Rensselaer
Working Papers in Economics

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Windows on Black Boxes?

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Number 0419

August 2004

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23 August 2004

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JEL Codes: L2, L3, and O3

Keywords: Industrial Research and Development, Management of R&D, Spillovers, Technology Transfer, Survey Data

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***** I am indebted to the National Science Foundation for support, under NSF grant SBR-9502968, of my research on industrial R&D laboratories. Eleanora Voelkel, Meg Fernando, and Richard Anderson administered the ***Survey of Industrial Laboratory Technologies 1996*** that yielded the data. I am solely responsible for any opinions expressed in this paper.

Abstract

This paper provides an overview of the survey-based literature on industrial Research and Development (R&D) laboratories, beginning with the work of Edwin Mansfield. Topics covered include R&D projects, new products, and new processes; the appropriability of intellectual property; the limits of the firm in R&D; and spillovers of knowledge from other firms and universities into the laboratories. I discuss the value of collecting information from industrial R&D managers, who participate in a wide range of R&D decisions and are the natural best source of information on these decisions. I also emphasize gaps in our knowledge concerning R&D from past studies, such as the private and social returns to R&D, the nature of firms' R&D portfolios, and other topics. The paper closes with a discussion of the benefits from building a national database on R&D laboratories that could be shared among researchers and that could take this area of research to a new and higher level of achievement.

I. Introduction

The opportunity to learn firsthand how firms invent and innovate is one that should not to be missed. It is surely a unique window on the black box of the firm, one that can be looked through from any angle to study interactions between the firm's innovative establishments, other divisions of the firm, and the rest of the economy. We owe this opportunity to Edwin Mansfield and his students. It is their field work that brought the study of R&D laboratories into economics, opened up research opportunities for the investigators that followed them, and created an economic literature on the subject. In this paper, mindful of this huge contribution, I survey some of the economic research that has illuminated the black box of industrial R&D. Along the way I shall comment on questions raised by this research that in my opinion remain unanswered.

The topic is important for several reasons, all of them based on the inability to substitute other information for data from R&D laboratories. This special attribute of the data rests on the extraordinary skills of their source, the laboratory managers of R&D[1]. An argument can be made that the data are irreplaceable because R&D managers are Renaissance individuals who engage in project selection, negotiate with operating divisions of the company, and work cooperatively with universities, federal laboratories, and other firms (Mansfield and Brandenburg, 1966; Cohen, Nelson, and Walsh, 2002; Adams, 2002; Adams, Chiang, and Jensen, 2003; Adams, 2003, forthcoming). Questions such as the efficient management of industrial R&D, the returns to R&D projects, the nature of cooperative research, and the role of universities, government, and other firms in invention and commercialization are best answered by asking those who know about them. And R&D managers specialize in functions of the kind just described.

Field research in this area has uncovered critical findings on industrial R&D that could not have been obtained using received data[2]. In practice this approach has relied on data collection by many different researchers and this has advantages as well as disadvantages. The data are heterogeneous and as a result are exceptionally rich. Also, the data are designed from the start to address the relationships of

[1] By industrial R&D laboratory I mean any research group within the firm, and not necessarily a formal, separately dedicated research establishment. Thus the data are not restricted to central research laboratories.
[2] The idea that field research is necessary for the study of industrial R&D is a major point of Mansfield's introduction to his collected works. See Mansfield (1995b), volume I. Also see Scherer (2004) in this issue for a discussion of the controversies that followed Mansfield's adoption of this approach.

interest rather than designed for an unrelated purpose. The questions posed are limited only by the ingenuity of investigators and the patience of respondents. But these same qualities make it hard to compare results, and confidentiality places strong restrictions on data access. However, given sufficient community, field work can have recombinant properties. Learning by one researcher passes to the next, lending a cumulative increasing returns to scale property to the investigations as a whole.

The rest of the paper consists of five sections. The next four sections form the heart of this paper. Each explores a specific topic related to R&D laboratories. I chose these topics because they have attracted attention and I am familiar with them. Section II samples the literature of R&D projects, products, and processes. Section III reports some of what we have learned about the appropriability of intellectual property from R&D laboratory studies. Section IV explores what studies of laboratory R&D have taught us about the limits of the firm in R&D. Evidence for spillovers of outside knowledge into the laboratory is examined in section V. Section VI is a summary, discussion, and conclusion.

II. R&D Projects, Products and Processes

A. R&D Projects

During the 1960s and 1970s Edwin Mansfield and his coworkers undertook a series of studies of R&D projects. I begin with Mansfield and Brandenburg (1966). Its subject is the decision-making process that governs projects in the R&D laboratory of a large manufacturer. Its findings are that forecasted profits are a key driver of project expenditures, but tempered by scientific appeal of projects to researchers and by practical needs of manufacturing divisions. Other findings include that laboratory managers are risk-averse and take on projects that are short-term (less than five years from development) and low on technical risk. As a result, projects are completed rapidly and rarely fail for technical reasons, though the risk of commercial failure remains. The paper raises questions having to do with the portfolio aspects of R&D projects. What is the correlation matrix of returns on the projects? What is the overall level of risk of the portfolio compared with individual projects? Questions like this are of interest to the Real Options approach to investment (Dixit and Pindyck, 1994) given that R&D projects are a collection of real assets subject to uncertainty.

The uncertainty of R&D projects is further highlighted by Mansfield and Beardsley's (1978) study of industrial forecasts of their returns in a large company. One finding is that forecasted profits on new products are poorly explained by actual profits. While this explanatory power of actual for forecasted profits is higher in process-oriented R&D, in both cases forecasted profits are under-predicted. Thus considerable uncertainty and discounting apply to the projects. To my knowledge little if any work has since been done that covers the portfolio of a firm's R&D. Only in this way can the entire landscape of its research can be understood.

A recent study of project-level R&D, though not of the portfolio of a single firm, is by Bizan (2003). He explores the determinants of technical and commercial success of Israeli-American research alliances. He finds that projects are more likely to be a success when one partner is a subsidiary of the other, when the two firms have complementary capabilities, and when project size and duration increase.

B. New Products and Processes

Mansfield, Romeo, Wagner and Beardsley (1977) estimate the private and social returns to industrial innovation. The work is based on a sample of 17 innovations in several industries that consist of new products and processes. The remarkable finding is that the median (pre-tax) *private* rate of return on the projects is 25 percent. The median *social* return is 56 percent. The figures seem to justify public subsidies for industrial R&D, and yet the high private rate of return calls for an explanation. Is it the risk characteristics of R&D projects and their hurdle rates that bring about a return of this size? The question harks back to whether the firm's R&D portfolio diversifies risk away, or not. Otherwise, are the private returns upward biased, perhaps because a new product replaces an older one in the same firm? How do these rates of return compare with returns on other industrial investments? Another issue concerns whether the social rate of return includes the creative destruction of profit streams on earlier products and processes by other firms. Our ability to resolve these issues seems limited at present.

Recent papers based on extensive field research explore the determinants of new drug discovery. Cockburn and Henderson (1994) regard the empirical relevance of R&D racing in pharmaceuticals as limited, suggesting instead that firms specialize according to comparative advantage. Henderson and Cockburn (1996) suggest that economies of scale, scope, and industry spillovers operate within and across drug programs in the companies.

III. Appropriability of Industrial R&D

A. Methods of Intellectual Property Protection

Research on industrial R&D laboratories has shed light on the means of protection of firms' intellectual assets. The Yale Survey on Industrial R&D seems to have been the first to do so. Levin, Klevorick, Nelson, and Winter (1987) find that patents are neither the only nor even the most important means of intellectual property protection. Instead, being first to market and ranking highest in sales and service play a more important role in this regard. The finding is significant because it shows that the role of patents can be overstated by failure to consider less visible means of securing appropriability of R&D.

Cohen, Nelson and Walsh (2000) revisit this subject using the Carnegie-Mellon Survey on Industrial R&D. In their recent findings, patents continue to be less emphasized by the majority of industries than advantages of lead time and secrecy. In large companies, though, patents seem to be a more important source of protection than in the Yale Survey, mainly for purposes of patent blocking and in negotiations that lead to cross-licensing. In addition, secrecy appears to have grown more important over time.

One question raised by both studies is the comparative effectiveness of the different methods of protecting intellectual property for the propensity to invent and the value of inventions. I am not aware of any studies that have probed this question on a large scale.

B. Evidence on the Security of Intellectual Property

Research on R&D laboratories has contributed to what we know about security of intellectual property. At issue is the length of time over which firms' innovations are secure and the degree of that security. Mansfield, Schwartz and Wagner (1981) examine the relationship between imitation costs and patents. Their key finding is that imitation costs are large, about two-thirds of original innovation costs. Another result is that imitation costs increase if inventions are patented. This suggests a different mechanism by which patents protect intellectual property. The mechanism is even more important in view of Mansfield (1985), which finds that knowledge of a firm's development efforts are in the hands of competitors within 18 months. The evolution of imitation costs seems an interesting topic to explore further. This is especially true given the arrival of the Internet, which may have lowered imitation costs.

Teece (1977) and Arora (1996) expand the study of appropriability to international technology transfer. At issue is the North-South question of whether returns to innovation can be protected when innovative firms build manufacturing plants in developing countries. Teece (1977) shows that despite (or because of) the help of the innovator, costs of technology transfer are one-fifth of total project costs. Thus the fixed costs of technology transfer are large. Arora (1996) seconds this point and offers an interpretation. His view is that innovators can and do design projects to overcome problems of appropriating the returns to innovation. They do so by deliberately packaging technology with training, quality control, and plant set-up services. This might explain why costs of technology transfer are high in Teece (1977): the costs reflect a deliberate strategy of bundling service with knowledge transfer. The same point can be made more generally and it is not limited to technology transfer between developed and developing countries.

IV. The Limits of the Firm in R&D

In this section I discuss findings from R&D laboratory studies on research alliances and joint ventures, R&D sourcing, and public-private partnerships. Two general references on this subject are by Mowery (1992, 1995). Mowery (1992) discusses the rapid growth of international collaborative research ventures. He finds that international ventures are increasing because capabilities of overseas partners are increasing, because of a rise in non-tariff barriers that foreign partners can help overcome, because of increasing complexity of technologies, and because of rising costs of commercializing new products. The increasing complexity of technologies and the value of complementary capabilities are common motives for both domestic and foreign collaborative research. Mowery (1995) discusses the R&D limits of U.S. firms in history. For most of the 20th century antitrust policy discouraged horizontal mergers, encouraged product diversification, and encouraged R&D as a means of entry into new lines of business. Court decisions showed leniency towards patent licenses and encouraged firms to accumulate patent portfolios. Only since 1980 has increasing leniency of antitrust reversed conglomeration and reduced the demand for central R&D laboratories. In this way antitrust and patent policies have shaped the limits of the firm in R&D over the very long term.

A. Research Alliances and Joint Ventures

Using case studies Von Hippel (1988) has documented the sources of innovation outside the firm, in the R&D of suppliers and customers and he uncovers general information sharing among suppliers, manufacturers, and customers, including competitors. The point is that R&D used in the firm commonly originates outside the firm. Findings of Cohen, Nelson and Walsh (2002) confirm this view, again using the Carnegie-Mellon Survey on Industrial R&D. Their results are that customers suggest new R&D projects more often than the firm's manufacturing operations, and that suppliers and competitors also suggest new projects, even if less often than customers and the firm's operating divisions.

Using a sample of firms Link (1988) finds that merger and acquisition are ranked as more important in R&D-intensive industries. Indirectly this finding suggests that research alliances and joint ventures are at least in part motivated by the option to purchase. Link and Bauer (1989) suggest as well that cooperative R&D is defensively motivated by foreign competition.

Adams and Marcu (2004) study the relationship between objective indicators of R&D outsourcing and a subjective indicator of the importance of research joint ventures, which is found to be a key driver of outsourcing. This and other papers raise the question, so far unanswered, of the sequence of events involved in the different arrangements. Does the chain of arrangements run from informal sourcing to joint research, to the possibility of acquisition? The dynamics of the different arrangements are imperfectly understood, in part because current surveys are cross-sections rather than panels of the same R&D laboratories followed over time.

B. R&D Sourcing

A number of papers have examined R&D sourcing, as opposed to joint research. Pisano (1990) explains the motivations for R&D sourcing using a sample of biotechnology projects. In addition he identifies the source of complementary capabilities in the industry: at the time pharmaceutical firms lack knowledge of the key process technology, biotechnology, while new biotechnology firms lack marketing and distribution divisions. Consistent with this, sourcing decreases when in-house biotechnology expertise and biotechnology focus increase. The paper offers a clue as to why sourcing might precede joint research and acquisition in rapidly changing industries: old-line firms purchase expertise and learning opportunities from newcomers, deciding only later whether to expand the research or bring the partner permanently within the firm. Another finding is that greater competition among R&D suppliers increases sourcing.

Azoulay (2003) examines R&D outsourcing of drug clinical trials. His emphasizes the buffering motive for outsourcing, in which contract research absorbs demand shocks rather than core R&D. Consistent with this motive he finds that outsourcing increases with the volatility of firm sales. However, larger firms respond less to demand shocks because they can buffer research groups through reassignment. These findings bring to mind the R&D portfolio analysis of Mansfield and Brandenburg (1966).

Adams and Marcu (2004) explore multiple indicators of R&D sourcing using a sample of 200 R&D laboratories in several industries. Their data include the percent of R&D budget insourced and outsourced and the percent of engineering hours on new products contributed by customers and suppliers. They find that percents of budget outsourced are small and respond to indicators of diversity of local suppliers and customers. This form of outsourcing appears transitory and occasional. In vivid contrast the engineering contributions of customers and suppliers are much larger, are not localized, and appear to be relatively permanent. Sourcing in its several forms is directly associated with the importance of research joint ventures and merger and acquisition, suggesting that sourcing could be a prelude to more formal R&D arrangements. However, more work is needed to verify this claim. Another finding is that sourcing has no bearing on new products by the laboratories, whereas joint ventures do. This implies that sourcing and joint ventures have differing functions, with joint ventures specialized in commercialization and sourcing specialized in cost-saving.

C. Public-Private Partnerships

Public-private partnerships are another boundary of the firm's R&D. An element of strategy enters into both sides of the partnership. To see this consider industry-university cooperative research centers as in Adams, Chiang and Starkey (2001). Faculty members are interested in the centers because they provide opportunities to consult, engage in joint research, and place PhD students. Firms are interested in gaining preferential access to students and university research.

Siegel, Westhead, and Wright (2003) consider university science parks, another kind of highly focused public-private initiative. Their interest lies in the impact of the parks on research productivity of firms holding constant firms' R&D expenditures. Their results (using British data) are as follows. Using new product counts and patents as measures of innovation they find that location in a science park increases research output and technical efficiency in producing this output. Siegel (2003) surveys the literature of public-private partnerships. He is specifically concerned with data collection by government agencies. The paper points out that the private and social returns to public-private relationships are largely unknown. It goes on to offer suggestions for the collection of data on output and performance including qualitative data of the type favored by respondents.

Adams, Chiang, and Jensen (2003) study the influence of federal laboratory R&D on industrial research. They find that Cooperative Research and Development Agreements, or CRADAs, are the primary channel by which federal laboratories increase patents and company-financed R&D. This result is consistent with the view that arrangements requiring mutual effort by firms and federal laboratories are the most likely to increase the R&D efforts of both parties. As before little is known about the private and social rates of return from CRADAs.

V. Spillovers of Outside R&D

In this section I discuss some of what has been learned about spillovers of outside R&D based on field studies of R&D laboratories. By spillovers I mean the acquisition of useful information at a cost that is substantially less than the original cost of discovery. The topic has many dimensions, in terms of lag structure, the identity of the sending sector (industry, university, government; domestic or foreign), and the specific sciences or technologies that spill over to R&D laboratories. A sample of background papers are these: Adams (1990) uncovers long lags in the peak effect of spillovers to industry from academic research while Jaffe (1989) finds a localized effect of university research spending on industrial research spending. Griliches (1992) surveys the difficulties that are involved in measuring knowledge spillovers and provides back-of-the-envelope estimates of their contribution to growth in per capita income.

Mansfield (1991) considers the effect of recent academic research, from the past 15 years, on new products and processes introduced by industry. His sample consists of U.S. firms in several industries. His findings are that 11 percent of new products, and nine percent of new processes, could not have been developed without substantial delay in the absence of recent academic research. Another eight percent of new products and six of new processes are would have been considerably more expensive in the absence of recent scientific research. These percentages are highest in drugs, followed by instruments, metals, and information processing. Other findings are that roughly five percent of the value of new products, and another two-three percent of the value of new processes, could not have been developed at all, or else with very substantial increases in cost, without the assistance provided by recent academic research. One issue, though, is whether old or new scientific research plays the larger role in industry.

Mansfield (1995a) details the characteristics of universities and academic researchers that contribute to industrial innovation in a sample of firms. Findings are that location of researchers within the same state as the R&D laboratory significant increases firm "citations" in several industries. Also important are research spending by a university. The effect of locality is greater for applied than for basic academic research.

Klevorick, Levin, Nelson, and Winter (1995) use the Yale Survey on Industrial Research and Development to explore sources of interindustry differences in technological opportunities. The three sources are: advances in scientific understanding and technique, technological advances in other firms and other industries, and feedbacks from earlier research within the same industry. Beginning with science, as in other studies, only a few fields—chemistry, computer science, materials science, and metallurgy—are viewed as highly relevant in most industries. A few industries rate more selected fields of science highly. For example, drugs and medical products rank biology and medicine highly, but few other industries do. Thus, relatively few sectors show close proximity to basic science and the majority of influence appears to be filtered through engineering disciplines and computer science. Nearly all industries view other firms in the same industry as important sources of technological advance. Firm also rely on other industries, especially materials and equipment suppliers, for technological knowledge. There is also the suggestion that certain technological activities are repetitious ('natural trajectories') within the industry and thus not subject to diminishing returns. In an indirect sense feedbacks could be implicated in the trajectories. The comparative importance of science, between firm and between industry, and within firm sources of technological opportunity remains an open question, though interindustry effects appear to be important.

Cohen, Nelson and Walsh (2002) examine the influence of public research on industrial R&D. One key finding is that public research findings are three to four times more likely to be used in industrial R&D projects than publicly derived prototypes. Instruments and techniques derived from the public sector are two to three times more likely to be used than prototypes. Results on scientific fields used in industry are similar to those of Klevorick et alia (1995). The majority of industries rely on fields such as materials science, computer science, chemistry, electrical engineering, and mechanical engineering. Only a few rely on basic disciplines such as biology, physics, and mathematics and statistics. Pharmaceuticals, which have been intensively studied by economists, are in this respect an outlier and are not at all representative.

Another finding is that the most common channels of influence from public research are papers and reports, meetings, informal interactions, and consulting. Licenses and formal cooperative research are in this respect strictly secondary. It is informal and unregulated interactions that are the chief avenues of knowledge spillovers. This to an extent argues that the strategic public-private interactions of recent years—industry-university cooperative research centers, patents and licenses, and science parks—are overrated as spillovers sources. Another observation is that larger firms, aside from university-based startups in drugs and biotechnology, are the firms that are most likely to utilize scientific research. This finding is contrary to opinions on the absorptive advantages of small firms, but appears well-grounded.

In a pair of papers I have carried out geographic and institutional comparisons of the sources of knowledge spillovers to R&D laboratories. In Adams (2002) I find evidence that spillovers from universities are more localized than spillovers from the rest of industry. This is true in the sense that R&D laboratories target learning efforts on universities to a greater extent within 200 miles than their learning efforts about firms. It is true also in the sense that closely affiliated universities are closer than the average university to the laboratories. And finally it is true in the sense that closely affiliated universities are closer to the laboratories than are closely affiliated firms[3]. The results are consistent with the free flow of information under Open Science, and with the Land Grant movement, which favors local consulting and joint research by universities. Other findings are that localization of learning effort by laboratories is driven by local pools of R&D, outsourcing, consulting, and university PhD placements.

In Adams (2003, forthcoming) I find that academic spillovers appear to selectively drive learning about universities, while industrial spillovers appear to selectively drive learning about industry. If these findings hold up under additional tests, then they suggest, plausibly enough, that the direction as well as rate of industrial research is driven by those sectors whose research is research is increasing the most. Put

[3] The exceptions to this rule are top universities. Their influence, as one might expect, is not localized, because firms go further to work with researchers at the top of their professions.

differently, if the above results are true, then overall research responds by more than the sum of its parts to research opportunities, since parts of the research respond to the rest of research.

VI. Summary, Discussion, and Conclusion

In this paper I have discussed the literature of technical change by R&D laboratories. The subject touches on industrial R&D that lies deep within the firm. For this reason it must be approached through field work and survey research. Much of the analysis is inspired by Edwin Mansfield, who believed that survey research was essential to progress in understanding the sources of technological change. Starting from Mansfield's premise that R&D managers possess a store of knowledge that economists cannot replace, I hope to have demonstrated the value and relevance of this approach as well as the element of sheer surprise that the research delivers at its best.

A few examples may suffice to illustrate value, relevance, and surprise. Industrial R&D projects are neither risky, nor long-term, nor are they dogged by technical failure (Mansfield and Brandenburg, 1966). The ability of firms to predict the returns from product R&D is very limited, and the returns are underestimated or discounted (Mansfield and Beardsley, 1978). Knowledge of industrial R&D leaks out to competitors within 18 months or so (Mansfield 1985), but a countervailing force is the high cost of imitation: two-thirds of original imitation cost (Mansfield, Schwartz, and Wagner, 1981). Industrial R&D projects in pharmaceuticals seem to have little to do with R&D races (Cockburn and Henderson, 1994), and projects in this industry benefit from economies of scale and scope and spillovers (Henderson and Cockburn, 1996). The main payoff to industrial R&D from federal laboratories seems to derive from cooperative agreements, or CRADAs (Adams, Chiang, and Jensen, 2003), an arrangement that has sometimes been derided as ineffective. The primary benefits to firms from university research do not come from patents or formal patent licensing. Instead they derive informally from academic publications and research instruments (Cohen, Nelson, and Walsh, 2002).

Despite this seeming value-added, several difficulties have stood in the way of acceptance of field research on industrial R&D. First, the research is costly and the data sets small. The data are cross-sections that cannot be analyzed using the more powerful methods of panel data econometrics, which control for unobserved individual effects and are better able to address problems of endogeneity. Confidentiality restrictions entailed in the data collection limit access by other researchers, and expose the research to the charge of non-reproducibility. Because of the individual design of the surveys issues of comparability hinder attempts to generalize across studies.

Besides all the above—and for good reasons—research on R&D laboratories has typically not conformed to the standard paradigm of empirical work in economics. In that ideal short chains of reasoning are tested in tightly specified environments in which a few variables fit the data well and satisfy the predictions of the model in repeated applications (Sutton, 2000)[4]. These conditions are almost met in "quasi-natural" experiments with convincingly exogenous variables. A good example is the dominance of Microsoft in PC operating systems and the subsequent expansion of its R&D laboratory, which proves in the singular that appropriability increases R&D (Stix, 2004). But R&D data in the plural that satisfy quasi-natural experiments are rare. One exception is a recent study of the effect of market size on the invention of new drugs, specified in terms of exogenous age-related demographics, that seems to meet these requirements (Acemoglu and Linn, 2004).

One solution to some of the difficulties listed in this conclusion is to initiate large-scale panel data collection of U.S. industrial R&D laboratories that can be linked to data on parent firms. Government has a comparative advantage in this activity for several reasons. Government is more capable of enforcing confidentiality of the data, and its horizon and resources exceed those of individual researchers. Furthermore, using as a model the Center for Economic Studies of the U.S. Census Bureau of years past, anyone swearing to observe confidentiality under penalty of law can in principle test empirical results by going to the sponsoring agency and working with the data. The situation in principle gets better if academics work jointly with statistical agencies on an ongoing basis to improve the data. This setting conduces to large cross sections that form panels over time. Moreover, the data are more comparable and more representative than individually collected data, and conclusions drawn from them can be cross-checked. But the catch is the sustained commitment of time, imagination, and money by both universities and government that such data would require to be useful.

[4] Sutton (2000) discusses the option pricing and auction models as case studies that fit these requirements.

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