Chapter 8
Economic and Social Significance of Scientific and Engineering Research

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HIGHLIGHTS

- **The study of economic returns to research and development (R&D) investment has developed over the past 30 years, and although there are differences in estimates of the exact levels of returns, the leading researchers in the field agree that R&D has a significant and important positive effect on economic growth and the overall standard of living.**

- **Research on the economic and social effects of science and engineering (S&E) research involves complex issues of measurement, analysis, and interpretation.** Results are often approximations, not absolutes, and observed relationships are subject to change as society, the economy, and science change.

- **Academic research plays a key role in enabling technological advances in the private sector, especially in medicine and electronics.** According to one survey, approximately 10 percent of new products and processes depend on recent academic research. Another survey provides evidence that the association between academic and industrial research has been strongest in medicine and electronics. For example, in 1990, universities were responsible for 18 percent of all U.S. patents dealing with genetic engineering and recombinant DNA, 16 percent of patents dealing with natural resins/peptides or proteins, and 12 percent of patents dealing with chemicals involving microbiology and molecular biology.

- **There often is a significant delay between the dissemination of fundamental knowledge and its eventual effect on industrial processes.** One estimate of the delay is approximately 10 years for new knowledge in computer science and engineering and 20 years for new knowledge in S&E in general.

- **The fast pace of recent scientific advances in areas such as information processing, communications, and biotechnology, as well as the wide variety of social effects that these advances may cause, has made the question of the effects of science and engineering on society extremely complex.**

Introduction

The purpose of this chapter is to provide information on the economic and social effects of science and engineering (S&E) research on society. It discusses indicators of and approaches to examining the economic significance of S&E research, and provides an overview of the broad aggregate effects of research and development (R&D) in the lives of Americans.

S&E research is extremely complex. How the results of individual projects and collections of projects interact to produce both positive and negative effects on society is even more complex. Furthermore, scientific knowledge accumulates, with each generation of new knowledge building on the previous ones. It is difficult for any study to provide a thorough accounting of all of the positive and negative social and economic effects of S&E discoveries or to include all of the research activity that leads to specific products or impacts.[1] Nevertheless, this is an increasingly important and interesting topic. Therefore, the National Science Board has developed this exploratory chapter to provide some initial indicators of the ways that S&E research influences the economy.

Measurements of the returns to investment of R&D have long been studied by economists. This chapter provides a review of available research findings on the topic. Less research has been done on how S&E research results affect aspects of the quality of life, or even what constitutes quality of life and what factors affect it. This chapter briefly discusses some possible areas of inquiry related to this complex topic. As research in these various fields progresses, new indicators will be developed, and they will be elaborated in future reports.

Economic analysis of S&E research offers a single, though limited, framework for evaluating the potential outcomes of public and private financial support of S&E research. The limitations of economic analysis take several forms; in particular, the economic value of anything is generally limited to the concept of the prices of goods and services, as determined in a market, or the "willingness to pay" for something that would be expressed by buyers under certain hypothetical market situations. Economic value, then, is not necessarily congruent with the idealistic, legal, or ethical values that also underlie social decisionmaking (Kelman, 1981). This concept of economic value distinguishes the field of economics from many of the other fields of social science and philosophy. Other limitations in economic analysis are operational and involve the way such analyses are conducted, such as limitations in data and conflicting theories among economists.

[1]For a discussion of the issues, see Cozzens (1994) and (1995).

Economic Studies of Productivity Growth

A key factor in economic studies has been the effect of R&D on "productivity," which has different meanings depending on the particular question being asked. The most common definition is the amount of a good or service, called an output, that can be produced with a certain number of workers. For example, productivity is said to rise in the United States when the total output per worker rises. A more detailed analysis of productivity recognizes other inputs into the production process besides labor, such as capital and materials. For instance, if the inputs remain the same in a factory but the existing machinery is adjusted to render greater output, the productivity of capital is said to rise. In economic studies of technical change, a concept called total factor productivity is often used. This represents the productivity that can be associated with *all* of the inputs involved in production. In many cases, total factor productivity is preferable for looking at the effects of technical change, because separating out productivities among inputs is often difficult or ambiguous.

The traditional method for analyzing productivity in economics has been to use a mathematical construct, called a production function, to interrelate the quantity of output produced with quantities of inputs utilized—primarily capital and labor.[2] Labor is measured in terms of full-time-equivalent employees per year, and capital in terms of how much the equipment and facilities would cost if they were rented for a year. Productivity is said to increase when more output can be produced with the same amounts of inputs. When observed changes in productivity can be associated with R&D activities, the *value* of those productivity changes is considered a *return* to R&D investment.

With regard to scientific research, productivity changes may best be associated with the link between (1) new equipment, facilities, and organizational structures, and (2) cost reductions in the supply of existing goods and services. Studies in this area range from examinations of a specific innovation and the particular effects that it had to examinations of aggregate estimates of productivity growth for an entire economy as a result of all R&D performed. These studies focus on particular types of research, such as academic, government sup-

[2]In production processes and services, materials are also used: the materials that the firm purchases to piece together into a final product (e.g., component parts, or supplies purchased by the firm for use in providing a service). Energy and other services purchased by the firm are usually significant as well. In some studies on productivity, the quantity of output with regard to the production function was measured as the sales value of the output, minus the costs for materials and other factors that were not classified as capital or labor. Such output measures are called value added because they reflect the extent to which the firm increased the value to the consumer of the materials which that firm had purchased. Recently, there have been greater attempts to include materials as inputs in the production function, thereby removing the need for the value-added calculation. See Gullickson (1995) and Jablonski (1995).

ported, and private, and on types of economic effect, such as cost reduction and quality improvement to the organization performing the research, as well as spillover effects that benefit those who did not pay for the research.

Terleckyj (1980, p. 376) divided the effects of private R&D into two groups: "(1) direct increases in productivity of industries conducting the privately financed R&D, and (2) indirect increases in productivity of industries purchasing capital and intermediate inputs from the industries conducting the privately financed R&D." He found the latter effect to be greater, on average, across all industries. In another study, Levy and Terleckyj (1982) examined government financed R&D and observed that it had the effect of stimulating additional private R&D expenditure. Similar complementarity between government and private R&D was observed again by Leyden and Link (1991).[3]

Economic analysis of R&D investments has progressed over the past 30 years, and although there are differences in estimates of the exact levels of returns, the leading researchers in the field agree that R&D offers high private and social returns in terms of high productivity. (See *Rates of Return*.) It should be noted, however, that the precise magnitude of these returns cannot be measured without the use of simplifying assumptions in the analysis. A recent survey article by Nadiri (1993) examined 63 studies in this area published by prominent economists, mostly in reference to the United States, but also in reference to Japan, Canada, France, and Germany. Looking at the results of these studies, he concluded that R&D activity renders, on average, a 20- to 30-percent annual return on private (industrial) investments. R&D renders a much greater return to society overall. Estimates of these "social rates of return" range from 20 to 100 percent, with an average of approximately 50 percent (Nadiri, 1993). These figures for the aggregate effects of R&D are consistent with the high returns often found in the analysis of individual innovations. For example, Mansfield (1994) examined three studies of sets of specific innovations, which reported social rates of return of 56, 70, and 99 percent. Recent work by Brynjolfsson and Hitt (1993) found the returns from information technology to be quite high, exceeding 80 percent per year from 1987 to 1991 (Magnet, 1994). Trajtenberg (1990), whose work is described in greater detail below, found the social rate of return from innovations in a particular type of medical equipment (computed tomography scanners) to be as high as 270 percent per year. This is not to say that every research project has a high, or even a positive, rate of return, but portfolios of scientific research projects selected for analysis have the rates of return cited above.

Several recent studies on U.S. industries estimate average rates of return from R&D investments. (See text table 8-1.) The rates of return are for individual firms ("firm-level" studies) or for industries as a whole ("industry-level" studies, often by standard industrial classification [SIC]). These rates differ, depending on the time period being studied, the type of data, and the analytical method employed. Nevertheless, taken together, they reveal that R&D does tend to render high rates of return.

Griliches (1994) examined data on different industries from 1958 to 1989 and provided strong evidence that industrial productivity increases with increased R&D expenditure as a proportion of sales volume. He noted that the computer industry is a major outlier in the data. It has both the highest productivity growth and the highest ratio of R&D to sales. With computers left out of the data, the relationship between R&D and productivity is not as strong, though it is still substantial. Although R&D is a statistically significant, contributing factor to productivity growth, productivity differences across sectors of the economy cannot be explained by R&D alone.

Because of difficulties in assessing the economic value of new and improved goods and services, it has always been difficult for economists to measure productivity precisely. Higher quality goods and services can have the same prices or be measured in the same quantities as lower quality goods and services. As a result, the real economic value of new goods and services is sometimes underestimated, along with the productivity of the industries that produce them (Gordon, 1990).

Many other types of measurement problems can arise. Suppose a newly developed computer costs the same amount to produce and to operate as its predecessor, but it performs twice as many calculations per second. Intuitively, the new computer is twice as productive as the former one.[4] Information about product characteristics is often unavailable, however, and even when it is available, its relationship to productivity can be extremely complicated. The productivity of the improved computer may be less than twice that of the former computer or more than twice that of the former computer, depending on how much of the capacity is tapped. Without such information, it is difficult for any researcher to determine the extent to which productivity increases are attributable to the new computer.

Traditionally, economists have evaluated a product's value using price. However, for instance, a new computer's price is not a good indicator of its productive value. Price depends on several factors not necessarily related to the computer's productivity, such as the costs of producing the unit, the competitiveness of the market, and speculation among computer buyers about the future availability of another even better computer (which would lower the price of the existing computer by reduc-

[3]The literature is quite extensive in this area, and therefore, an adequate literature review would not be possible within the confines of this chapter.

[4]In a more complicated analysis, one might consider the economic concept of diminishing returns, in which the additional calculations are not as valuable as the first set of calculations.

Rates of Return

All investments have rates of return that measure the extent to which investors earn money for their initial investment. Many rates of return are based on a preset arrangement between the borrower and lender. For example, if a person opens a savings account that has a 3-percent interest rate and places an initial investment of $100 in the account, 1 year later, the investor would have $103 in the account—the original investment, plus 3-percent interest.

For most investments, neither total expenditures nor total earnings occur at a single point in time, but in flows of different quantities in different years. Investors use the concept of net present value to equilibrate amounts of expenditures or gains occurring at different points in time. Net present value represents the comparison of an amount of money at the present time and its value in the future.

For any risky investment, once the flow of expenditures and gains has stopped, investors can calculate the internal rate of return based on these values. In effect, this calculation answers the following question for the investor: Suppose there were a savings account with a constant interest rate that could have been invested in, instead of making the investment actually made. What would that theoretical interest rate have to be to make the investor equally content to have made the investment?

The internal rate of return allows for a concise and objective method of comparing the relative success of different investments. Suppose one investment involved an initial expenditure of $100 and yielded a single gain, 1 year later, of $105, while another investment also involved an initial investment of $100, but yielded a single gain of $106.12 after 3 years. In this example, the first investment would be regarded as economically preferable, even though the specific amount of money received was less, because it had an internal rate of return of 5 percent, while the second investment had an internal rate of return of only 2 percent. The superiority of the first investment is evidenced by the fact that the investor could have recycled the earnings in the same investment for 2 more years, which would have rendered a total of $115.76 after 3 years instead of $106.12.

For any given income stream of expenditures and gains from a research project or collection of projects, with expenditures represented by negative numbers and gains by positive numbers, the internal rate of return can be interpreted mathematically as the hypothetical interest rate that would cause the net present value of the income stream to be zero. It can be calculated by solving an equation in which the sum of all time-adjusted expenditures and gains is set to zero.*

From its definition, the internal rate of return can be calculated once all the gains, losses, and timeframes are known. Estimating rates of return for scientific research is difficult because of inherent problems that exist in estimating a project's potential gains and losses. For instance, research in one area may be interdependent with research in a related area, making it difficult for investors to separate their individual effects. Furthermore, society often gains more from a successful scientific advancement than does the organization conducting the research. Consequently, there are two rates of return: the private rate of return, which is based on the expenses incurred and profits made by the company conducting the research, and the social rate of return, which is based on the overall effects on society, including the firm conducting the research.

*Set $0 = \Sigma_{t=0} X_t(1+r)^{-t}$ and solve for r, the internal rate of return (as a proportion), where the investment begins at time $t = 0$, and X_t is an expenditure (negative) or gain (positive) at time t. For example, if one invests $100 dollars at $t = 0$, and receives $105 dollars in the next year when the investment is terminated, then we have: $-100 + 105/(1+r) = 0 \Rightarrow r = .05$, i.e., the internal rate of return is 5 percent.

ing demand for it). Finally, the improved productivity of the firm that purchases the new computer may be strongly interrelated with the application of new software associated with the new computer, as well as its employees' programming skills.

These concerns regarding productivity measurement, especially as they relate to the quantification of new forms of capital equipment, have long been recognized by economists. In one of the earliest works on the productivity effects of R&D, Solow (1957, p. 312) notes that his analysis is limited by "the profound difficulties that stand in the way of giving any precise meaning to the quantity of capital." Given the complexity of production processes, the difficulties of calculating productivity changes attributable to R&D involve not only informational difficulties, but often analytical and philosophical ones as well (Blaug, 1992; Boskin and Lau, 1994; Chase, 1979; Eichner, 1983; Griliches, 1992). On the other hand, such limitations have tended to produce underestimates, more than overestimates, of the importance of R&D (Nordhaus, 1994). Consequently, the high rates of return to R&D observed by economists serve as evidence of the importance of scientific research to the Nation's economy.

When investment in physical capital or in inventories of raw materials yields a high return, it is often due, indirectly, to scientific or engineering advances, even

Text table 8-1.
Estimated annual rates of return to R&D expenditures in the United States, according to various economic studies

Firm-level studies		Industry-level studies	
Author(s) and year of study	Rate of return[1]	Author(s) and year of study	Rate of return[1]
	— Percent —		— Percent —
Link (1983)	3	Terleckyj (1980)	NS[2]
Bernstein-Nadiri (1989b)	7	Griliches-Lichtenberg (1984a)	4
Schankerman-Nadiri (1986)	13	Patel-Soete (1988)[3]	6
Lichtenberg-Siegel (1991)	13	Mohnen-Nadiri-Prucha (1986)	11
Bernstein-Nadiri (1989a)	15	Terleckyj (1974)	15
Clark-Griliches (1984)	19	Wolff-Nadiri (1987)	15
Griliches-Mairesse (1983)	19	Sveikauskas (1981)	16
Jaffe (1986)	25	Bernstein-Nadiri (1988)	19
Griliches (1980)	27	Link (1978)	19
Mansfield (1980)	28	Griliches (1980)	21
Griliches-Mairesse (1984)	30	Bernstein-Nadiri (1991)	22
Griliches-Mairesse (1986)	33	Scherer (1982, 1984)	36
Griliches (1986)	36		
Schankerman (1981)	49		
Minasian (1969)	54		

[1]For studies for which Nadiri (1993) reports a range of possible returns, the midpoint of that range is provided in this table.

[2]Not significantly different from zero in a statistical sense. This result, however, may be a reflection of limitations in the quantity of data used in the study.

[3]Economy-level study (all industries grouped together).

SOURCE: M.I. Nadiri, "Innovations and Technological Spillovers," Working Paper No. 4423 (Cambridge, MA: National Bureau of Economic Research, 1993).

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though the investment itself does not fall under the heading of R&D. In effect, R&D conducted in one industrial sector has beneficial spillover effects in another, in the form of returns to investors and consumer satisfaction. These ripple effects have continual and strong influence on investment opportunities, many of which are not directly associated with scientific research.

These results should be viewed in a larger context. Although average rates of return to R&D investment have been estimated to be quite high, economists have also observed equally high, and sometimes even greater, rates of return for other types of investment by firms. Non-R&D investments could include, for example, enhancement of productive capacity through the acquisition of new machinery, advertising, marketing research, building up of inventories, hiring consultants to improve managerial practices, and speculative purchases of assets in anticipation of price increases. Because results of research cannot always be predicted and often require a long time to develop, individual R&D investment decisions carry an element of risk and, in many cases, R&D may not be the most profitable investment a firm could make; the best type of investment would depend on the circumstances particular to a firm.

Industrial Innovations Arising from Academic Research

The sharing of basic knowledge among scientists is essential to the progress of many areas of science. It prevents an enormous amount of redundancy and unnecessary experimentation. Yet, because basic research is often published in scientific journals and shared among colleagues, it cannot be owned the way someone might own a patent. It is generally not possible for the benefits of basic research to be captured only by the scientists and institutions that conduct it. The spillovers, or ripple effects, of basic research have often yielded high returns to subsequent applied research or have had positive effects for consumers of final goods or services that rely on the new technology. Consequently, the overall net benefits of basic research to private investors and to society may be quite high, even when such returns cannot be captured by the individuals and institutions that originally performed the basic research. Basic research frequently is funded by public sources of support or by industrial alliances among private companies that can pool together funds for basic research (Romer, 1993). Basic research is also viewed as a necessary and/or important investment by numerous industrial firms in an effort to remain competitive and to open new markets.

Basic research very often generates knowledge involving many different domains of study including the systematic examination of the physical and biological world as well as human activity, interaction, and behavior.

Because such research cuts across many disciplines and industrial categories, there traditionally has been widespread consensus on the important role of government funding of basic research. Basic scientific research that is supported through public funding is carried out primarily in academic settings. In a recent study, Mansfield (1995) examined the importance of academic research in the development of new industrial products and processes. He surveyed a total of 76 firms in seven industries and asked them about the new products and processes they developed. The firms reported that approximately 10 percent of their new products and processes could not have been developed without academic research. (See text table 8-2.) This type of analysis is understood more easily, and appears to be less ambiguous, than the aforementioned studies on productivity. Moreover, Mansfield's findings confirm the notion that some industries do benefit considerably from certain types of research, including academic research. (For more information on Mansfield's research in this area, see chapter 5, *Academic Research and Development: Infrastructure and Perfrmance, Selected Research on University/Industry R&D Linkages.*)

Rosenberg and Nelson (1994) examine the interrelationship between industrial and academic research. They observe, as many others have done, that academic research is oriented more toward acquiring fundamental knowledge in the sciences, while industrial research focuses more on immediate market applications of R&D. They remark:

> Basic research became increasingly viewed as the task of universities…However, by this we do not mean that such research is not guided by practical concerns…Nor does it mean that university scientists and engineers are not building and working with prototypes of applicable industrial technology…What university research most often does today is to stimulate and enhance the power of R&D done in industry, as contrasted with providing a substitute for it (Rosenberg and Nelson, 1994; p. 340).

Rosenberg and Nelson also recognize a relatively strong association between academic and industrial research in several areas of medicine and electronics, which they attribute, in part, to research support from the Department of Defense and the National Institutes of Health. They observe that, in 1990, universities accounted for 18 percent of U.S. patents in genetic engineering and recombinant DNA, 16 percent in natural resins/peptides or proteins, 12 percent in chemicals involving microbiology and molecular biology, 11 percent in organic compounds under patent class #536, and 11 percent for superconductor technology (Rosenberg and Nelson, 1994).

Jaffe (1989) also examined academic research and industry patents, exploring the possibility of regional effects, in which companies conducting research may benefit from universities in their general location. He argued that such a relationship between industry and academia is consistent, for example, with "conventional wisdom that 'Silicon Valley' near San Jose, California, and Route 128 around Boston owe their status as centers of commercial innovation and entrepreneurship to their proximity to Stanford and MIT" (Jaffe, 1989, p. 957). Using data from the NSF Industrial R&D survey, Jaffe compared research conducted in academic departments with incidences of industry patents within the same state. He carried out the analysis for 29 states for the years 1972–77, 1979, and 1981, covering five broad areas of research: pharmaceuticals and medical technology; chemical technology; electronics, nuclear technology, and optics; mechanical arts; and all other research. He

Text table 8-2.
Percentage of new products and processes that were dependent on academic research, for selected industries in the United States: 1975–85

	Percent dependent, at least partially, on recent academic research for their timely development		Percent developed with "very substantial aid" from recent academic research	
Industry	Products	Processes	Products	Processes
All S&E	3.6	1.7	6.5	15.5
Information processing	11	11	17	16
Electronics	6	3	3	4
Chemical	4	2	4	4
Instruments	16	2	5	1
Pharmaceuticals	27	29	17	8
Metals	13	12	9	9
Petroleum	1	1	1	1
Average	11	9	8	6

SOURCES: E. Mansfield, "Academic Research and Industrial Innovations," *Research Policy* 1991, 20:1–12; and E. Mansfield, "Academic Research Underlying Industrial Innovations: Sources, Characteristics, and Financing," *The Review of Economics and Statistics* 77(1): 55–65, 1995.

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found a significant positive relationship between industrial patents and university research conducted on the same topic in the same state. The strongest effect was in pharmaceuticals and medical technology; followed by chemical technology; and electronics, nuclear technology, and optics. On the other hand, Jaffe mentions that his study does not rigorously establish the causal relationship between university research and industrial patents. That relationship may be reversed, to some extent, by feedback mechanisms, in which industrial patents encourage further research by local universities.

Contribution of Scientific Knowledge to Productivity Growth

As already mentioned, productivity effects are changes in output that are not explained by changes in inputs. In this context, productivity is measured as a "residual effect"—something that is left-over, or unexplained by standard factors. Some economists have explored more direct approaches for understanding technological change. However, because technological change is so broad and diverse, studies are generally unable to characterize aggregate productivity enhancements in terms of a small number of specific factors. Consequently, many economists who are interested in the overall effects of R&D on productivity have focused on relatively broad factors associated with the behavior of firms and the mechanisms through which they evolve via the acquisition of knowledge, e.g., Nelson and Winter (1982) and Rosenberg (1994).

Adams (1990) performed a study combining the two approaches of aggregate productivity measurement and knowledge acquisition by firms. His study used a production function, as in other productivity studies, but with two added inputs: knowledge acquired by firms, and spillovers of knowledge between firms of different industries. As a proxy for knowledge, Adams used the number of articles appearing in technical journals in nine fields: agriculture, biology, chemistry, computer science, engineering, geology, mathematics, medicine, and physics. He attributed these quantities of knowledge to scientific and engineering personnel in those fields, and used data on personnel counts by industry to approximate levels of knowledge by industry. He measured spillover effects among industries based on the commonality of their scientific personnel. He observed that these knowledge inputs explained part of the "residual" defining productivity, and found them to be "sizable determinants of productivity growth" (p. 698).

The principal findings to emerge from Adam's study are that lags in time exist between the appearance of research in the academic community and their effect on productivity. More precisely, Adams (p. 676) found that knowledge strongly contributes to growth, but lags 20 years behind the first appearance of research in the science community. The lag for interindustry spillovers is approximately 30 years. However, computer science and engineering have shorter lags of approximately 10 years.

In analyzing broad categories of goods or services, useful results are often difficult to acquire because of the variation that exists within a category. If a specific product, rather than a category, is considered, then the interrelationship between scientific discoveries and economic effects can be identified more easily. In 1990, Trajtenberg performed such an analysis in one of the most rigorous and sophisticated studies of its kind. He investigated computed tomography (CT) scanners, which are often used in medical diagnosis and had been proven to be superior to X-ray machines. Through detailed collection of expenditure data on R&D by U.S. firms, and complicated analysis of the economic and social benefits that result from different CT scanners, Trajtenberg approximates the annual social rate of return to R&D to be 270 percent.

Quality Improvement, Cost Reduction, and New Goods and Services

Industries that replace existing products with unique products rely heavily on scientific discovery. Siegel (1994) provides the number of new products introduced for broad categories of U.S. industry. Having defined new products as those appearing in different time intervals (1972–77 and 1977–82), Siegel calculates the percentage of shipments in 1982 (in dollar values) devoted to these new products for 20 manufacturing categories (SIC codes 20–39). The two industries with the lowest proportion of sales in new products from 1977 to 1982 were primary metals and electric machinery, with 6.6 and 9.0 percent, respectively, while the two with the highest proportion were nonelectric machinery and instruments, with 26.3 percent and 32.0 percent, respectively. For the 1972–77 period, the percent sales for the instruments category was again highest, this time at 47.2 percent. The second highest category in 1977, however, was petroleum, at 38.2 percent, and the lowest two categories were furniture at 7.4 percent and apparel at 9.4 percent. In 1977, primary metals registered 22.8 percent and electrical machinery 25.1 percent, which differ dramatically from their percentages in 1982.[5] The inconsistency across periods suggests that overall trends in industrial use of R&D could be difficult to observe in terms of new products.

If a particular good or service is defined in terms of scientifically measurable quantities, then measurement difficulties involving quality changes could sometimes be avoided. For example, Nordhaus (1994) examined "lighting," in which he defined quantities of light in lumens, the same measurement employed by physicists studying light flow. He found that, because of scientific and engi-

[5]Because his study focused on price-indexing, Siegel does not offer an explanation for why these percentages across time were different. A simple explanation does not exist, although the circumstantial, individual successes of a small number of new products might provide a partial explanation.

neering advances in lighting technology and in energy generation and transmission, the amount of human labor needed to produce light throughout history has gone down dramatically. In particular, the amount of light that, in 1800, required 5.4 hours of total labor for all aspects of production, required only 0.22 hours in 1900, 0.00060 hours in 1990, and 0.00012 hours in 1992. Nordhaus does not associate these achievements with the R&D expenditures that made them possible. Nonetheless, he demonstrates that, in terms of basic, physical definitions of progress (such as lumens produced per hour of human labor), the benefits of scientific advancement can be quite large and tend to be much larger than what is often revealed by traditional, economic measures of change.

Average Versus Marginal Effect, and Other Considerations

R&D returns can best be understood when a distinction is drawn between an average return and a marginal return. The average return to expenditure on scientific research is the total change in earnings divided by the total amount spent on research. The marginal return is the change in earnings attributable to an additional dollar spent on research, above and beyond what has already been spent. If a society employs the very best scientists first, and conducts research in the most worthwhile areas first, then the average return will be higher than the marginal return. (See *Illustration of the Difference Between Average and Marginal Effects of Research.)*

Statistics on the economic growth of high-tech industries might reflect the investment effects of R&D. For instance, jobs in the United States supported by exports of high-technology manufacturing industries grew from 1.4 million in 1983 to 2.3 million in 1992. Total employment supported by exports from all manufacturing industries grew at roughly the same rate, from 3.5 million in 1983 to 5.7 million in 1992 (Davis, 1995; p. 32). For services, high-tech industrial categories have not been as well established, but statistics defined in terms of specific high-tech products, like computers, may best reflect the growth of high-technology industries. As an example, the share of computers in total investments in durable equipment (by producers) rose from less than 1 percent in 1960 to 11 percent in 1992 (Griliches, 1994).

The effects of scientific research have not always been captured well by aggregate statistics on the growth of industrial groups. For instance, the bottom line for investors is more often profitability than growth, and the two may be distantly related when there is substantial cost reduction through scientific advances in process innovation. For example, an industry that employs more robots in its factories, and replaces factory labor, may be able to produce its goods more cheaply. On paper, it may seem to be "declining" in terms of lower revenues (due to price reductions) and in terms of lower employment, yet, by making profitable use of technology, it may be successful in the eyes of stockholders.

Potential for Additional Research on Social and Educational Indicators

In addition to the indicators presented thus far, indicators of the social and educational impact of science and engineering are also relevant. In particular, several researchers are examining the interrelationships that exist

Illustration of the Difference Between Average and Marginal Effects of Research

Suppose, for the sake of illustration, that a type of research involves only new medical treatments, each of equal value to society. If 100 scientists work on this research, and they tend to discover 10 medications per year, then the "average effect" would be 1 medication per 10 scientists. If a society were generally pleased with this outcome, it may want to hire more scientists to obtain more medications per year.

Suppose it hired an additional 20 scientists, expecting to increase the number of medications per year by two. However, simply increasing the number of scientists by 20 percent may not increase output by 20 percent. Some of the additional scientists hired may not be as productive as those in the first 100, especially if there had been a tendency for organizations to hire the most qualified scientists first. Secondly, even if those additional 20 scientists are as qualified as the first ones, they may not be able to work in laboratories of the same quality or have access to the same resources. Thus, the output per scientist may be reduced.

The output produced by the second group of scientists would be a "marginal effect," not an "average effect." Suppose this second group produced only one additional medication per year instead of two. In this case, society's decision to expand the number of scientists from 100 to 120 should have involved a comparison between the "marginal cost" to society of employing 20 more scientists against the "marginal benefit" of one additional medication per year. This decision rule may seem obvious, but the rule itself could be overlooked by society if it overemphasizes the observation of average effects. For instance, a previous study might have demonstrated "an average return of 1 medication for every 10 scientists." People may mistakenly take this to mean that there will always be 1 medication for every 10 scientists, regardless of how many scientists are employed.

among levels of education, technological advancement of the workplace, and wages.[6] This research is ongoing, however, and has yet to be fully realized. Moreover, while economists have reached a consensus on the methodology of measuring economic returns, they and other social scientists have not reached a consensus on a framework for examining and measuring other social effects of science and engineering. For example, even the concept of the quality of life is not well understood. Consequently, it would be inappropriate, at this stage, to present the findings of studies in this area, although it might be useful to mention what these studies are beginning to explore.

Some early work was done on setting up a framework for monitoring social change.[7] In the late 1960s, a panel of social scientists co-chaired by Daniel Bell and Alice Rivlin came together to discuss and make recommendations to the government concerning the importance of establishing an effort to measure and report on social indicators. Their findings[8] led to the development of a report series on social indicators.[9] However, one of the important missing keys is a consensus on the nexus between science and engineering indicators and social indicators.

Although there is little consensus on a general framework to approach this vast and complex topic, researchers from various disciplines have done work on certain aspects of social and educational impacts of science and engineering. For example, some recent studies have examined wage differentials among groups of people who differ in the level of education they have achieved.[10] These differences in salary may change over time as a consequence, in part, of scientific and engineering advances. That is, changes in the workplace may tend to increase the salaries of highly educated employees, whose skills are more commensurate with new technologies, while decreasing the salaries of less educated employees (Baldwin et al., 1995). As more research is conducted in this area, useful results are likely to emerge.

A related area of interest is educational opportunity, which has recently been linked to information technology. In particular, the quality of many forms of precollege education now depends on children's access to computers. Recent studies have examined the availability of computers to children in schools and at home. These studies have indicated differences in computer availability by income level, suggesting that low-income households may face increased barriers to ensuring their children receive an adequate education for competing in future job markets.[11]

[6]See, for example, Department of Health, Education, and Welfare (1969), which reports on the deliberations and recommendations of a panel of social scientists concerning the importance of measuring and reporting on social indicators.

[7]See, for example, Sheldon and Moore (1968), a compendium of research papers on the concepts and problems of developing various indicators of social change.

[8]See Department of Health, Education, and Welfare (1969).

[9] See, for example, Department of Commerce (1977).

[10]See, for example, Acs and Danzier (1993) and Doms et al. (1995).

[11]See, for example, Rockman (1995).

Science Education and Public Understanding of Scientific and Technological Issues

Science education, at all levels, has given us a greater understanding of environmental issues, food safety issues, medical research issues, and others. (See also Chapter 7, *Science and Technology: Public Attitudes and Public Understanding*.) Education in these areas has enabled people to improve at various activities that often escape formal analysis. Some of these are

- *Choosing the right products and services to consume* by understanding what makes products and services more attractive, safer, healthier, and consistent with other idealistic principles involving their production or use (such as whether they are environmentally safe).
- *Interacting with others*, including raising children (which is enhanced by education on the scientific characteristics of infants and children), helping others in emergency situations (such as administering emergency medical treatment), and interacting with individuals who have physical or cognitive disabilities.
- *Participating in decisionmaking processes involving scientific matters*, such as public decisionmaking on science policy (Petersen, 1984; and Krimsky, 1996), which could call for voicing opinions to others and/or voting, and private decisionmaking, e.g., determining how much physical exercise a person should perform.

Finally, research and the acquisition of knowledge in science and engineering have had beneficial spillover effects on other disciplines. For example, much of the credence that many social scientists pay to the "scientific method," which some believe provides quality control in the social sciences, may be attributed to the influence of the commitment scientists and engineers have demonstrated toward the scientific method.[12] In this sense, science and engineering not only expand scientific knowledge, but provide an epistemological framework that other researchers in other disciplines sometimes emulate (Eichner, 1983; Rutherford and Algren, 1990). That is, scientific research not only teaches about science, it teaches about the process of thinking itself. It helps to promote a culture of *reasoned discourse*, and the economic and social significance of this effect alone could be quite substantial.

Conclusion

The examination of economic indicators showed the difficulties of calculating the "rates of return" on scientific and engineering research. Not only is much of this information unobtainable, or ambiguous, but many of the gains from research are simply monetarily intangible. Translating a medical breakthrough that saves a human

[12] See, for example, Keeports and Morier (1994) on the importance of the scientific method in scientific inquiry.

life into monetary terms is difficult. Studies that have attempted to do so have varied greatly in their estimates. On the other hand, when an analysis is restricted to the sales value of goods and services, or the profits earned by firms, scientific research is often found to have very high rates of return. These results suggest that the true benefits of science and engineering, in terms of all effects—tangible and intangible—could be even higher. Average estimated rates of return have been high, as in Nadiri's (1993) estimate of a 20- to 30-percent return, which he based on several economic studies. This does not mean, however, that each scientific research project will have this rate of return—some will have much lower rates and others much higher.

The complete contribution of a particular scientific project or program is often difficult to trace because research in one area enhances or benefits research in other areas. For instance, the benefits of magnetic resonance imaging (MRI) technology extend beyond its use in medical diagnosis, because the technology is also employed in medical, biological, and neuroscience research. Thus, one cannot assess these benefits without knowing something about MRI's usefulness as a research tool, which is an aspect of the device that extends beyond the "medical sector."

We must also keep in mind that many of the important effects of scientific research may not, themselves, be scientific in character. That is, studies on scientific discoveries have always focused on what makes science interesting, but economic and social effects of scientific advances may not, in themselves, be scientifically interesting. These advances may include improvements in office equipment, industrial robots that can produce goods more cheaply, and diapers that are more absorbent. Scientific advances that are less spectacular may receive less public attention, or the attention they do receive may not be associated with the allure of scientific discovery. Nevertheless, even the seemingly mundane and incremental advances are important to consider in assessments of the economic and social importance of scientific research.

One of the most dramatic effects of recent scientific and engineering research has been the explosive growth of information technology (IT). Some studies have found that IT and other high-tech developments tend to increase disparities among subgroups of the population in terms of employment and educational opportunities. In many instances, technological advances increase the demand for employees with skills in high-tech and IT-related areas, while decreasing the demand for employees without such skills. As a result, the importance of exposure to IT in education, as a factor related to future employment, is growing. Like the proverbial tree falling in the forest, S&E research must be perceived in order to have any real effect. Therefore, S&E research, to be most effective, should be integrated with an education system.

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