider the Federal research budget as a whole, but it has no decisionmaking authority over Administration budget requests.

In Congress, responsibilities are equally dispersed. Three different authorizing committees and six largely independent appropriations subcommittees scrutinize the Federal R&D budget in each House. Thus even if some economic or financial model could be devised to determine the return on the Federal research "investment" and serve as a guide to allocating scarce resources, there is no single decisionmaker in the Federal Government who could ensure its uniform application across all research fields and budgets. Without such a decisionmaker, such a model would have little operational power or efficacy.

BIBLIOMETRICS AND SCIENCE INDICATORS

A major problem with the use of economic models in research decisionmaking is that they deal with economic "indicators" that are at best indirectly influenced by research. To measure research output more directly, alternative "indicators" have been extensively developed by students of science policy over the past two decades. However, these have only recently begun to be considered seriously by research policymakers as possible aids to their decision processes. The two main approaches are bibliometrics, which evaluates research output via scientific publications; and science indicators, which measure the vitality of the research enterprise in terms of degrees, personnel, awards, and education. Although these methods appear to be more appropriate measures of scientific quality and productivity, they do not offer the decisionmaker the simple, quantitative economic "bottom line" that economic models provide. The "indicators" can only supplement, and not replace, informed peer judgment of the scientific process. But they can help complete the anecdotal, fragmentary, and, necessarily, somewhat self-interested picture of the state of science presented by the researchers themselves. Science indicators, and especially bibliometric measures, are reviewed in chapter 3 of this technical memorandum.

Bibliometrics is based on the assumption that progress in science comes from the exchange of research findings, and that the published scientific literature is a good indicator of a scientist's knowledge output. Publications are the medium of formal information exchange in science and the means by which scientists stake their claims to intellectual "property. " Therefore, the more publications a scientist has, the greater is his or her presumed contribution to knowledge.

Simple publication counts have a number of obvious flaws: quantity of publications does not measure the quality of the knowledge contained therein; publications vary greatly in creativity and impact. Simple counts also cannot be used for cross-disciplinary analysis because of differences in publication rates by research field, type of research, research institutions, and a number of other external factors.

Citation analysis addresses the problem of measuring the quality of research output. It assumes that the greater the quality, influence, or importance of a particular publication, the more frequently it will be cited in the scientific literature. Citation counts based on comprehensive databases are being used on a limited basis to monitor the performance of research programs, facilities and faculties in Europe, and at the National Institutes of Health (NIH) and NSF.

The problems of citation analysis include: technical problems with the database, variations in the citation rate over the "life" of a paper, the treatment of critical or even refutational citations, variations in the citation rate with the type of paper, and biases introduced by "self-citation" and "in-house" citations. Developers of the citations database are working to minimize these problems, but some are inherent. Sophisticated variations on the approach include co-citation and co-word analysis, which are described in chapter 3,

Combinations of several research productivity indicators (publications, citation counts, and peer evaluation) have been used in the hope of overcoming problems associated with each method en its own. To the extent that the "partial indicators" converge, proponents argue, the evaluation may be more meaningful than if only one indicator were used. Significant degrees of convergence have been found by using this methodology to evaluate large physics and astronomy facilities. Since partial indicators depend in large part on a peer review system, they can be used as an independent check on scientists' peer assessments of research activities.

Despite the limitations of bibliometrics, NSF and NIH have undertaken extensive studies to refine the techniques and explore their applicability to research program evaluation. In addition, agencies of the French, Dutch, and British Governments, and the European Organization for Economic Cooperation and Development have applied some of these indicators to research programs in their countries. The results of these studies, and the limitations of this methodology, are discussed in chapter 3.

Science "indicators" assess the ongoing vitality of the research enterprise, complementing the "output" measures of bibliometric analyses. These indicators include statistics on scientific and engineering personnel; graduate students and degree recipients by field, sector, and institution; and the support for graduate education and training. NSF, NIH, and the National Research Council. (NRC) publish detailed indicators on a regular basis. However, the science policy community lacks consensus on which indicators are most useful or reliable. A report or workshop on the use of science indicators to measure the health of the research effort in the United States would be a useful first step in that direction.

It is important to remember that all measures or "indicators" of research inevitably are flawed. Any number describing research is an abstract symbol that depicts, imperfectly, only one aspect of it. Choosing one measure over another implies that the measurement user has made some assumption about what is important. The chosen measure has meaning only through interpretation.

These points underscore the subjective nature of quantitative measures of research—''objectivity" is only apparent. Attaching numbers to some phenomena allows the expression of certain features in symbols that can be manipulated and configured for analysis. This ability is invaluable for analytical comparisons and the descriptions of trends. Nevertheless, a number remains no more than an abstract symbol that someone decided best captures a particular aspect of some real-world phenomena.

RESEARCH DECISIONMAKING IN INDUSTRY AND GOVERNMENT

To determine the degree to which economic and noneconomic techniques are used by research managers today, OTA reviewed the literature on the use of these techniques in industry and government and interviewed experienced officials in both sectors. A list of those techniques is provided in table 2. The findings were quite surprising.

In industry, where one might expect quantitative techniques to prevail due to the existence of a well-defined economic objective for the individual firm or business, OTA found great skepticism among research managers about the utility of such techniques. Managers found them to be overly simplistic, inaccurate, misleading, and subject to serious misinterpretation. At the project selection and program evaluation levels, there is little systematic data about the use of quantitative techniques. Most articles describe a process adopted by one firm or another without any indication as to how widespread the practice is in industry as a whole. This literature is reviewed in chapter 4.

Peer review dominates program evaluation in industry, with an occasional firm attempting bibliometric analyses. For project selection, firms use standard economic return on investment techniques for projects at the development end of the cycle, where costs and benefits are generally well known and the risk can be quantified using past experience. At the basic research end of the spectrum, industry's project selection techniques tend to be quite subjective and informal, supplemented occasionally by scoring models. (See ch. 4 for definitions of the different techniques used in project selection.) At the applied research or exploratory development stage, simple, unsophisticated selection procedures, based on a page or two of qualitative information or a simple rating scheme, dominate.

Table 2.—Quantitative Methods Used To Evaluate R&D Funding

Economlc (measure output in terms of dollars or productivity)
- Macroeconomic production function (macroeconomic)
- Investment analysis
  - –Return on investment (ROI)
  - –Cost/benefit analysis (CBA)
  - —Rate of return
  - —Business opportunity
- Consumer and producer surplus

Output (measure output in terms of published information)
- Bibliometric (publication count, citation, and co-citation analysis)
- Patent count and analysis
- Converging partial indicators
- Science indicators

Project selection models
- Scoring models
- Economic models
- Portfolio analysis (constrained optimization)
- Risk analysis and decision analysis

SOURCE: Office of Technology Assessment.

At the level of strategic planning and resource allocation for R&D in industry, some interesting patterns have emerged. Industry tended to fund research somewhat unquestioningly in the 1950s and 1960s, only to become skeptical of a lack of demonstrable return on the investment in the 1970s. Each industry tended to have a rule of thumb; R&D should bes percent of sales, or perhaps 10 percent in an R&D-intensive industry. In the 1970s, corporate strategic planning came into vogue, and technological change came to be recognized as an integral part of corporate planning. R&D planning and budgeting was integrated into the overall corporate strategic effort. Many firms set up committees and other formal mechanisms to assess long-term technical opportunities, establish broad goals for the commitment of resources, ensure that resources are properly allocated to develop the technology necessary to support those goals, approve major new product programs, and monitor progress.

The primary goal of such committees appears to have been to ensure that R&D managers communicate regularly and formally with planning, financing, marketing, manufacturing, and other concerned parts of the corporation in setting and achieving technological goals. Corporate managers have learned that R&D planning and budgeting is primarily an information and communication process, involving many persons and many levels of the corporate hierarchy, using many criteria and several iterations. The goal of corporate managers has been to improve communication by involving all affected parties. Economic and financial modeling appear to play a secondary role in this process, seining primarily as inputs to overall corporate strategic planning.

Government R&D managers also avoid quantitative techniques for project selection and program evaluation. Surveys of government research managers reveal little use of quantitative methods for choosing projects or evaluating program: (some notable exceptions are discussed inch. s) Peer review tends to be the preferred method of project selection, with the term "peer" often broadened to include agency technical staff. Bibliometric techniques have been used extensive> by NIH and on a limited basis by NSF in program evaluation. NASA and the National Bureau of Standards have carried out economic return-on investment analyses, with limited success.

Budgeting for research and development share many of the characteristics of traditional Federa budgeting. It is incremental, fragmented, special ized, repetitive, and based, to a large degree, or recent history and experience. Much of the bud geting is carried out by experts in narrow special ties, who focus their attention on increments to existing base programs. Attempts to "rationalize the system by introducing techniques such a "program planning and budgeting (PPB)" and "zero based budgeting (ZBB)" have largely bee: abandoned as unworkable and inappropriate given the political nature of the Federal budge process.

Some R&D forecasting and strategic planning is carried out by agency advisory committees such as NSF's National Science Board, DOE Energy Research Advisory Board, and NHI's advisory councils. NRC and its constituent bodies forreally review Federal research programs and produce *Research Briefings* and *Five-Year Outlook* that identify promising new avenues of research None of those efforts constitutes true strategic planning or forecasting. The Japanese, however provide an interesting model of systematic forecasting and planning for R&D.

Chapter 5 also describes the R&D forecasting carried out by Japan's Science and Technology Agency and Ministry of International Trade and Industry. These forecasts identify research areas of long-term strategic importance using background information on research trends gleaned from industry, government, and academic reports from around the world. They incorporate "technology-push" and "market-pull" perspectives by involving both laboratory researchers and industrial users, and utilize a bottom-up rather than a topdown approach, drawing heavily on recommendations from the affected communities. The process provides a forum for people from different groups and different professions to communicate about R&D priorities. This enables policymakers, professional forecasters, scientific analysts, and academic and industrial researchers to coordinate research plans and to form a consensus on priorities for future strategic research. Participants have a stake in the successful outcome and follow-through of the process, which tends to make the forecasts self-fulfilling. The emphasis on communication and involvement of all affected parties is strikingly similar to the lessons learned by U.S. corporate management with respect to R&D planning and resource allocation described above.

The review of industry and government R&D decisionmaking presented in chapters 4 and 5 leads to two conclusions. First, R&D management and resource allocation are complex decision-making processes involving trade-offs between factors that often cannot be precisely measured or quantified. Any effort to substitute formalistic quantitative models for the judgment of mature, experienced managers can reduce rather than improve the quality of R&D decisionmaking. The resistance of R&D managers to the use of quantitative decision tools is, to some degree, a rational response to the complexity and uncertainty of the process.

Second, the process of decisionmaking can often be as important as the outcome. In both the U.S. and Japanese cases, bringing together experts from a variety of fields and sectors and providing them with a vehicle to discuss R&O priorities, budgets, and plans, was critical to success. It may be that discussions of R&D resource allocations in the United States should focus less on the overall numbers and more on the process by which those numbers were generated, with special attention paid to questions of stakeholder involvement and communications.

SUMMARY

In summary, OTA finds that the metaphor of research funding as an investment, while valid conceptually, does not provide a useful practical guide to improving Federal research decisionmaking. The factors that need to be taken into account in research planning, budgeting, resource allocation, and evaluation are too complex and subjective; the payoffs too diverse and incommensurable; and the institutional barriers too formidable to allow quantitative models to take the place of mature, informed judgment. Bibliometric and other science indicators can be of some assistance, especially in research program evaluation, and should be used more widely. However, they are extremely limited in their applicability to inter-field comparisons and future planning. The research planning and budgeting experience in some U.S. corporations and the R&D forecasting efforts in Japan suggest a need to improve communication between the parties that carry out and utilize research, and to assure that a wide range of stakeholders, points of view, and sources of information are taken into account in formulating R&D plans and budgets.