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CHAPTER 6

The Private and Social Returns to Research and Development

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THE PRINCIPAL argument for government intervention in industrial innovation has always been the potential gap between the private and social returns to innovative activity.[1] During the more than twenty years since the National Science Foundation Colloquium on R&D and Economic Growth/Productivity in 1971, a large amount of research effort has been expended both on measuring the extent of the gap and on evaluating efforts to close it via government policy. I will survey what has been learned from this research, focusing on the microeconomic evidence, and leave to others the task of integrating the evidence into a macroeconomic perspective. Even restricting my effort to firm or industry-level research, it remains a formidable task, and I will rely in some cases on research that went into some detail on particular topics.[2] In addition, I will confine my review to empirical evidence; theory is included only to the extent that it helps to frame the questions to be asked or to interpret the evidence.

The channels by which the benefits from innovative activity may spill over to agents other than those undertaking it are several. Although they have often been enumerated by other authors, repeating them is worthwhile.[3] First, firms in the same or related industries as an innovating firm may benefit through reverse engineering of products, the hiring away of scientists and engineers involved in innovation, or simply increased gen-

1. Nelson (1959); Arrow (1962).

2. See, for example, Mairesse and Sassenou (1991) and Mairesse and Mohnen (1995) on the contribution of R&D to productivity growth; Griliches (1992) and Mohnen (1994) on the measurement of spillovers and externalities; Terleckyj (1985) on the economic effects of federal R&D; and Cohen and Levin (1989) on market structure and innovation.

3. See, for example, Mansfield and others (1977, pp. 144–66) and Griliches (1992).

eral knowledge of the technology in question. The strength of these spillovers is likely to be a function of proximity, either in technology or geographic space. Second, to the extent that innovative firms are competitive (unable to behave as discriminating monopolists), firms and consumers that buy new products from an innovating industry may benefit by acquiring goods at prices lower than their willingness to pay for such goods. Third, research undertaken in the public or nonprofit sector that is freely disseminated will benefit innovating firms in that the cost of any particular innovation is reduced.

The role of these spillovers at the level of the individual firm has been studied to a greater or lesser extent during the past twenty years. This paper surveys the evidence on the flows from government and university-based research to individual firms, and from the firms to overall productivity growth. The focus is on the impacts of government spending in this area.[4]

Measurement Problems

Several important factors confound attempts to make precise measurements of the private and social returns to research and development (R&D) at the firm and industry level. None is a precisely new concern, but being reminded of them is useful. These factors are (1) the effect of price index (price deflator) measurement on the measurement of productivity growth, (2) the low variability of R&D spending in individual firms and the difficulties that creates for identifying the intertemporal aspects of knowledge production, and (3) the importance of R&D depreciation estimates for measuring rates of return.

In his article "Issues in Assessing the Contribution of R&D to Productivity Growth," written in 1979, Zvi Griliches outlined the difficulties of interpreting firm-level returns to R&D when price indices are poorly measured. The problems he describes are particularly severe with respect to new product innovation. If anything, these problems have worsened, as new and improved products have become an increasingly important part of the output of R&D.[5] Two implications can be drawn about the

4. For spillovers between and among firms, see the survey by Griliches (1992).

5. I have not been able to find statistical evidence on the trends in the relative proportions of industrial R&D devoted to new and improved products as opposed to new and improved processes, but casual observation and a glance at the major R&D–performing industries suggests that this proportion has risen over time. Mansfield (1988) presents

measurement of the contribution of R&D to productivity growth at the firm level. First, if the price indices do not adjust adequately for quality improvement in the output of the firm, measured output will grow too slowly and the contribution of R&D to its growth will be underestimated. Second, if the input price indices do not adjust adequately for quality improvement in the inputs to production, the measured input will grow too slowly and the contribution of R&D to productivity will be overestimated.

To quote Griliches, "Conventional productivity measures reflect, therefore, the cost-reducing inventions made in the industry itself, the privately appropriated part of product innovations within the industry, and the social product of inventions in the input-producing industries which have not already been reflected in the price of purchased inputs."[6] The extent to which this statement is true depends on the kind of price deflation carried out before estimation is performed.

A second measurement difficulty that has confounded researcher after researcher as they explore lag structures in the impacts of research on output is that R&D spending is a smooth series at the firm level. That is, measuring and describing the lags between spending and productivity growth using econometric methods has proved almost impossible.[7] A related implication is that distinguishing between statements such as "R&D intensive firms tend to have higher productivity on average" and "Raising R&D investment increases the productivity of a firm" has proved extremely difficult.

Provided one is careful about the interpretation of results with different deflators, estimating the marginal revenue elasticity of R&D at the firm level with some precision is possible; except for its potential heterogeneity across firms, this measure is probably the easiest to obtain.[8] The reason is that this measure is a function of (relatively) well-measured quantities: real sales and R&D spending.[9] The difficulties arise when turning this measure into a measure of the returns to R&D.

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evidence that this proportion is much higher in the United States than in Japan (two-thirds as opposed to one-third), which makes the issue particularly important in the U.S. context.

6. Griliches (p. 99, 1979).

7. See Hall, Griliches, and Hausman (1984) and Lach and Schankerman (1988) for evidence on the low within-firm variance of R&D.

8. The marginal revenue elasticity is the percentage increase in the sales of a firm in a particular year that can be attributed to a percentage increase in R&D spending. In principle, this should be the percentage increase in the present discounted value of sales over all future years that arise from the increase in R&D in one year.

9. In this case, failing to use a firm- or industry-specific deflator for output is the right

Consider a simple stylized model of the intertemporal effects of R&D on firm revenue:

$$V(0) = \sum_{t=0}^{\infty} \beta^t \, [S(\ldots,R_{-1},R_0,R_1,\ldots,Rt,X_t) - R_t - Xt], \tag{6-1}$$

where R is R&D spending, X is spending on other (variable) inputs, β is a discount rate, and $V(0)$ denotes the present discounted value of this program of R&D spending. Note that the revenue function $S(\cdot)$ is written as a function of all past R&D inputs; no particular pattern has been imposed on their productivity. In this framework, the returns to R&D spending in any year are the partial derivative of firm value with respect to that year's R&D spending:

$$\frac{\partial V}{\partial R_0} = \sum_{t=0}^{\infty} \beta_t \frac{\partial S(t)}{\partial R_0} - 1. \tag{6-2}$$

The marginal cost of a dollar of R&D spending is one dollar in the current year, and the marginal benefit is the present discounted value of the marginal contribution of that dollar to sales in all subsequent years. If the world were stationary (if the returns structure were stable over time) and R&D stopped contributing to revenue after several years, this form of the returns function could be estimated from a simple regression of sales on the past history of R&D.[10] Note that depreciation of R&D is implicit in specifying this relationship, but that it is estimated, not assumed.

However, most researchers go further than the equation above, partly because of the difficulties arising from the high correlation across years of R&D spending at the firm level. Two approaches are possible; both involve assuming the existence of some sort of R&D capital within the

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thing to do. If one is interested in measuring the marginal revenue product to the firm (and ultimately, private returns), adjusting the output for the effects of lower prices would be a mistake, because the firm is not receiving those benefits. Alternatively, if the R&D is producing improved goods, enabling the firm to charge higher prices (that is, increasing product differentiation and, hence, the firm's market power), deflating by an increasing price index will remove some of the revenue gains that accrue to the firm from its R&D. Either way, if the concept to be measured is revenue elasticity (or the profit elasticity), it is incorrect to deflate output by anything more than a gross domestic product (GDP) or consumer price index (CPI) deflator.

10. This is because the coefficients of current sales on lags of R&D would be the same as the partial coefficients of sales in subsequent years on this year's R&D if the relationship were stationary.

firm, assuming a depreciation rate for this capital, and constructing a measure of the capital from a declining balance formula:

$$(6\text{-}3) \qquad K_t = (1 - \delta)\, K_{t-1} + R_t,$$

where K is the R&D capital and δ is its depreciation rate. Given such a capital measure, the revenue function $S(\cdot)$ is now rewritten as a function of R&D capital instead of the infinite stream of past R&D expenditures. The marginal revenue product of R&D in a given year becomes

$$(6\text{-}4) \qquad \frac{\partial S_t}{\partial R_0} = \frac{\partial S_t}{\partial K_t}\frac{\partial K_t}{\partial R_0} = \gamma \frac{S_t}{K_t}\frac{\partial K_t}{\partial R_0},$$

where γ is the elasticity of sales with respect to R&D capital. Substituting equation 6-4 into equation 6-2 results in

$$(6\text{-}5) \qquad \frac{\partial V}{\partial R_0} = \sum_{t=0}^{\infty} \beta^t \gamma \frac{S_t}{K_t}\frac{\partial K_t}{\partial R_0} - 1 = \sum_{t=0}^{\infty} \beta^t (1 - \delta)^t \gamma \frac{S_t}{K_t} - 1.$$

To go any further, depreciation rates, discount rates, and the sales-to-R&D capital ratio must be assumed to be roughly constant over time. Under these assumptions the net excess return to R&D spending is the following:

$$(6\text{-}6) \qquad \frac{\partial V}{\partial R_0} = \frac{\gamma}{r + \beta\delta}\frac{S}{K} - 1 = \frac{\rho}{r + \beta\delta} - 1,$$

where r is the discount rate $(1 - \beta)$ and ρ is simply dS/dK, the marginal revenue product of R&D capital. When ρ is equal to the discount rate plus the discounted depreciation rate, the net excess returns are zero, as expected.[11]

Equation 6-6 is used to obtain rates of return to R&D in two distinct ways in the literature: the first estimates the marginal revenue product r directly as dS/dK, and the second estimates the elasticity γ and multiplies it by the sales-to-capital ratio S/K to obtain an estimate of r. The first method has the advantage that it assumes equalization of gross rates of return (the increase in sales from increases in knowledge capital) across firms, which may be a more plausible assumption than the equalization of

11. The treatment abstracts from the effects of corporate tax system; taking account of the special tax treatment of R&D will change the cost of R&D capital but will not affect the basic point.

sales or output elasticities. However, more plausible might be to assume that the net returns are equalized. This is not the same thing unless the rental price of R&D capital faced by all firms is the same. Note the role of the depreciation rate δ in the denominator of equation 6-6.

The second method has the advantage of not being sensitive to the choice of depreciation rate until the final step, when γ is multiplied by S/K.[12] In the absence of separately measured depreciation rates for the output of R&D spending, making definitive statements about net rates of return to R&D spending is difficult, although measuring revenue elasticities fairly well is possible.

The three issues discussed here by no means exhaust the list of difficulties with the production or cost function approach to measuring the returns to R&D, but they are the most important that arise within that framework. Difficulties with the measurement of other inputs or worries about returns to scale and imperfect competition are secondary, at least for this purpose; the former because it has not had a major impact on the estimates (except via the previously mentioned deflation route), and the latter because they are easily accommodated within the framework.

Private Returns to R&D

Private returns to R&D at the firm level provide a good illustration of the effects of the measurement problems on conclusions reached about the contribution of R&D to economic growth. The productivity growth slowdown of the 1970s produced a wave of research exploring the contribution of R&D to productivity growth. Much of that research has been summarized in a series of survey papers.[13] Using data through the end of 1977, the consensus estimate of the R&D elasticity in these studies was about .10 to .15 in the cross-section, and somewhat less than that over time within a firm (equal to zero using one-year growth rates and

12. To the careful reader, this statement should not be obvious. γ has been defined as the elasticity of sales to R&D capital K, and in principle, the choice of depreciation rate in computing K should affect its estimate. However, numerous researchers have demonstrated that the logarithmic form of the production function is not sensitive to the choice of depreciation rate and that estimates of γ hardly change as δ is varied. (For example, see Griliches and Mairesse (1984) and Hall and Mairesse (1995).)

13. Mairesse and Sassenou (1991); Lichtenberg and Siegel (1991); Mohnen (1992).

as high as .09 using average growth rates). Results on the private rate of return to R&D were extremely variable.

Unfortunately, the surveys are often not explicit about the type of output deflation that was used; in principle, whether the results are interpreted as measurements of private returns depends crucially on deflation. In many cases, these studies were conducted using a single manufacturing sector deflator, so that the elasticity computed is a real sales elasticity and not an output elasticity. The implication thus is that substantial private returns accrued to being an R&D–intensive firm during the 1960s and 1970s.

Three studies of the contribution of R&D to productivity growth take the data through the end of the 1980s: Griliches in 1993 and Eric J. Bartelsman in 1990 using industry data and Bronwyn H. Hall and Jacques Mairesse in 1995 (building on work in Hall's 1993 paper) using firm data. Griliches as well as Hall and Mairesse demonstrate that conclusions about the magnitude of the R&D output elasticity rest on whether or not the output of the computing industry is deflated by the Commerce Department's new hedonic price deflator for computers.[14] Table 6-1 displays the results of firm-level and industry-level total factor productivity growth regressions, with and without Standard Industry Classification (SIC) 357 (office and computing equipment). In the industry-level regressions, the deletion of a single three-digit industry lowers the gross rate of return to R&D from 33 percent to 12 percent.[15] In the firm-level regression, the output elasticity falls by a factor of ten. The reason is that the price deflator for SIC 357 falls by 80 percent between 1981 and 1989, inducing a substantial measured increase in the output of this industry. Because the industry also has high R&D intensity and increasing R&D budgets, the output increase is explained by R&D.

Two conclusions can be drawn from the data in table 6-1 and the papers from which they are derived. First, the excess revenue elasticity

14. Griliches (1993); Bartelsman (1990b); Hall and Mairesse (1995); Hall (1993b). Bartelsman does not explicitly investigate this question, but his estimate of the R&D output elasticity is based on data that have been deflated by the new hedonic deflator, and the estimate is consistent both with Griliches (1993) and Hall and Mairesse (1995). (The within-firm estimate for company-funded R&D is .180 (.012) in table 5 of Bartelsman (1990b)).

15. Griliches (1993) also made an attempt to correct the inputs (semiconductors and components) to this industry for incorrect deflation and also to deflate pharmaceuticals by a properly constructed hedonic index. These corrections raise the R&D intensity coefficients in table 6-1 to .461 (.070) and .348 (.070), respectively, but they leave the gap resulting from deleting the computer industry essentially unchanged.

Table 6-1. *The Returns to R&D*

	Firm-level	*Firm-level*	*Industry-level*
Years	1981–89	1981–89	1978–89
Number of observations	7,616 or 8,110	5,967 or 6,520	142 or 143
R&D variable	R&D or growth in R stock	R&D-to-sales ratio	R&D-to-sales ratio
With computers	.108 (.006)	.269 (.058)	.330 (.073)
Without computers	.012 (.006)	.202 (.057)	.115 (.062)
With computers, no deflation	.027 (.006)	.231 (.055)	

Source: Mairesse and Hall (1994); Compustat data; Griliches (1993); National Bureau of Economic Research 4-digit database; and author's calculations based on Compustat data.

Note: The data are the estimated coefficient of R&D in a TFP regression, with and without firms in Standard Industry Classification (SIC) 357. In the first column, the R&D variable is the first difference of the log of R&D spending (which is approximately equal to the first difference of the log of R&D capital), and the coefficient measures of the elasticity of output with respect to R&D. In the other two columns, the R&D variable is the ratio of R&D to lagged sales, and the coefficient measures the gross return to R&D directly.

for R&D spending at the firm level appears to have declined toward zero during the 1980s. This by itself is not surprising; R&D is no longer a major source of sustainable rents. In his 1986 article reporting the results of an investigation into the private returns to R&D in the 1970s, Griliches said, "R&D as a major component of firm activity was undergoing a diffusion process in the 1950s and 1960s and may not have reached full equilibrium by the end of our period." By the end of the 1980s, at least a temporary equilibrium in the market value of this R&D had been reached.[16]

Second, the computer industry is an anomaly only in that it is one of the few industries for which a serious attempt has been made to adjust for quality change in the official price indices. To measure the output effects of R&D spending at the firm or industry level, the impact of new and improved products on prices in all industries, not just computing equipment, must be taken seriously. This is not a new point, but its importance has grown over the last ten to fifteen years.

Private Returns to Public R&D

Research and development spending covers a wide range of activities: basic laboratory research, or research aimed at the advancement of scientific knowledge, with or without commercial objectives; applied research directed toward practical applications; and research directed toward the development and production of specific new products and processes. The innovative activity itself encompasses even more activities, such as the identification of potential commercial opportunities, assessment of technical feasibility, marketing studies and research, the construction of new manufacturing facilities, and so forth. Nowhere is this more apparent than when considering the impact of federal R&D spending on private industry. More than half of the federal R&D budget goes to the Defense Department; of that 90 percent is spent on development, most of it in private industry (see table 6-2). The rest of the federal R&D budget is split roughly equally among health research, the National Aeronautics and Space Administration (NASA), energy research (including "big" science), and miscellaneous categories (in order of importance, the National Science Foundation (NSF), Departments of Agriculture, Interior, Commerce, and Transportation, the Environmental Protection

16. See Hall (1993a, 1993b) for evidence on this point.

Table 6-2. *Federal Funds for R&D, 1991*
Estimated, in millions of current dollars

Agency	*Federal intramural*	*Industry (including FFDRCs)*	*Universities (including FFDRCs)*	*Nonprofits, other government*	*Total*
Defense	8,988	25,640	1,693	596	36,917
Health	1,879	417	4,979	1,613	8,888
NASA	2,573	4,263	1,234	250	8,320
Energy	428	2,674	2,593	312	6,007
Other	2,528	580	2,346	522	5,976
Total	16,396	33,574	12,845	3,293	66,107

Source: National Science Foundation (1991, table 4-10).
FFDRC = Federally Funded Research and Development Centers.
NASA = National Aeronautics and Space Administration.

Agency, and so forth).[17] Thus looking for the impact of federal R&D is not likely to be a productive activity if only a single metric is used.

Consider the contrast between two examples of federally funded research projects: a Defense Department project to improve the technology of flat computer screens, mostly via grants to private industry, and Department of Energy funding for the construction of a new supercolliding accelerator (now canceled). In principle, the benefits from the first project are likely to flow primarily to firms in the industry (in addition to benefiting national defense) and possibly to consumers if there is price competition.[18] The benefits for society from the second project would be far more diffuse. Direct benefits arising from an increase in knowledge of the structure of matter are likely to take extremely long (decades or longer) to appear and to be exceedingly difficult to trace back to their source.[19] The more immediate impact comes as a by-product of the basic research activity. In their discussion of the supercollider project and its possible benefits, Paul A. David, David Mowery, and W. Edward Steinmueller identified three important by-products of basic research: (1) the education of scientists; (2) the creation of social networks through which

17. See National Science Board (1991, table 4-8).

18. Although contracts may be let to ensure market power for the firm(s) undertaking research (for example, allowing patent waivers so that the firms benefit from the patents they take out), this market power is likely to be greatly weakened, both by the fact that strong foreign competition exists already in this technology and by the rapid evolution that has been characteristic of technologies in this area.

19. See Rosenberg (1994) for some examples of the slow diffusion between fundamental scientific knowledge and important innovations that use that knowledge (for example, laser technology).

information diffuses rapidly before publication; and (3) the stimulus to technology and advances in instrumentation and techniques.[20] Although these effects may not have as long and variable a lag in their impact on growth, they, too, will be hard to measure except at fairly aggregate levels.

Thus two major research questions arise: The first asks specifically about the private returns to federal R&D performed within the firm (about half of all federal R&D is performed within industry; see table 6-1 for a breakdown). That is, does the R&D funded by the federal government act as a subsidy to the firm, or does it simply generate products that are demanded by the government without enhancing the firm's performance in other markets? The second and more difficult question concerns the spillovers to private firms from the part of federal R&D that is performed by governments, universities, and nonprofit research institutions (including FFRDCs, or Federally Funded Research and Development Centers). How large are these spillovers, and does their existence reduce the amount of R&D that the firms would otherwise undertake?

As part of the data collection effort that generates the aggregate statistics reported in the Science and Engineering Indicators, issued biennially, the National Science Foundation collects data on the R&D spending of a comprehensive sample of U.S. corporations and on the share of that spending that is funded by the federal government. Since 1972 microeconomic studies have repeatedly demonstrated that federally funded R&D generates a direct return of zero for the firms that do it, either at the firm or the industry level. Using data from U.S. firms, studies have been conducted by Griliches (firm-level data from 1957 to 1965), Griliches and Frank Lichtenberg (industry-level data from 1959 to 1976), Bartelsman (industry-level data from 1958 to 1986), and Lichtenberg and Donald

20. David, Mowery, and Steinmueller (1988, 1992). See also Rosenberg (1982) for a discussion of the role of basic research in developing and improving scientific instruments. In the specific case of elementary particle physics, Brooks (1985) identifies the technologies of massive data processing and analysis, high-precision surveying, mechanical design, cryogenics, high-power electric transmission, radio-frequency engineering, electronic engineering, control systems engineering, and large volume ultra-high vacuum design as those in which particle physics research has produced the impetus that led to advances. (On a personal note, I spent five years as a computer programmer in this field and can be considered an example of a spillover. At the time of my shift into econometrics programming in 1970, economists had just begun to use the large-scale datasets whose analysis had been familiar to elementary particle physicists for at least ten years and had not yet begun serious use of the nonlinear estimation methods that were routine in particle physics.)

Siegel (firm- and establishment-level data from 1972 to 1985).[21] Although superficially similar, the firm and industry studies sometimes differ significantly in the way in which federally funded R&D enters. In most of the firm-level studies and in the industry-level study of Bartelsman, the R&D in question is the R&D conducted by the firm but funded by the government.[22] Griliches, Lichtenberg and Siegel, and Bartelsman found zero or negative excess returns from this R&D.[23] Other researchers have found that the major impact of federal R&D spending at the firm level may be to increase the firm's own R&D spending.[24]

Griliches and Lichtenberg used the figures for R&D applied to particular product classes (27) that are collected by NSF; these product classes correspond approximately to an "industry of use" rather than "industry of origin" definition, so the experiment is fundamentally different from that being conducted at the firm level, where "industry of origin" numbers are being used.[25] Even so, they were able to find much evidence of a positive impact of federal R&D in an applied product field on the total factor productivity growth in the corresponding 2+–digit industry. If anything, the contribution appeared to be negative in the more R&D–intensive sectors, and zero in others.[26] Taken at face value, these results suggest that the impact of federal R&D on cost reduction or productivity growth may be too diffuse to be captured even at the two-digit level.

The same result has been found using firm-level data in several other countries.[27] In addition, in a cross-country study of fifty-three countries, Lichtenberg found the contribution of government-funded R&D to be zero in a TFP regression that also contained privately funded R&D. The result is somewhat stronger in that it includes potential spillovers across

21. Griliches (1980); Griliches and Lichtenberg (1984); Bartelsman (1990a); Lichtenberg and Siegel (1991).

22. Although the discussion in Bartelsman suggests that the federal R&D data he uses is assigned to product fields (industry of use), the data available to him are only broken down into industries in which the R&D is performed. Zvi Griliches, private communication, 1995.

23. Griliches (1980); Lichtenberg and Siegel (1991); Bartelsman (1990a).

24. Mansfield (1984); Scott (1984); Terleckyj (1985); Lichtenberg (1985).

25. Griliches and Lichtenberg (1984).

26. Using a cost function approach, Mamuneas and Nadiri (1993) have conducted a similar exercise with data on twelve manufacturing industries between 1957 and 1988. They used a single aggregate federal R&D figure to construct public R&D capital as an infrastructure variable and included this variable in a set of conventional cost function estimations. This aggregate R&D measure appeared to reduce costs. The impact was highest in the food, chemicals, machinery, and electrical equipment industries.

27. See Harhoff (1993) for Germany; Klette (1991) for Norway.

industries and firms performing the R&D.[28] The sole exception is Hall and Mairesse, which concluded that in France the returns to R&D were 50 percent higher for those firms for which the government funded more than 20 percent of their R&D.[29] The result may reflect a combination of the relatively high prices at which the output of these industries is sold (at least to some of their customers) and the lack of good price deflators that would correct for the first problem.

How should the finding of zero returns to federal R&D at the firm or industry level be interpreted? Industries in which federal R&D is a major share of R&D spending are the following, in order of importance: guided missiles and spacecraft (376), ordnance and accessories (348), aircraft and parts (372), fabricated metal (34), transportation equipment excluding motor vehicles and aircraft (373–75, 379), communication equipment and electronic components (365–67), and electric transmission and distribution equipment (361). In some of these industries, such as ordnance and guided missiles, the government is the major purchaser, and both prices and output deflators for these industries can be expected to convey little information about true productivity. But in some of the other industries, customers for the products embodying the R&D should include other firms, and this would tend to move measured prices closer to true quality-adjusted prices.[30] A more likely explanation is simply that the R&D is not subject to a market test, and so it should not be expected to yield returns that are localized to the firms and industries that perform it or use its output.

Another channel exists through which the government funding of R&D in private firms may act as a subsidy to innovative activity: It may raise the productivity of privately funded R&D and thus cause the firms to increase their own spending. From the perspective of private or social returns to R&D, this complementarity effect ought to be included. It implies that government-funded R&D raises the returns to private R&D, which in effect lowers the cost of R&D to the firm. Several studies have tried to measure the response of private R&D to government-funded

28. Lichtenberg (1992).

29. Hall and Mairesse (1995). Approximately forty or fifty such firms are in the sample, and they are primarily in the machinery, electrical machinery, electronics, and aircraft industries.

30. But see the discussion in the previous section. If the price deflators make no attempts at quality adjustment, the revenue elasticity, and not the output elasticity, is being measured. Thus zero private returns to federal R&D may be found, but this may have no implication for productivity effects.

Table 6-3. *Federally Funded R&D in Industry*
Millions of 1982 dollars

Industry (2-digit SIC)	*1980*	*1989*
Chemicals (28, extracting 283)	401	67
Drugs and medicines (283)	31	3
Petroleum refining and extracting (29)	177	D[a]
Stone, clay, and glass (32)	51	D[a]
Primary metals (33)	156	27
Fabricated metals (34)	58	107
Machinery (35, extracting 357)	429	
Computing equipment (357)	326	D[a]
Communications equipment and electronics (366, 367)	4,367	4,107
Other electronics equipment (36 ex 366, 367)	D[a]	27
Motor vehicles and other (37 ex 372, 376)	661	1,694
Aircraft (372, 376)	7,732	15,544
Professional and scientific instruments (38)	669	99
Other manufacturing (20–27, 30, 31, 39)	401	924
Nonmanufacturing	907	2,150
Total	16,366	24,833

Source: National Science Foundation (1987, tables 6-5, 6-6, and 6-7); and National Science Foundation (1991, table 4-8).

a. D means the National Science Foundation omitted the number to avoid disclosing the operations of individual companies.

R&D within the firm, and all have concluded that there is a small complementarity effect, on the order of 7 percent (every dollar of federally funded R&D raises the firm's private R&D spending by seven cents).[31] Using survey data and focusing only on energy R&D, Edwin Mansfield and his colleagues found essentially the same number for a sample of forty large eastern U.S. manufacturing firms.[32] A number of this magnitude, although interesting because it is not negative, will have a relatively small effect on the measured private or social returns to this government R&D.

Table 6-3 provides a breakdown of the industries that receive federal R&D funds, drawn from the publications of the National Science Foundation. The table is incomplete owing to the spottiness with which the data have been reported in recent years, but it indicates that only two industries receive more than 75 percent of this funding: aircraft and parts, and communication equipment and electronic components. This reinforces the view that cross-industry regressions may not be the way to

31. Link (1981); Levy and Terleckyj (1982); Levin and Reiss (1984); Scott (1984).
32. Mansfield and Switzer (1984).

look for returns to this kind of R&D. Fortunately, in the case of aircraft and civilian space technology, two excellent case studies are available: Mowery on aircraft and Henry R. Hertzfeld on civilian space technology.[33] The technologies examined by these two studies are different—the first is close to commercial application in general, and the second is more like the supercollider.

Mowery's paper presents several estimates of the rates of return to the government's investment in technology applicable to commercial aircraft. It concludes that these returns depend heavily on how much of the military portion of the aircraft research budget is allocated to civilian aircraft and on whether the budget of the Civil Aeronautics Board (CAB), which had an impact on the diffusion of the technology through its regulatory role, is included. The paper's important finding is that for this technology, the successful outcome of federal R&D efforts depended on the fact that the funding extended far beyond simple basic research into diffusion and utilization. Mowery emphasizes the role of backward linkages in the technological change process in this industry.

The rate of return estimates for civilian R&D investment computed by Mowery illustrate the problems of computing returns to specific R&D investments by the government in environments where there are multiple spillovers, possibly long lags before the embodiment of the output of the investment into products, and institutional structures that impose costs on the economy. He obtains a range of estimates of the internal rate of return to investment in civilian aircraft technology all the way from −4.3 percent to 60 percent. This range does not reflect the true range possible, because he did not compute the return under the most extreme combination of assumptions.[34] The size of the returns hinges on what one includes as the R&D cost in this industry: industry-financed R&D (always), government-financed R&D on civilian aircraft (most of the time), government-financed R&D on military aircraft (up to 25 percent), and the welfare costs of CAB regulation (from zero to 100 percent). The estimates are also affected by the choice of the lag between R&D spending and its embodiment in aircraft; a range of zero to seven years is used. Were one forced to choose a number from this menu, an estimate with a seven-year lag that accounted for the returns to all research on civilian aircraft would seem the most appropriate; this estimate was 24 percent. However, the important message in the paper is that this estimate should

33. Mowery (1985); Hertzfeld (1985).
34. These estimates are reported in table 5 of Mowery (1985).

be qualified by the regulatory environment in which the industry was operating and that potential spillovers from R&D on military aircraft have been neither measured nor accounted for.

In his review of the measurement of the economic impact of federal R&D in civilian space technologies, Hertzfeld is more cautious than Mowery, refusing even to report measures of the rate of return to such activities. This is probably appropriate when dealing with technologies with such a long and uncertain payoff, and whose goal may not be the achievement of a particular target social rate of return. Hertzfeld surveys the range of evaluation types, from large macroeconomic studies to the computation of patent statistics. The macroeconomic studies seem problematical for the obvious reason: Sorting out the benefits from a single federal R&D program from those of a hundred other programs is next to impossible using aggregate economy time-series data. The other studies fall into two basic categories: The first traces the commercial application of particular technologies and attempts to construct cost-benefit ratios. The second relies on patent statistics and measures of the licensing success of NASA. Although the second type clearly indicates a certain amount of commercial activity resulting from research done for NASA, the studies are essentially uninformative as the actual economic contribution of the patented innovations. As Hertzfeld indicates, none of these measures captures the importance of the technological advances arising from the space endeavor—satellite communications, weather and remote sensing satellites, private space launch vehicles, and new materials such as carbon and graphite composites.

Science and Industrial Innovation

Large chunks of nondefense federal R&D spending goes to health and the space program, the rest to energy (including large-scale basic physics research) and other areas, mostly basic scientific research (see table 6-2). Tracing the downstream effects of spending on basic scientific research in any area is a daunting task, and few researchers have attempted to quantify the returns to this activity. As Nathan Rosenberg has pointed out, often technological innovations are based not on new scientific discoveries, but on old science, that is, on scientific principles that have been known for decades or more.[35] Only one serious attempt has been made

35. Rosenberg (1994, pp. 142–43).

at quantifying the contribution of basic science research to productivity growth at a fairly aggregate level, that by James D. Adams and by Adams and Leo Sveikauskas.[36]

Adams describes the construction of a series of industry- and field-specific stocks of scientific knowledge based on the counts of articles published in a large number of scientific journals, weighted by the number of scientists in that field employed in the industry, either currently or with a lag of less than ten years.[37] While such stocks do not summarize investment in basic science in any dollar-financial sense, they allow certain hypotheses to be tested about the contribution of science to industry and possibly reflect on the aggregate effects of science on productivity growth in ways that are not available using the much more refined and targeted, but potentially biased, case study approach. In use, these publication counts are both field-specific and can be weighted by the number of scientists within a particular field working within an industry, so that one can characterize not only the stock of knowledge available, but also the potential to make use of it.

The drawbacks of Adams's approach were the variation in the relative importance of a scientific paper across disciplines, the imprecision with which lags are measured (citation data might help here), the arbitrariness of the obsolescence assumption used (about thirteen years), the unidimensional direction of information flow, and so forth.[38] Nevertheless it is a worthwhile addition to the arsenal for the measurement of the sources of technical change. Adams uses these stocks to help explain total factor productivity growth in a set of nineteen manufacturing industries from

36. Adams (1990, 1993); Adams and Sveikauskas (1993).

37. Adams (1990). The scientific fields considered are agriculture, biology, chemistry, computer science, engineering (combined), geology, mathematics and statistics, medicine, and physics. Typically, these articles are counted with a lag in constructing the stock of knowledge—about twenty to thirty years for most fields and ten years for engineering and computer science. The length of the lag is chosen by some preliminary data exploration for the best predictors of productivity growth. As in the case of R&D spending, estimating the lag length precisely is difficult.

38. Adams and Sveikauskas (1993) present some evidence that science precedes industrial R&D, which then leads to effects on output. But the evidence is not completely compelling, as this fact seems to have been built into their model. Although the nature of technological change may have evolved over the past century toward change that is more purposefully knowledge-based, Rosenberg's (1982) critique of the linear model for scientific research and innovation presumably still has some validity. It would be interesting in this connection to conduct model-free causality tests on the processes of scientific output, patenting, R&D investment, and the numbers of scientists and engineers in a field, in the spirit of Pakes (1985).

1953 to 1980 and finds that they enter significantly, with a longer lag of twenty years preferred for their own industry stock of knowledge and thirty years for the knowledge that spills over from other industries.[39] This work is suggestive, although fraught with interpretive difficulties because of its time-series nature. The topic could be pursued further with more detailed data in the future.

Wesley Cohen, Richard Florida, and W. Richard Goe; Adam B. Jaffe; and Edwin Mansfield all document the flow of university-based scientific research toward industry.[40] Cohen, Florida, and Goe report on the results of a major survey of the activities of University-Industry Research Centers (UIRCs) in the United States. Among other findings, they report that UIRCs have become the principal vehicle for direct industry support of academic science and engineering R&D, although government provides half of their total funding. Patent production was comparable to university patent production as a whole, indicating that, in many ways, these centers are simply an extension of the normal university-based research system. The most interesting finding was that the closer integration of industry and university research reflected in UIRC formation "appears to pose a trade-off for society" in that industrial participation promotes technical advance while it restricts communication flow and information sharing and causes publication delays.[41] The centers were successful in achieving the goal of bringing technical advances in the university lab to industry and the commercialization stage sooner.

Jaffe is closest in spirit to Adams, although he goes only as far as the technological output of university-based R&D and does not continue all the way to economic outcomes.[42] He uses variation across states in corporate and university-based R&D to tease out the contribution of university R&D to corporate patenting activity at the state level in five broad technological areas (drugs and medicine, chemicals, electronics and electrical, mechanical arts, and other). With various corrections for the simultaneity between corporate R&D and university R&D at the state level, he finds that the overall elasticity of patenting with respect to university R&D is about 0.1 and that for corporate R&D is 0.9. Because corporate R&D is six times the level of university R&D, this result implies that the marginal product in terms of patents is nearly equal. He

39. Adams (1990).
40. Cohen, Florida, and Goe (1994); Jaffe (1989); Mansfield (1991).
41. Cohen, Florida, and Goe (1994).
42. Jaffe (1989).

also finds that the effects are even bigger in the medical, chemical, and electrical technology areas (0.13 to 0.19). Although measuring the output of university-based R&D in this way is subject to all the usual problems associated with the use of patents as an indicator of technological output, patents arguably are as well suited for this particular exercise as they might be anywhere, because propensities to patent across states, even if they exist, are unlikely to be correlated with anything in particular (once one controls for the industrial mix).[43]

Finally, Mansfield takes more of a case study approach. He begins with commercial innovations in seventy-six firms and traces these back to their academic source (if there is one).[44] Using estimates obtained from the firms concerning the importance of recent academic research for their innovations and the time lags between that research and the first commercial introduction of the relevant product, as well as the total sales from such products, he is able to produce a rough estimate of the returns to the firms from the academic research. This is probably a lower bound on the social return, as it does not include any benefits flowing to consumers from the new products that are above the prices they have paid.

Mansfield reports that approximately 10 percent of new products and processes of these firms could not have been developed in the absence of recent academic research.[45] Using a series of heroic, but plausible, assumptions, he is able to compute a rough lower bound to the social rate of return to this academic research and reports estimates in the 20-30 percent range. As he is careful to point out, his estimates ignore the social benefits from other innovations based on the same academic research, those stemming from sales beyond the first four years of commercialization, those accruing outside the United States, and those accruing to consumers and other firms in and outside of the industry in question.

In his 1995 study, Mansfield goes back to the academic research itself, finding that about two-thirds of the funding of the researchers and projects that ultimately generated these innovations came from the federal government. This is to be compared with the overall 60 percent share of federal government funding in the research performed at universities and colleges, implying that government-funded R&D is slightly more oriented toward science that is eventually useful for industry than university R&D

43. See Griliches, Pakes, and Hall (1987) and Griliches (1990) for further discussion of the use of patent statistics as economic indicators.

44. Mansfield (1991, 1992, 1995).

45. Mansfield (1991).

as a whole. The conclusion from this series of studies is that academic research, much of which is funded by the federal government, is likely to generate extremely high social rates of return in spite of the difficulty of measurement of these returns.

Conclusion

In the past twenty-five or so years, both an increased understanding of the difficulties of measuring returns to R&D precisely and (in spite of this difficulty) some substantive results have been reached.

First, when the primary output of R&D is new and improved products, the allocation of the measured returns to R&D between private returns (the returns to the individual or organization undertaking the R&D) and excess social returns (the returns to society at large net of the private returns) depends crucially on the price indices that are used.

Second, given the intertemporal nature of most R&D investment projects, establishing the lag structure of the contribution of R&D to productivity and measuring the depreciation rate of R&D capital are difficult tasks. Most measures of the total returns to a particular R&D dollar will be imprecise, because these estimates depend crucially on the time pattern of the returns.

Third, the private returns to R&D in U.S. manufacturing have declined between the 1960s and 1980s, approaching something like a normal rate of return, typical of that obtained by the firms from their other activities.

Fourth, the excess private returns to federal R&D performed by individual firms is measured to be zero overall in the United States and in several other countries. Given the goals of such R&D (primarily defense, space exploration, and health in the United States, other national goals such as technological catch-up in other countries), this result is perhaps not surprising.

Fifth, case study evidence of individual research areas (such as satellites and civilian aircraft) supports the view that the social return to such R&D can be substantial, although extremely difficult to trace and measure. Little precise measurement has been made of the returns to federally funded basic science, except in a fairly aggregative manner. But, again, case study and the history of individual technologies suggest that these returns are positive and could be substantial.

What are the areas in which further research would be helpful in answering the kinds of questions asked by government policymakers? To answer this question, a brief review is necessary of the issues that policymakers might like addressed. Given the overwhelming evidence that some positive externalities exist for some types of R&D, the questions being asked typically fall into two categories: How much government subsidy should exist for R&D investment, and on what types of investment should it be spent? The set of policy instruments typically under consideration includes lowering the private cost of R&D (tax credits), direct government subsidy to private firms (for example, defense and energy) or universities (basic science), and performance by the government itself (for example, space and health).

I have written elsewhere about the issues surrounding the use of tax policy to lower the private cost of R&D, thereby increasing the level of privately supported R&D toward that called for by the social returns to such R&D.[46] In evaluating the use of tax policy to achieve this goal, the important issue is the dominant role played by the choice of price deflator in the allocation of the returns to private R&D between a firm and its customers.

The computer industry provides a clear example that the measured gap between private and social returns to R&D, which might be used to guide tax policy toward private R&D, depends crucially on whether and how the output a particular industry is adjusted for the quality change induced by the R&D. Using a conventional price index to measure output, the conclusion could be reached that the industry has achieved a social rate of return to its R&D investment that is similar to the return on ordinary capital. Using a hedonic price deflator that adjusts for the rapid quality change in this industry, the conclusion could be reached that the social return to R&D in the industry has been substantial. Simply put, the elasticity of industry sales with respect to R&D is the sum of two elasticities: the elasticity of price with respect to R&D and the elasticity of output with respect to R&D. If input costs are controlled, firms are concerned with the sales elasticity, consumers benefit from the price elasticity, and society as a whole cares about the output elasticity. Given this, how the sales growth in an industry is decomposed into price and output growth is important for the measurement of returns.

The importance of deflators in computing the returns to R&D calls for further research into the quality adjustment of output deflators at a fairly detailed industry level. A first step has been made by the Bureau of

46. Hall (1993c, 1995).

Economic Analysis in the computer industry, and some efforts also exist in autos and pharmaceuticals, but more is needed. The results should be incorporated into the National Income Accounts, as has been done with computers. In passing, the importance of extending some of this effort to outputs in the service sector should be mentioned, because an increasing share of the nation's industrial R&D is going toward this sector.

In many ways, the question about which the least is known is: What types of R&D investment should be subsidized and can the subsidy be targeted without inducing enormous rent-seeking activity? This question is important for a couple of reasons. First, whether the tax subsidy to R&D induces R&D spending that is as socially useful as direct subsidy is uncertain. Many (including myself) would argue that maximizing the diversity of ideas through decentralized choice of projects is important and would therefore favor some kind of tax subsidy approach on a priori grounds. It would be interesting, however, to attempt to track the progress of the various recent project-oriented funding programs undertaken by the Clinton administration to try to gain some insight into this question.

A related issue concerns the behavior of industry itself in choosing R&D projects. Mansfield presents the finding that two-thirds of the R&D conducted by private firms in the United States is product-oriented instead of process-oriented (as opposed to one-third in Japan).[47] Is this good or bad? Some product-oriented R&D benefits the consumer, as indicated in the computer industry example, but some may be an attempt to increase the market power of one firm at the expense of others by means of product differentiation, with no real welfare gain for consumers. Careful empirical research on this topic in several industries would be helpful in understanding the ultimate effectiveness of the R&D tax credit as innovation policy.

Second, considerable debate has ensued in the United States and other countries over the benefits of targeting government-funded research more closely to specific goals. To help evaluate the trade-off, the line of research that focuses on the downstream benefits of government investment in basic science and technology should be pursued, using the various approaches of Adams (stocks of scientific papers); Jaffe, Manuel Trajtenberg, and Rebecca Henderson (citation-weighted patents); and Lynne Zucker, Michael Darby, and Jeffrey Armstrong (biotechnology case

47. Mansfield (1988).

study, using statistical methods), among others.[48] Jaffe, Trajtenberg, and I have begun a project using patent citations that should produce the information that would enable one to link government activity in a technology to the activity of private firms. The benefit of this type of project is that, in the absence of R&D spending by field (or even in its presence), the use of bibliometric measures is both more output-oriented and more informative as to specific technological field. Research into the benefits of basic science is important because they are likely to be large and they are difficult to measure. Case study evidence, although positive, occasionally suffers from its focus on winners, and it would be helpful to try to fill it out with the computation of returns as in Mansfield's 1991 study.

Comment by Van Doorn Ooms

Edwin Mansfield summarizes primarily the findings of his own research on the contributions of new technology to the economy. For many, this would be a brief undertaking and perhaps not worth commenting upon. For Mansfield, it is the opposite. This industry, which is no longer a cottage industry, over the past nearly a quarter of a century has belonged in large part to him.

Bronwyn H. Hall entered the industry later and, as befits a later entrant, has raised some important challenges. Here she focuses primarily on the impact of government and university-based research on individual firms' contribution to overall productivity growth. In particular, she raises questions about what is known about private returns to research and development (R&D) in light of the conceptual and methodological problems involved in the research.

The two papers reach different conclusions about progress in the field. Mansfield is heartened that a great many gaps in understanding have been filled, at least partially. Hall is discouraged to discover how few of these topics have been completely explored or understood since 1972, even though a great deal of effort has been expended on research.

I am not an expert in the field, so I am not competent to say whether this research glass is half full or half empty. However, this tension is hardly unique to these particular questions. It is a characteristic of eco-

48. Adams (1990); Jaffe, Trajtenberg, and Henderson (1993); Zucker, Darby, and Armstrong (1994).

nomic research broadly and of scientific research paradigms more generally. Nevertheless, Hall is correct to call attention to some of the peculiar problems in this field. As she notes, the problems relate not only to inadequate or unsuitable data, which is characteristic of virtually all fields of economic research, but also to an inability to describe the kind of data desired in some instances—and this is not characteristic of all fields.

M. Abramovitz many years ago warned that the residual measures of technical change were measures of ignorance. The objects of inquiry are still being specified. And while some progress has been made, the difficulties remain formidable.

Mansfield provides a well-organized summary of the major issues and one that is accessible to noneconomists involved in the policy process. A few require underlining.

First, investments in new technology do produce large returns that are diffused among immediate consumers and innovators and the larger society, with a persistent gap between private and social returns. That gap provides a strong case, at least in principle, for public intervention. This is hardly news, but it raises important issues today in a political environment in which it is assumed by many, and certainly by many in the media and the public at large, that the government can do nothing right. Many large public interventions, as Linda Cohen and Roger Noll have shown, unfortunately lend support to that belief.

Second, legal and institutional protections to the innovation process, such as patents, have limited value. Here, time—and lead time, in particular—is money. Policymakers, and especially regulators, should take note.

Another point is that Mansfield's research shows that resources do matter, and in expected and systematic ways with respect to a number of issues in this area. It is not an accident or some deep mystery of eastern culture that Japanese firms successfully appropriated returns from innovations in the United States and in Europe.

Finally, academic research and the federal support underlying it are critical to innovation and economic growth. The economic theory of public goods is strongly supported by testimony on the ground from the consumers.

I do have a couple of relatively minor questions or qualifications. One is that Mansfield finds no reason that university research should not move toward closer alliances with industry. However, he also notes that the function of universities is to provide highly trained individuals, managers, scientists, and citizens. Resources are not unlimited in universities either. They have to be allocated, and the tensions between these uses are often great. Although no necessary conflict exists here, many universities are finding that the teaching function is becoming increasingly problematic with the pressures on teachers and researchers to do other things.

Second, Mansfield notes that the economic significance of new technology depends not only on the research, per se, but also on its commercialization. Not discussed is that spillovers are increasingly likely to spill across national boundaries. Firms now are increasingly global rather than national; the spillovers are likely to be appropriated hither and yon. The question arises for national policymakers: "Who is us?" U.S. consumers, for instance, benefited greatly from Japanese process innovations, even though many of the returns did not accrue to U.S. firms.

Hall's paper reiterates how difficult it is to define, let alone to accurately measure, the variables required to estimate the impact of R&D expenditures on real value added and thereby productivity. As she says, the problem is not that computers are an anomaly. Computers are anomalous because they represent the only serious attempt to develop price indices that would allow economists to try to correctly measure quantities rather than to fall back in confusion on revenues. For that reason, I would strongly subscribe to the conclusions that she and David Mowery came to on the statistical research agenda.

Despite many of the qualifications that have been noted here today, by Hall, Michael J. Boskin, and others, I think most economists believe that spillovers are large, the social returns to R&D being an order of magnitude of perhaps twice that of risky physical capital. In principle, then, a strong case can be made for public intervention to support research. Nevertheless, the political process is likely to become even less supportive than it has been. The characteristics of research are not likely to be especially attractive to elected policymakers. Research expenditures are characterized by long lags before the innovation takes place, very high uncertainty, and beneficiaries that are not easily identifiable. All of those are anathema to politicians who would prefer speed, certainty, and being able to target expenditures on powerful beneficiaries.

This is not a new problem, but a long-standing one in terms of the federal budget. Over the past thirty years, what the Office of Management and Budget has characterized as short-term benefits, principally transfer programs, have risen from about 6 percent of potential gross domestic product (GDP) to approximately 12 percent. Expenditures generally characterized as long-term investments, including R&D and physical capital, have remained at about 2 percent of GDP, or almost exactly where they were in 1960. At the margin, during the cold war, some additional resources were mobilized for long-term investments, and especially for R&D, in the name of national security. But research has now lost its security blanket, and competitiveness (if this term is viewed as a synonym for productivity) has not yet become a satisfactory replacement. It is perhaps less likely to become one while economists wage semantic war about whether the term can be used.

However, and paradoxically, as the case in principle for public support has become stronger, the difficulties in practice have increased. Congress has become an institution of independent contractors, and the discipline that was previously imposed by a stronger committee system and more careful oversight has eroded. Therefore, a coherent policy involving hard choices between expenditures, or between expenditure cuts, has become more and more difficult to implement, even if the administration proposes one. The progression is moving, with the help of armies of well-paid lobbyists, toward government by earmark, and this has been exacerbated by fiscal austerity.

As Boskin said, in principle, austerity should impose discipline and help to make hard choices. But often, at least at this stage in the development of federal budgeting, austerity largely produces what is known on Capitol Hill as fairness, which is a synonym for across-the-board cuts.

A coherent politics is badly needed—public support for long-term investments of all kinds, not only R&D, focused even more on quality and incentives than on the total amounts of resources involved; getting one is a long way off.

Comment by David C. Mowery

The Edwin Mansfield and Bronwyn H. Hall papers take different but complementary approaches, both of which should be preserved. The top-down, aggregated approach of Hall and many others who draw on public or quasi-public data and the bottom-up approach that relies on data from individual firms or individual cases, which is illustrated by the extensive labors of Mansfield, have made important contributions. However, the conclusions of these studies are limited, for a number of reasons. As retrospective studies, they tell much about how the past has operated but provide little insight into what the future will look like.

In most cases, these studies, particularly the work in the top-down tradition, do not allow one to disaggregate among industries, among types of research and development (R&D) investments, or between public and private R&D investments. The conclusions do not provide a sense of where the returns have been highest among different programmatic structures or among different areas of investment. Moreover, because one cannot determine where these returns have been highest in the past, knowing where they are likely to be highest in the future is difficult. So aggregation adds difficulties to those resulting from the retrospective focus.

The retrospective focus is problematic because of the abundant evidence that the U.S. R&D system is undergoing significant structural change. The R&D system within which many of these studies have been conducted may differ substantially from the system that will emerge over the next decade.

It is not only the U.S. R&D system that is experiencing structural change. Some of Mansfield's conclusions about U.S. versus Japanese R&D management also are likely to be qualified or slightly revised in future studies. How might these structural changes affect some of the results of Hall's and Mansfield's work? Hall suggested that some evidence is available that the expansion of R&D investment within the U.S. economy has reduced the private returns to this investment. More study of the causes and consequences of this is important for understanding what the future evolution of the system is likely to resemble.

In Mansfield's work, the role of intellectual property and the degree of formal protection afforded to industrial intellectual property by patents has substantially increased in the past fifteen years. Certainly, a number of statutory changes have been made to try and increase it; arguably, those have had some effect. Other influences are operating, but this is an important issue and may affect the speed with which new industrial technologies leak from one firm to another. Moreover, the entire approach of U.S. firms to the management of their industrial research has changed in ways that may move some practices of industrial R&D management in U.S. firms closer to what Mansfield described in Japan as an attempt to look outside the firm more systematically, to develop links to an array of external institutions, not just universities—national labs in some cases; other firms; various consortia, publicly or jointly publicly and privately financed.

So both of these analyses are snapshots of a series of rapidly evolving or changing targets and, arguably, the pace of this structural change has increased since the mid-1980s.

Two other areas may be important in Mansfield's work on the role of universities. First is the implication of greater reliance by academics on industrial funding. What does that imply about the findings of future work on the returns to academic R&D? Second, with respect to the role of public universities, how are state-level R&D or technology development and regional development strategies influencing the attractiveness of local universities for firms that are pursuing research links? A number of these programs have expanded in the past ten to fifteen years, and they are probably playing a role in some of Mansfield's findings. What that role might be is uncertain.

Other aspects of the Mansfield and Hall analyses raise broader issues. Both Mansfield and Hall emphasize the importance of adoption of the results of R&D for realization of social returns of these investments. This has some complicated implications.

As Hall and Charles L. Schultze suggested, policies favoring the adoption environment for technologies can have a substantial impact. Adoption policy that complements policy influencing investment in and the creation of much of this technology may significantly raise the social returns to these investments. As Schultze suggested, public investments in human capital may complement the innovations resulting from the R&D capital and raise the social returns to R&D investment.

Examining the effects of public R&D investment, as Hall suggested, the interaction between technology creation and technology adoption gets more complicated. Much of the postwar federal R&D spending in industry has been closely linked to federal procurement, especially in defense. The economic effects of federal R&D spending in defense-related technologies are tightly linked to the effects of federal government procurement of goods embodying many of the technologies created from the federal R&D investment.

For example, the realization of effects on industrial structure, certainly much of the so-called military-civilian spillovers, are the result of the joint influence of R&D and procurement investment. This observation has some complicated implications for the estimation of the returns to this federal R&D investment, as Frank R. Lichtenberg has explored. But federal policy on the demand side has influenced the returns to federal R&D procurement in other sectors.

In the U.S. commercial aircraft industry, for example, federal regulation of interstate air travel accelerated technology adoption. In the biomedical industry, federal policies since the mid-1960s have created a buoyant environment for the adoption of medical device technology and pharmaceutical technology by replacing the price sensitivity of users. The influence of federal policies on the adoption of innovations needs to be incorporated more directly into analysis of the effects of federal R&D programs on industrial innovation and national economic performance.

Several important areas need additional work in the aggregate approach to studying R&D. The data on R&D investment and like activities in nonmanufacturing industries must be more systematically counted, to link those data to productivity growth and to other economic quantities that matter.

But if the problems of both R&D data and deflation are severe in manufacturing, as Hall suggested, they are far more severe in the nonmanufacturing sector. Nevertheless, this is something that cannot continue to be ignored as systematically as at present. The public statistical agencies desperately need to improve data collection, analysis, and updating.

Other important research extensions are in the bottom-up analytic approach and complement the aggregate analysis of other scholars. Although individual cases can be misleading, there is a strong argument for further disaggregation and systematic differentiation among industries, among technologies, and among types of R&D investment. Reaching any conclusions about program design or evaluation without this more disaggregated research is difficult. Aggregate analysis cannot be relied upon exclusively.

Another important area for further work is a systematic attempt to update this work, much of which was written by Mansfield, to take account of some of the structural change in this R&D system, both within the United States and elsewhere in the industrial world.

Why does this matter? Enormous political pressure, which is likely to increase, is being felt for better metrics and approaches to evaluating current and prospective federal R&D programs. Current methods for assessing the economic effects of federal R&D programs are weak. As a result, economists are not well positioned to respond to the political demand for evaluation, nor are they well positioned to assess the consequences of shifts in program design or reallocation of R&D investment funds among different areas of research. One real danger is that near-term results will overshadow long-term results in such evaluation, influencing the design of programs in the area.

My final remarks deal with the role of universities in the U.S. innovation system. First is the survey, widely cited, by Wesley Cohen and Richard Florida on the role of industry R&D funding within U.S. university research. The Cohen and Florida survey revealed a surprisingly high financial contribution by industry to academic research. I do not have a good explanation for this unrepeated finding. One reason may be that the sample of universities included in the survey is a much broader one than is typically analyzed in much of the work on university-industry research relationships. The typical sample tends to be confined to the research universities. That the broader sample yields evidence of higher financial contributions from industry suggests that in overlooking this lower tier of universities, those focused on by Mansfield, a more sustained interaction may have been missed between industry and universities that goes back much earlier into the postwar period than previously thought.

Another interesting implication from Mansfield's work on the role of the second-tier universities deals with peer review. One of the subversive implications of some of Mansfield's work is that the kinds of academic excellence that are rewarded by the peer review system that has driven so much of federally funded academic research is of limited relevance to industry-funded research, at least some parts of it. What do these conclusions imply about the political robustness of peer review in a future academic research enterprise in which industry funding is likely to play a much more prominent role? The growing role of industry-funded academic research may reduce the importance of peer review in the creation or development of academic research centers.

References

Adams, James D. 1990. "Fundamental Stocks of Knowledge and Productivity Growth." *Journal of Political Economy* 98: 673–702.

———. 1993. "Science, R&D, and Invention Potential Recharge: U.S. Evidence." CES Discussion Paper 93–2. Washington: Census Bureau (January).

Adams, James D., and Leo Sveikauskas. 1993. "Academic Science, Industrial R&D, and the Growth of Inputs." CES Discussion Paper 93–1. Washington: Census Bureau (January).

Arrow, Kenneth. 1962. "Economic Welfare and the Allocation of Resources for

Invention." In *The Rate and Direction of Inventive Activity,* edited by Richard R. Nelson, 609–25. Princeton University Press.

Bartelsman, Eric J. 1990a. "Federally Sponsored R&D and Productivity Growth." FEDS 121. Washington: Federal Reserve Board of Governors.

———. 1990b. "R&D Spending and Manufacturing Productivity: An Empirical Analysis." FEDS 122. Washington: Federal Reserve Board of Governors (April).

Cohen, Wesley, Richard Florida, and W. Richard Goe. 1994. "University Industry Research Centers in the United States." Carnegie-Mellon University.

Cohen, Wesley M., and Richard C. Levin. 1989. "Empirical Studies of Innovation and Market Structure." In *The Handbook of Industrial Organization,* edited by Richard Schmalensee and Robert D. Willig, 1059–1107. Vol. II. Amsterdam: North-Holland.

David, Paul A., David Mowery, and W. Edward Steinmueller. 1988. "The Economic Analysis of Payoffs from Basic Research: An Examination of the Case of Particle Physics Research." CEPR Publication 122. Stanford University (November).

———. 1992. "Analyzing the Economic Payoffs from Basic Research." *Economics of Innovation and New Technology* 2: 73–89.

Griliches, Zvi. 1979. "Issues in Assessing the Contribution of R&D to Productivity Growth." *Bell Journal of Economics* 10: 92–116.

———. 1980. "Returns to Research and Development Expenditures in the Private Sector." In *New Developments in Productivity Measurement and Analysis,* edited by John W. Kendrick and Beatrice N. Vaccara, 419–62. University of Chicago Press.

———. 1990. "Patent Statistics as Economic Indicators: A Survey." *Journal of Economic Literature* 27: 1661–1707.

———. 1992. "The Search for R&D Spillovers." *Scandinavian Journal of Economics* 94 (3, Supplement): S29–47.

———. 1993. "Productivity and the Data Constraint." *American Economic Review* 83: 1–43.

Griliches, Zvi, and Frank Lichtenberg. 1984. "R&D and Productivity Growth at the Industry Level: Is There Still a Relationship?" In *R&D, Patents, and Productivity,* edited by Zvi Griliches, 465–501. Chicago University Press.

Griliches, Zvi, and Jacques Mairesse. 1984. "Productivity and R&D at the Firm Level." In *R&D, Patents, and Productivity,* edited by Zvi Griliches, 339–74. University of Chicago Press.

Griliches, Zvi, Ariel Pakes, and Bronwyn H. Hall. 1987. "The Value of Patents as Economic Indicators." In *Economic Policy and Technological Performance,* edited by Partha Dasgupta and Paul Stoneman. Cambridge University Press.

Hall, Bronwyn H. 1993a. "The Stock Market Valuation of R&D Investment in the 1980s." *American Economic Review* 83: 259–64.

———. 1993b. "Industrial Research during the 1980s: Did the Rate of Return Fall?" *Brookings Papers on Economic Activity: Microeconomics* (2): 289–344.

———. 1993c. "R&D Tax Policy during the Eighties: Success or Failure?" *Tax Policy and the Economy* 7: 1–36.

———. 1995. "Fiscal Policy toward R&D in the United States: Recent Experience." Paper prepared for the Organization for Economic Cooperation and Development meeting on Fiscal Policy and Innovation, Paris, France, January 19.

Hall, Bronwyn H., and Jacques Mairesse. 1995. "Exploring the Relationship between R&D and Productivity in French Manufacturing Firms." *Journal of Econometrics* 65 (1): 263–93.

Hall, Bronwyn H., Zvi Griliches, and Jerry A. Hausman. 1984. "Patents and R&D: Is There a Lag?" Working Paper 1454. Cambridge, Mass.: National Bureau of Economic Research.

Harhoff, Dietmar. 1993. *R&D and Productivity in German Manufacturing Firms.* Universitaet Mannheim Zentrum fuer Europaeische Wirtschaftsforschung.

Hertzfeld, Henry R. 1985. "Measuring the Economic Impact of Federal Research and Development Investments in Civilian Space Activities." Paper prepared for the Workshop on the Federal Role in Research and Development, National Academies of Science and Engineering, November 21–22.

Jaffe, Adam B. 1989. "Real Effects of Academic Research." *American Economic Review* 79: 957–71.

Jaffe, Adam B., Manuel Trajtenberg, and Rebecca Henderson. 1993. "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations." *Quarterly Journal of Economics* 108: 577–98.

Klette, Tor Jacob. 1991. "On the Importance of R&D and Ownership for Productivity Growth: Evidence from Norwegian Micro-Data 1976–85." Discussion Paper 60. Oslo: Norwegian Central Bureau of Statistics (February).

Lach, Saul, and Schanderman. 1988. "Dynamics of R&D and Investment in the Scientific Sector." Working Paper. Mount Scopus, Jerusalem: Hebrew University of Jerusalem, Department of Economics.

Levin, Richard C., and Peter Reiss. 1984. "Tests of a Schumpeterian Model of R&D and Market Structure." In *R&D, Patents, and Productivity,* edited by Zvi Griliches. University of Chicago Press.

Levy, David, and Nestor Terleckyj. 1982. "Effects of Government R&D on Private R&D Investment and Productivity: Macroeconomic Evidence." Paper prepared for the Southern Economic Association.

Lichtenberg, Frank R. 1985. "Assessing the Impact of Federal Industrial R&D Expenditure on Private R&D Activity." Paper prepared for the Workshop on the Federal Role in Research and Development, National Academies of Science and Engineering, November 21–22.

———. 1992. "R&D Investment and International Productivity Differences." Working Paper 4161. Cambridge, Mass.: National Bureau of Economic Research (September).

Lichtenberg, Frank R., and Donald Siegel. 1991. "The Impact of R&D Investment on Productivity—New Evidence Using Linked R&D-LRD Data." *Economic Inquiry* 29: 203–28.

Link, Albert N. 1981. "Allocating R&D Resources: A Study of the Determinants of R&D by Character of Use." Auburn University.

Mairesse, Jacques, and Bronwyn H. Hall. 1994. "Estimating the Productivity of R&D: An Exploration of GMM Methods Using Data on French and United States Manufacturing Firms." In *International Productivity Comparisons*, edited by Karin Wagner.

Mairesse, Jacques, and Pierre Mohnen. 1995. "Research and Development and Productivity." INSEE, Paris and Universite du Quebec a Montreal (January).

Mairesse, Jacques, and Mohamed Sassenou. 1991. "R&D and Productivity: A Survey of Econometric Studies at the Firm Level." *OECD Science-Technology Review* 8: 9–44.

Mamuneas, Theofanis P., and M. Ishaq Nadiri. 1993. *Public R&D Policies and Cost Behavior of the U.S. Manufacturing Industries*. Report 93–44. New York University, C. V. Starr Center for Applied Economics, Research (November).

Mansfield, Edwin. 1984. "R&D and Innovation: Some Empirical Findings." In *R&D, Patents, and Productivity*, edited by Zvi Griliches, 127–54. University of Chicago Press.

———. 1988. "Industrial R&D in Japan and the United States: A Comparative Study." *American Economic Review* 78: 223–28.

———. 1991. "Academic Research and Industrial Innovation." *Research Policy* 20: 1–12.

———. 1992. "Academic Research and Industrial Innovation: A Further Note." *Research Policy* 21: 295–96.

———. 1995. "Academic Research Underlying Industrial Innovations: Sources, Characteristics, and Financing." *Review of Economics and Statistics* (February): 55–65.

Mansfield, Edwin, and Lome Switzer. 1984. "Effects of Federal Support on Company-Financed R&D: The Case of Energy." *Management Science* 30: 562–71.

Mansfield, Edwin, and others. 1977. *The Production and Application of New Technology*. W. W. Norton.

Mohnen, Pierre. 1992. "International R&D Spillovers in Selected OECD Countries." Montreal, Quebec: Cahiers de recherche du departement des sciences economiques de l'UQAM, no 9208 (August).

———. 1994. "The Econometric Approach to Externalities." Montreal, Quebec: Cahiers de recherche du departement des sciences economiques de l'UQAM, no 9408 (November).

Mowery, David C. 1985. "Federal Funding of R&D in Transportation: The Case of Aviation." Paper prepared for the Workshop on the Federal Role in Re-

search and Development, National Academies of Science and Engineering, November 21–22.
National Science Foundation. 1987. *Science and Engineering Indicators 1987.* Government Printing Office.
———. 1991. *Science and Engineering Indicators 1991.* Government Printing Office.
Nelson, Richard R. 1959. "The Simple Economics of Basic Scientific Research." *Journal of Political Economy* 67: 297–306.
Pakes, Ariel. 1985. "On Patents, R&D, and the Stock Market Rate of Return." *Journal of Political Economy* 93: 390–409.
Rosenberg, Nathan. 1982. "How Exogenous Is Science?" In *Inside the Black Box*, edited by Nathan Rosenberg, 141–59. Cambridge University Press.
———. 1994. "Critical Issues in Science Policy Research." In *Exploring the Black Box*, edited by Nathan Rosenberg, 139–58. Cambridge University Press.
Scott, John T. 1984. "Firm versus Industry Variability in R&D Intensity." In *R&D, Patents, and Productivity*, edited by Zvi Griliches, 233–48. University of Chicago Press.
Terleckyj, Nestor. 1985. "Measuring Economic Effects of Federal R&D Expenditures: Recent History with Special Emphasis on Federal R&D Performed in Industry." Paper prepared for the Workshop on the Federal Role in Research and Development, National Academies of Science and Engineering. November 21–22.
Zucker, Lynne G., Michael R. Darby, and Jeff Armstrong. 1994. "Intellectual Capital and the Firm: The Technology of Geographically Localized Spillovers." Working Paper 4946. Cambridge, Mass.: National Bureau of Economic Research (December).

APPENDIX
BIBLIOGRAPHIC SUMMARY OF RECENT RESEARCH ON TECHNOLOGICAL CHANGE

In his article at the 1971 National Science Foundation conference, Professor Edwin Mansfield enumerated questions toward which future research should be directed. This bibliography is an idiosyncratic collection of papers written since then that bear on the topics he suggested.

In some respects, it is discouraging to read over the list of topics on which Mansfield recommended further research and discover how few of them have been completely explored or understood since 1972, despite the great deal of effort that has been expended. To a great extent, this reflects the extreme complexity of the relationship between technological advance and economic welfare, as well as the resistance of some of the most important concepts to quantification. Among other problems, research in this area suffers both from inadequate or unsuitable data and the inability to describe the kind of data desired. In spite of these reservations, a considerable amount has been learned through the efforts of many researchers (to say nothing of the financial support of several branches of the National Science Foundation as well as other agencies, both government and private).

Research and Development

Improvements to the Data

R&D in Various Industries

Lichtenberg, Frank R. 1990. "Issues in Measuring Industrial R&D." *Research Policy* 19: 157–66.

Mansfield, Edwin. 1981. "Composition of R&D Expenditures: Relationship to Size of Firm, Concentration, and Innovative Output." *Review of Economics and Statistics* (November): 610–15.

Better Price Indices

Jankowski, John E., Jr. 1990. "Construction of a Price Index for Industrial R&D Output." Washington: National Science Foundation.

Mansfield, Edwin. 1987. "Price Indices for R&D Inputs: 1969–83." *Management Science* 33: 124–29.

Mansfield, Edwin, A. Romeo, and Lorne Switzer. 1983. "R&D Price Indices and Real R&D Expenditures in the United States." *Research Policy*: 105–12.

Disaggregate R&D in Models Explaining Productivity Growth

Cohen, Wesley M., and David C. Mowery. 1984. *The Internal Characteristics of the Firm and the Level and Composition of Research Spending*. Interim Report to the National Science Foundation. Grant PRA 83–10664. Carnegie-Mellon University.

Basic versus Applied and Development

Griliches, Zvi. 1986. "Productivity, R&D, and Basic Research at the Firm Level in the 1970s." *American Economic Review* 76: 141–54.

Hall, Bronwyn H., and Jacques Mairesse. 1995. "Exploring the Relationship between R&D and Productivity in French Manufacturing Firms." *Journal of Econometrics* 65: 263–93.

Lichtenberg, Frank R., and Donald Siegel. 1991. "The Impact of R&D Invest-

ment on Productivity—New Evidence Using Linked R&D-LRD Data." *Economic Inquiry* 29: 203–28.
Link, Albert N. 1982. "An Analysis of the Composition of R&D Spending." *Southern Economic Journal* 49: 342–49.
Mansfield, Edwin. 1980. "Basic Research and Productivity Increase in Manufacturing." *American Economic Review* 70: 863–73.

Private versus Publicly Funded

Bartelsman, Eric J. 1990. "R&D Spending and Manufacturing Productivity: An Empirical Analysis." FEDS 122. Washington: Federal Reserve Board of Governors (April).
Griliches, Zvi. 1986. "Productivity, R&D, and Basic Research at the Firm Level in the 1970s." *American Economic Review* 76: 141–54.
Klette, Tor Jacob. 1991. "On the Importance of R&D and Ownership for Productivity Growth: Evidence from Norwegian Micro-Data 1976–85." Discussion Paper 60. Oslo: Norwegian Central Bureau of Statistics.
Lichtenberg, Frank R. 1992. "R&D Investment and International Productivity Differences." Working Paper 4161. Cambridge, Mass.: National Bureau of Economic Research (September).
Lichtenberg, Frank R., and Donald Siegel. 1991. "The Impact of R&D Investment on Productivity—New Evidence Using Linked R&D-LRD Data." *Economic Inquiry* 29: 203–28.

Profitability and Risk, Decisionmaking at Firm Level, Strategy Literature

Hall, Bronwyn H. 1993. "Industrial Research during the 1980s: Did the Rate of Return Fall?" *Brookings Papers on Economic Activity: Microeconomics* (2): 289–344.
———. 1993. "The Stock Market's Valuation of R&D Investment during the 1980s." *American Economic Review* 83: 259–64.

Economies of Scale and Scope in R&D

Scale

Cohen, Wesley M., and Richard C. Levin. 1989. "Empirical Studies of Innovation and Market Structure." In *The Handbook of Industrial Organization*, edited by Richard Schmalensee and Robert D. Willig, 1067–72. Vol. 11. Amsterdam: North-Holland.

Scope

Helfat, Constance E. 1992. "Know-How Complementarities and Knowledge Transfer within Firms: The Case of R&D." University of Pennsylvania, Wharton School.

Henderson, Rebecca, and Iain Cockburn. 1994. "Scale, Scope, and Spillovers: The Determinants of Research Productivity in the Pharmaceutical Industry." Working Paper 4466. Cambridge, Mass.: National Bureau of Economic Research (September 1993).

Translation of Basic Science into New Products and Processes

Adams, James D. 1990. "Efficient Funding of Scientific Research: An Experiment in Applied Welfare Economics." University of Florida.

———. 1993. "Science, R&D, and Invention Potential Recharge: U.S. Evidence." CES Discussion Paper 93–2. Washington: Census Bureau.

Adams, James D., and Leo Sveikauskas. 1993. "Academic Science, Industrial R&D, and the Growth of Inputs." CES Discussion Paper 93–1. Washington: Census Bureau.

Cohen, Wesley, Richard Florida, and W. Richard Goe. 1994. "University-Industry Research Centers in the United States." Carnegie-Mellon University.

Gibbons, Michael, and Ron Johnston. 1974. "The Roles of Science in Technological Innovation." *Research Policy* 3: 220–442.

Link, Albert N., and John Rees. 1990. "Firm Size, University-Based Research, and the Returns to R&D." *Small Business Economics* 2: 25–31.

Mansfield, Edwin. 1995. "Academic Research Underlying Industrial Innovations: Sources, Characteristics, and Financing." *Review of Economics and Statistics* (February): 55–65.

Mowery, David C., and Nathan Rosenberg. 1989. "The Growing Role of Science in the Innovation Process." In *Technology and the Pursuit of Economic Growth*, edited by David C. Mowery and Nathan Rosenberg, 21–34. Cambridge University Press.

Trajtenberg, Manuel. 1990. *Economic Analysis of Product Innovation: The Case of CT Scanners*. Harvard University Press.

Trajtenberg, Manuel, Rebecca Henderson, and Adam Jaffe. 1992. "Quantifying Basicness and Appropriability of Innovations with the Aid of Patent Data: A Comparison of University and Corporate Research." Paper prepared for the International Seminar on Technological Appropriation, June.

Coupling of Industrial R&D with Marketing and Production

Mansfield, Edwin. 1981. "How Economists See R&D." *Harvard Business Review* (November): 98–106.

Appropriability

Cockburn, Iain, and Zvi Griliches. 1987. "Industry Effects and Appropriability Measures in the Stock Market's Valuation of R&D and Patents." NBER Working Paper 2465.

Cohen, Wesley, and Daniel Levinthal. 1986. "The Endogeneity of Appropriability and R&D Investment." Carnegie-Mellon University.

Hanel, Petr, and Krstian Palda. 1992. "Appropriability and Public Support of R&D in Canada." Quebec: Universite de Sherbrooke.

Levin, Richard C. 1988. "Appropriability, R&D Spending, and Technological Performance." *American Economic Review* 78: 424–28.

Levin, Richard C., and others. 1987. "Appropriating the Returns from Industrial Research and Development." *Brookings Papers on Economic Activity 3: Microeconomics*, 783–832.

Levin, Richard C., Wesley M. Cohen, and David C. Mowery. 1985. "R&D Appropriability, Opportunity, and Market Structure: New Evidence on Some Schumpeterian Hypotheses." Carnegie-Mellon University and Yale University.

Mansfield, Edwin. 1985. "How Rapidly Does New Industrial Technology Leak Out?" *Journal of Industrial Economics* 34: 217–23.

Nelson, Richard R., and Edward N. Wolff. 1992. "Factors behind Cross-Industry Differences in Technical Progress." Columbia University.

Pakes, Ariel. 1985. "On Patents, R&D, and the Stock Market Rate of Return." *Journal of Political Economy* 93: 390–409.

Trajtenberg, Manuel, Rebecca Henderson, and Adam Jaffe. 1994. "University versus Corporate Patents: A Window on the Basicness of Inventions." CEPR Publication 372. Stanford University (January).

The Process of Technical Change

Role of R&D in Innovation

Acs, Zoltan J., and David B. Audretsch. 1988. "Innovation in Large and Small Firms: An Empirical Analysis." *American Economic Review* 78: 678–90.

Mowery, David C., and Nathan Rosenberg. 1989. "The Growing Role of Science in the Innovation Process." In *Technology and the Pursuit of Economic Growth*, edited by David C. Mowery and Nathan Rosenberg, 21–34. Cambridge University Press.

Rosenberg, Nathan. 1994. "Uncertainty and Technical Change." Paper prepared for the Conference on Growth and Development: The Economics of the Twenty-First Century, Stanford University, Center for Economic Policy Research, July.

Determinants of the Conversion of Invention into Innovation (Commercialization)

Geroski, Paul, John van Reenen, and Chris Walters. 1994. "The Demand and Supply of Knowledge: Innovations, Patents, and Cash Flow in a Panel of British Companies." London Business School and University College London. (December).

Mazzoleni, Roberto. 1993. "A Historical Analysis of the Evolution of Numerical Control of Machine Tools: Another Story of Technological Lead and Competitive Disadvantage." Stanford University.

Trajtenberg, Manuel. 1990. *Economic Analysis of Product Innovation: The Case of CT Scanners*. Harvard University Press.

Sources of Invention and Innovation, Importance of Organization Type

Henderson, Rebecca, and Iain Cockburn. 1994. "Scale, Scope, and Spillovers: The Determinants of Research Productivity in the Pharmaceutical Industry." Working Paper 4466. Cambridge, Mass.: National Bureau of Economic Research (September 1993).

Irwin, Douglas A., and Peter J. Klenow. 1994. "High Tech R&D Subsidies: Estimating the Effects of Sematech." Working Paper 4974. Cambridge, Mass.: National Bureau of Economic Research (December).

Malerba, Franco, and Salvatore Torrisi. 1992. "Internal Capabilities and External Networks in Innovative Activities: Evidence from the Software Industry." *Economics of Innovation and New Technology* 2: 49–72.

Nelson, Richard R., and Edward N. Wolff. 1992. "Factors behind Cross-Industry Differences in Technical Progress." Columbia University.

Pisano, Gary P. 1990. "The R&D Boundaries of the Firm: An Empirical Analysis." *Administrative Science Quarterly* 35: 153–76.

von Hippel, Eric. 1976. "The Dominant Role of Users in the Scientific Instrument Innovation Process." *Research Policy* 5: 212–39.

Walsh, Vivien. 1984. "Invention and Innovation in the Chemical Industry: Demand-Pull or Discovery-Push." *Research Policy* 13: 211–34.

Effect of Market Structure on an Industry's Rate of Technological Change

Cohen, Wesley M., and Richard C. Levin. 1989. "Empirical Studies of Innovation and Market Structure." In *The Handbook of Industrial Organization*, edited by Richard Schmalensee and Robert D. Willig, 1059–1107. Vol. II. Amsterdam: North-Holland.

Mowery, David C. 1983. "Innovation, Market Structure, and Government Policy in the American Semiconductor Industry." *Research Policy* 12: 183–97.

Factors Influencing the Diffusion of Innovations

Dunne, Timothy. 1991, "Technology Usage in U.S. Manufacturing Industries: New Evidence from the Survey of Manufacturing Technology." CES Discussion Paper 91-7. Washington: Census Bureau.

———. 1994. "Plant Age and Technology Use in U.S. Manufacturing Industries." *Rand Journal of Economics* 25: 488–99.

Ireland, N., and Paul Stoneman. 1983. "Technological Diffusion, Expectations, and Welfare." University of Warwick.

Karshenas, Massoud, and Paul L. Stoneman. 1993. "Rank, Stock, Order, and Epidemic Effects in the Diffusion of New Process Technologies: An Empirical Model." *Rand Journal of Economics* 24: 503–28.

Mansfield, Edwin. 1993. "The Diffusion of Flexible Manufacturing Systems in Japan, Europe, and the United States." *Management Science* 39.

———. 1989. "The Diffusion of Industrial Robots in Japan and in the United States." *Research Policy* 18: 183–92.

Nooteboom, Bart. 1993. "Adoption, Firm Size and Risk of Implementation." *Economics of Innovation and New Technology* 2: 203–16.

Stoneman, Paul, and Myung Joong Kwon. 1993. *Technology Adoption and Firm Performance.* Coventry, United Kingdom: Warwick Business School.

Stoneman, Paul. 1984. Untitled. University of Warwick.

Trajtenberg, Manuel. 1990. *Economic Analysis of Product Innovation: The Case of CT Scanners.* Harvard University Press.

Zettelmeyer, Florian, and Paul Stoneman. 1993. "Testing Alternative Models of New Product Diffusion." *Economics of Innovation and New Technology* 2: 283–308.

Spillovers from Military, Space, and Other Federal R&D to Civilian Technology

Bartelsman, Eric J. 1990. "Federally Sponsored R&D and Productivity Growth." FEDS 121. Washington: Federal Reserve Board of Governors.

David, Paul A., David Mowery, and W. Edward Steinmueller. 1991. "Analyzing the Economic Payoffs from Basic Research." Stanford University.

Lichtenberg, Frank. 1985. "Assessing the Impact of Federal Industrial R&D Expenditure on Private R&D Activity." Paper prepared for the Workshop on the Federal Role in Research and Development, National Academies of Science and Engineering, November 21–22.

Lichtenberg, Frank R., and Donald Siegel. 1991. "The Impact of R&D Investment on Productivity—New Evidence Using Linked R&D-LRD Data." *Economics Inquiry* 29: 203–28.

Link, Albert N. 1993. "Evaluating the Advanced Technology Program: A Preliminary Assessment of Economic Impacts." *International Journal of Technology Management* 8: 726–39.

Mamuneas, Theofanis P., and M. Ishaq Nadiri. 1993. "Public R&D Policies and Cost Behavior of the U.S. Manufacturing Industries." Report 93–44. New York University, C. V. Starr Center for Applied Economics Research (November).

Mansfield, Edwin, and Lome Switzer. 1984. "Effects of Federal Support on Company-Financed R&D: The Case of Energy." *Management Science* 30: 562–71.

Mowery, David C., and Nathan Rosenberg. 1989. "Postwar Federal Investment in Research and Development." In *Technology and the Pursuit of Economic Growth,* edited by David C. Mowery and Nathan Rosenberg, 123–68. Cambridge University Press.

Nadiri, M. Ishaq, and Theofanis P. Mamuneas. 1991. "The Effects of Public Infrastructure and R&D Capital on the Cost Structure and Performance of U.S. Manufacturing Industries." Working Paper 3887. Cambridge, Mass.: National Bureau of Economic Research (October).

Reiss, Peter C. 1985. "Economic Measures of the Returns to Federal R&D." Paper prepared for the Workshop on the Federal Role in Research and Development, National Academies of Science and Engineering, November 21–22.

Terleckyj, Nestor. 1985. "Measuring Economic Effects of Federal R&D Expenditures: Recent History with Special Emphasis on Federal R&D Performed in Industry." Paper prepared for the Workshop on the Federal Role in Research and Development, National Academies of Science and Engineering, November 21–22.

Economic Growth and Productivity Increase

Improved Measurement, Extended Periods

Better Measures of Output, New PPIs for the Computing Sector, Pharmaceutical Sector, Social Welfare Effects

Bartelsman, Eric J. 1990. "R&D Spending and Manufacturing Productivity: An Empirical Analysis." FEDS 122. Washington: Federal Reserve Board of Governors (April).

Griliches, Zvi. 1993. "Productivity and the Data Constraint." *American Economic Review* 83: 1–43.

Mairesse, Jacques, and Bronwyn H. Hall. 1994. "Estimating the Productivity of R&D: An Exploration of GMM Methods Using Data on French and United

States Manufacturing Firms." In *International Productivity Comparisons*, edited by Karin Wagner.

Trajtenberg, Manuel. 1990. *Economic Analysis of Product Innovation: The Case of CT Scanners*. Harvard University Press.

Better Inputs to Productivity Studies, Engineering Data and Experience

Lichtenberg, Frank R., and Donald Siegel. 1989. "Using Linked Census R&D-LRD Data to Analyze the Effect of R&D Investment on Total Factor Productivity Growth." CES 89–2. Washington: Census Bureau.

Interrelationship among R&D, Education, Management, and Capital Formation in Economic Growth; Human Capital Measures

Cameron, Gavin. 1995. "Innovation and Economic Growth in U.K. Manufacturing." Oxford: Nuffield College (February).

Mankiw, Gregory, David Romer, and David Weil. 1992. "A Contribution to the Empirics of Growth." *Quarterly Journal of Economics*, 107 (May): 407–37.

Technical Change Embodied in Capital, Learning-by-Doing

Jorgenson, Dale W., and Kevin Stiroh. 1994. "Computers and Growth." Discussion Paper 1707. Harvard Institute of Economic Research (December).

Interindustry, Interfirm, International, and Geographical Spillovers

Mairesse, Jacques, and Pierre Mohnen. 1995. "Research and Development and Productivity." INSEE, Paris, and Universite du Quebec a Montreal (January).

Mohnen, Pierre. 1994. "The Econometric Approach to Externalities." Montreal: Cahiers de recherche du departement des sciences economiques de l'UQAM no 9408 (November).

Interindustry and Interfirm

Bernstein, Jeffrey I., and M. Ishaq Nadiri. 1988. "Interindustry R&D Spillovers, Rates of Return, and Production in High-Tech Industries." *American Economic Review* 78: 429–34.

Bresnahan, Timothy F. 1986. "Measuring Spillovers from Technical Advance: Mainframe Computers in Financial Services." *American Economic Review* 76: 741–55.

Griliches, Zvi. 1992. "The Search for R&D Spillovers." *Scandinavian Journal of Economics* 94 (3, supplement): 529–47.
Jaffe, Adam. 1986. "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value." *American Economic Review* 76: 984–1001.
Mansfield, Edwin, Mark Schwartz, and Samuel Wagner. 1981. "Imitation Costs and Patents: An Empirical Study." *Economic Journal* (December): 907–18.

Geographical

Audretsch, David B., and Maryann P. Feldman. 1994. "R&D Spillovers and the Geography of Innovation and Production." Carnegie-Mellon University and Wissenschaftszentrum Berlin.
Jaffe, Adam B., Manuel Trajtenberg, and Rebecca Henderson. 1993. "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations." *Quarterly Journal of Economics* 108: 577–98.
Zucker, Lynne G., Michael R. Darby, and Jeffrey Armstrong. 1994. "Intellectual Capital and the Firm: The Technology of Geographically Localized Spillovers." Working Paper 4946. Cambridge, Mass.: National Bureau of Economic Research (December).

International

Bernstein, Jeffrey I., and Pierre Mohnen. 1994. "International R&D Spillovers between U.S. and Japanese R&D Intensive Sectors." Working Paper 4682. Cambridge, Mass.: National Bureau of Economic Research (March).
Lichtenberg, Frank R. 1992. "R&D Investment and International Productivity Differences." Working Paper 4161. Cambridge, Mass.: National Bureau of Economic Research (September).
Mohnen, Pierre. 1990. "The Impact of Foreign R&D on Canadian Manufacturing Total Factor Productivity Growth." Montreal, Quebec: UQAM, CREPE, Cahier de recherche no 58 (July).
1992. "International R&D Spillovers in Selected OECD Countries." Montreal, Quebec: UQAM, Cahiers de recherche du departement des sciences economique no 9208 (August).

International Comparisons

Blundell, Richard, Rachel Griffith, and John van Reenen. 1995. "Dynamic Count Data Models of Technological Innovation." *Economic Journal* 105 (March): 333–44.
Coe, D., and Elhanan Helpman. 1993. "International R&D Spillovers." Discussion Paper 840. London: Center for Economic Policy Research.
Hall, Bronwyn H., and Jacques Mairesse. Forthcoming. "Exploring the Relation-

ship between R&D and Productivity in French Manufacturing." *Journal of Econometrics.*

Hanel, Petr. 1994. "R&D: Interindustry and International Spillovers of Technology and the Total Factor Productivity Growth of Manufacturing Industries in Canada, 1974–89." Sherbrooke, Quebec: U de Sherbrooke Departement d'Economique Cahier de recherche 94–04 (October).

Harhoff, Dietmar. 1993. "R&D and Productivity in German Manufacturing Firms." Mannheim, Germany: Zentrum für Europäische Wirtschaftsforschung.

———. 1995. "R&D, Spillovers, and Productivity in German Manufacturing Firms." Mannheim, Germany: Universitaet Mannheim and Zentrum für Europäische Wirtschaftsforschung (January).

Klette, Tor Jacob. 1992. "On the Importance of R&D and Ownership for Productivity Growth: Evidence from Norwegian Micro-Data 1976–85." Discussion Paper 60. Oslo: Norwegian Central Bureau of Statistics.

Lederman, Leonard L. 1993. "A Comparative Analysis of Civilian Technology Strategies among Some Nations: France, the Federal Republic of Germany, Japan, the United Kingdom, and the United States." *Policy Studies Journal* 22: 279–95.

Lichtenberg, Frank R. 1992. "R&D Investment and International Productivity Differences." Working Paper 4161. Cambridge, Mass.: National Bureau of Economic Research (September).

Mairesse, Jacques, and Mohamed Sassenou. 1991. "R&D and Productivity: A Survey of Econometric Studies at the Firm Level." OECD *Science-Technology Review* 8: 9–44.

Mansfield, Edwin. 1988. "The Speed and Cost of Industrial Innovation in Japan and the United States: External versus Internal Technology." *Management Science* 34: 1157–68.

———. 1988. "Industrial R&D in Japan and the United States: A Comparative Study." *American Economic Review* 78: 223–28.