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5 The Boundaries of the U.S. Firm in R&D

David C. Mowery

5.1 Introduction

An important part of the restructuring of U.S. manufacturing firms during the late nineteenth and early twentieth centuries was the development of corporate research laboratories within the firm. The in-house industrial research laboratory first appeared in the German chemicals industry during the 1870s (Beer 1958), and a number of U.S. firms in the chemicals and electrical equipment industries had established similar facilities by the turn of the century. The growth of industrial R&D in both the United States and Germany was influenced by the dramatic advances in physics and chemistry during the last third of the nineteenth century, which created considerable potential for the profitable application of scientific and technical knowledge. Indeed, many of the earliest corporate investors in industrial R&D, such as General Electric and Alcoa, were founded on product or process innovations that drew on advances in physics and chemistry.

But change in the scientific and technological knowledge base does not suffice to explain the growth of industrial R&D within the U.S. corporation. Although changing technical opportunities influenced the decision to invest in industrial R&D, they do not account for the growing share of R&D activity within the boundaries of the firm. A substantial network of independent R&D laboratories provided research services on a contractual basis throughout

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the formative years of industrial R&D in the United States. These contract research organizations' share of total R&D employment, however, declined during the first half of the century, and their R&D services often complemented client firms' in-house R&D activities.

The expansion in the boundaries of the U.S. firm is central to any explanation of the growth of U.S. industrial R&D. The corporate R&D laboratory brought more of the process of developing and improving industrial technology into the boundaries of U.S. manufacturing firms, reducing the importance of the independent inventor as a source of patents (Schmookler 1957). But during much of the period before 1940, the in-house research facilities of large U.S. firms were not concerned exclusively with the creation of new technology. They also monitored technological developments outside of the firm and advised corporate managers on the acquisition of externally developed technologies.

Although their corporate laboratories were important devices for the acquisition of technologies from external sources before 1940, many large firms shifted to greater reliance on in-house sources of technology during the postwar era. In other words, the porousness of their boundaries in industrial research declined. This shift in the uses of intrafirm research was one response to the more stringent antitrust environment of the postwar U.S. economy. The relationship between the in-house R&D activities of large firms and innovative activities elsewhere in the economy also was affected by postwar expansion in defense-related federal R&D funding and procurement. These developments contributed to the creation of a postwar U.S. national innovation system that differed in important respects from the prewar system, and contrasted as well with the innovation systems of other postwar industrial economies.[1]

This paper surveys the historical development of U.S. industrial research. I discuss the reasons for the location of industrial R&D within the firm, and consider the historical and organizational implications of the changing boundaries of the firm in industrial R&D. The growth of U.S. industrial research was heavily influenced by R&D in other institutions, such as universities and government laboratories, and I briefly discuss the changing structure of these components of the U.S. national innovation system. Because federal R&D and antitrust policies of the postwar era significantly changed the industrial R&D strategies of U.S. firms in industrial research, I examine this period in some detail.

1. A "national innovation system" is the network of private- and public-sector institutions that exert the primary influence on the creation and adoption of new technologies. Like the Holy Roman Empire, national innovation systems may be in the process of becoming "none of the above," increasingly international in scope and boundaries; concerned with the adoption, as much as with the creation, of new technologies; and (especially in the United States) exhibiting few if any of the hallmarks of planning that one associates with the term "system." Nelson 1993 contains a set of studies of the national systems of a number of industrial and industrializing economies.

During the past decade, many U.S. firms have experimented with new organizational structures for their R&D operations, seeking ways to strengthen linkages to external sources of scientific and engineering knowledge such as universities, foreign and other domestic firms, and publicly financed national laboratories. Some of these experiments are genuinely novel, but others are simply a renewal of linkages that were weakened during and after World War II. I return briefly to this point in the conclusion.

5.2 Why Is Industrial R&D Located within the Firm?

In contrast to the predictions of George Stigler,[2] U.S. industrial research during this century has been located mainly within the firm, rather than being dominated by independent firms selling R&D via contract. Nevertheless, independent R&D contractors have played an important role in U.S. industrial research throughout the twentieth century, and were cited by early proponents as an important source of R&D services for small firms.[3] In addition, in-house R&D organizations were not wholly insulated from the market, but actively sought to purchase patents and technologies from external sources. In this section, I discuss the basis for the coexistence of markets and hierarchies in industrial R&D.

Two factors explain the failure of market-based forms of organization to dominate the organization of industrial R&D. First, the sources and characteristics of knowledge employed in the industrial innovation process tend to favor vertical integration among manufacturing, marketing, and R&D activities. Second, transaction-cost considerations make contractual R&D transactions feasible for only a narrow class of R&D activities.

The advantages of placing R&D within the firm reflect the fact that the sources of many commercially valuable innovations do not lie in scientific laboratory research. Instead, much of the knowledge employed in industrial innovation flows from the firm's production and marketing activities. The technical

2. "[W]ith the growth of research, new firms will emerge to provide specialized facilities for small firms. It is only to be expected that, when a new kind of research develops, at first it will be conducted chiefly as an ancillary activity by existing firms. . . . We may expect the rapid expansion of the specialized research laboratory, selling its services generally. The specialized laboratories need not be in the least inferior to 'captive' laboratories" (Stigler 1956, 281).

3. John J. Carty, director of Bell Telephone Laboratories, argued in 1916 that "[c]onditions today are such that without cooperation among themselves the small concerns cannot have the full benefits of industrial research, for no one among them is sufficiently strong to maintain the necessary staff and laboratories. Once the vital importance of this subject is appreciated by the small manufacturers many solutions of the problem will promptly appear. One of these is for the manufacturer to take his problem to one of the industrial research laboratories already established for the purpose of serving those who cannot afford a laboratory of their own. Other manufacturers doing the same, the financial encouragement received would enable the laboratories to extend and improve their facilities so that each of the small manufacturers who patronized them would in the course of time have the benefit of an institution similar to those maintained by our largest concerns" (512).

knowledge that is produced by the interaction of R&D and other functions within a given firm often is highly specific to that enterprise. Moreover, this information is difficult to transfer within an organization, let alone across organizational boundaries. Its transfer within or between organizations requires considerable shared expertise and knowledge, as well as sufficient expertise to absorb and apply the knowledge within the recipient division or firm.[4]

Because interaction among the different functions within the firm contributes to a stock of firm-specific knowledge that is not easily transferred across organizational boundaries, organizations that do not conduct "downstream" activities such as manufacturing or marketing may be unable to develop specific bodies of know-how. A free-standing contract research organization, for example, is not likely to produce the technological knowledge that results from the intraorganizational interaction of engineering, production, marketing, and research.

Contracting problems also limit a firm's reliance on market-based forms of organization in R&D, especially for specialized projects that involve fundamental research. These types of projects are likely to involve investments in specialized physical or human capital, they will typically involve small numbers of buyers and sellers, and their outcomes will be uncertain. Transaction-specific investments in an R&D project that cannot be easily redeployed to other uses or sold make it easier for one party to a contract to "hold up" the other, threatening to break the contract and negate the value of the other party's investment. The thin market, that is, the small number of buyers and sellers, for specialized research services makes opportunistic behavior more likely and discourages reliance on contracts for these forms of R&D (see Teece 1988 for a more detailed discussion of contracting problems).

When the knowledge or equipment needed for the research is less highly specialized or firm-specific, competition among research institutions is more likely, making it more difficult for a contractor to exploit its client. High uncertainty about outcomes means that contracts for such R&D services will be incomplete, incapable of specifying all contingencies, and therefore of limited use.

4. Arrow's "Classificatory Notes on the Production and Transmission of Technical Knowledge" pointed out that "[w]hen the British in World War II supplied us with the plans for the jet engine, it took ten months to redraw them to conform to American usage" (1969, 174). Concerning Japanese technology imports from the industrialized West, Caves and Uekusa (1976, 126) stated: "The level and pattern of research and development within Japan are closely related to the import of technology from abroad. Firms must maintain some research capacity in order to know what technology is available for purchase or copy and they must generally modify and adopt foreign technology in putting it to use. A 1963 survey of Japanese manufacturers showed that on average one-third of the respondents' expenditures on R&D went for this purpose. The moderate level, wide diffusion, and applied character of Japan's research effort are consistent with a facility for securing new knowledge from abroad." See also Evenson and Kislev 1975; Cohen and Levinthal 1989; and Mowery 1983a.

An additional limitation on firms' use of independent R&D contractors as a substitute for in-house R&D is the client firm's need for considerable internal expertise. A client firm needs an ability to select and evaluate an R&D contractor, to assess contractor performance, and even to pose a feasible project to a contractor. All of these requirements create a need for considerable project-specific and general knowledge within the client firm. In addition, the transfer and internal application of the results of the R&D rely on the in-house expertise of the client firm. Contract R&D services thus will complement, rather than substitute for, in-house R&D in many firms.

These arguments are consistent with two findings concerning the role of independent R&D firms during the formative years of U.S. industrial research: (1) they specialized in the provision of relatively simple R&D services, such as materials analyses, and tended to avoid open-ended, highly uncertain undertakings in advanced research; and (2) a large and growing share of their client population during the pre-1940 era consisted of firms with in-house R&D operations. For three major independent research laboratories (the Battelle Institute, the Mellon Institute, and Arthur D. Little, Inc.), for example, the share of client firms with in-house R&D laboratories during 1930–40 was 43.6, 51.8, and 22.8 percent, respectively, significantly higher than the share of firms with in-house R&D laboratories in the larger population (Mowery 1983c). The share of clients with in-house research facilities was higher still for the small number of more complex research projects undertaken by the Battelle Institute and Arthur D. Little during this period (these shares respectively were 47 and 69.6 percent).

R&D contractors thus provided a limited array of services, and for many of their clients, contractually governed R&D complemented in-house R&D. Firms lacking in-house R&D facilities were less likely to have access to a full range of R&D services, and were handicapped in obtaining even the limited services available via contract (Mowery 1983c). Reflecting these realities, the importance of independent contract research laboratories within the U.S. private industrial research system declined during the 1921–46 period. Although employment in contract and independent research organizations grew during this period, their share of overall industrial research employment in U.S. manufacturing shrank.[5]

In-house industrial R&D nonetheless was not completely divorced from markets for intellectual property and new technologies. The very uncertainties that discouraged firms from contracting for some R&D services also prevented them from relying exclusively on in-house R&D for new technologies; no firm could ensure that all technological threats and opportunities would be pursued

5. The employment of scientific professionals in independent research organizations, expressed as a fraction of employment of scientific professionals in all in-house and independent research laboratories, was 15.2 percent in 1921, 12.9 in 1927, 10.9 in 1933, 8.7 in 1940, and 6.9 in 1946 (Mowery 1981, chap. 2).

successfully in-house.[6] Precisely because the outcomes of many research projects cannot be known ex ante, the portfolio of in-house projects may not adequately explore all technological alternatives, and important technological developments are likely to emerge from sources other than intrafirm R&D. Many firms therefore used their in-house R&D for two "outward-oriented" activities: monitoring their technological environment, often through research links with universities, and acquiring innovations from external sources. Contractual governance was infeasible for the provision of some classes of R&D services, but market mechanisms could be and were used, with the aid of internal R&D, to acquire the products of independent inventors and other manufacturing firms. Internal R&D facilities also served to monitor and interpret the progress of research in other laboratories.

Firms generally purchased an innovation in the early stages of its development, rather than contracting for R&D services, with the attendant uncertainties relating to contractor performance, opportunism, and outcomes. Nevertheless, the considerable risks and uncertainty associated with the acquisition of a patent or an unproven technology meant that in-house expertise was essential to these technology acquisitions. In effect, the purchaser firm exploited its capabilities in development, manufacturing, distribution, and marketing to complement the inventive capabilities of another firm or individual. The in-house R&D facilities of the purchasing firm monitored opportunities for technology acquisitions, managed the transfer and absorption of the innovation, and undertook its further development and commercialization.

This "outward-looking" use of in-house R&D served as a hedge against one class of competitive risks. An exclusive reliance on intrafirm sources of new technologies, especially in an environment of rapidly expanding technical opportunities and intensified competition from other firms, could narrow the area of search and lead a firm to overlook technological developments or threats from other sources. But the ability to recognize and exploit these external opportunities, like the purchase of contract R&D services, required an effective in-house R&D organization.

5.3 The Growth of U.S. Industrial Research, 1921–45

Although recent historiography on U.S. industrial research has focused primarily on the electrical industry (an exception is Hounshell and Smith 1989), the data on the growth of U.S. industrial research during the early twentieth century suggest that chemicals and related industries were the leading sector. The chemicals, glass, rubber, and petroleum industries accounted for nearly 40 percent of the laboratories founded during 1899–1946. The chemicals sector also dominated research employment during 1921–46.

6. Swann (1988, 55) emphasizes this consideration in explaining U.S. pharmaceutical firms' use of university research during the 1930s and 1940s.

Chandler (1977, 1990) and Landau and Rosenberg (1992) have noted that the growth of research employment within the chemicals and chemicals-related industries was associated with the exploitation of high-pressure, continuous-flow production processes. The adoption of these process technologies by other industries, including petroleum, foodstuffs, and paper, increased their reliance on industrial research (Mowery 1983b). The dominance of research employment by chemicals-related industries was supplemented during 1921–46 by industries whose product and process technologies drew heavily on physics. Electrical machinery and instruments accounted for less than 10 percent of total research employment in 1921. By 1946, however, these two industries employed more than 20 percent of all industrial research scientists and engineers in U.S. manufacturing, and the chemicals-based industries had increased their share to slightly more than 43 percent of total research employment.

Table 5.1 contains data on research laboratory employment for 1921, 1927, 1933, 1940, and 1946 in nineteen two-digit manufacturing industries. Employment of scientists and engineers in industrial research within manufacturing grew from roughly three thousand in 1921 to nearly forty-six thousand by 1946.[7] As note 5 indicates, the growth of industrial research employment during this period was dominated by in-house research. By 1946, there were slightly more than twenty-three hundred industrial research laboratories within U.S. manufacturing firms, a dramatic increase from the number (slightly more than one hundred)[8] that appear to have been active in 1900 (Mowery and Rosenberg 1989, table 4.1).

The ordering of industries by research intensity in table 5.1 is quite stable—chemicals, rubber, petroleum, and electrical machinery are among the most research-intensive industries, accounting for 48–58 percent of all scientists and engineers employed in industrial research within manufacturing, throughout this period.[9] The geographic concentration of industrial research employment

7. The data in table 5.1 were drawn originally from the National Research Council surveys of industrial research employment, as tabulated in Mowery 1981. My discussion of these data draws on Mowery 1981, 1992 and Mowery and Rosenberg 1989.

8. As Hounshell (1993) has pointed out, the estimate of the number of industrial research laboratories in Mowery and Rosenberg 1989 may be high; he argues that the number of in-house research laboratories that did more than simple materials testing or quality control was in fact far smaller. The estimate in Mowery and Rosenberg is based on the reported foundation dates of laboratories listed in the 1940 edition of the National Research Council survey (1940), and therefore is subject to the vagaries of corporate memory, as well as differences among firms over the definition of an industrial research laboratory. The employment data reported in table 5.1 are less likely to suffer from this flaw, since they are gathered from contemporaneous surveys published by the National Research Council.

9. An exception to the pattern of stability in research intensity is transportation equipment, which increased in research intensity throughout the period, and by 1946 was among the five most research-intensive manufacturing industries. The upward movement in the relative research intensity of this industry (which includes aircraft) is attributable to federal support of research and federal procurement during 1940–46, and to the rapid growth of the automobile industry throughout 1921–46. Federal government funding of wartime research in industry also contributed to research employment within electrical machinery and instruments after 1940.

Table 5.1 **Employment of Scientists and Engineers in Industrial Research Laboratories in U.S. Manufacturing Firms, 1921–46**

	1921	1927	1933	1940	1946
Food/beverages	116 (0.19)	354 (0.53)	651 (0.973)	1,712 (2.13)	2,510 (2.26)
Tobacco	—	4 (0.031)	17 (0.19)	54 (0.61)	67 (0.65)
Textiles	15 (0.015)	79 (0.07)	149 (0.15)	254 (0.23)	434 (0.38)
Apparel	—	—	—	4 (0.005)	25 (0.03)
Lumber products	30 (0.043)	50 (0.16)	65 (0.22)	128 (0.30)	187 (0.31)
Furniture	—	—	5 (0.041)	19 (0.10)	19 (0.07)
Paper	89 (0.49)	189 (0.87)	302 (1.54)	752 (2.79)	770 (1.96)
Publishing	—	—	4 (0.015)	9 (0.03)	28 (0.06)
Chemicals	1,102 (5.2)	1,812 (6.52)	3,255 (12.81)	7,675 (27.81)	14,066 (30.31)
Petroleum	159 (1.83)	465 (4.65)	994 (11.04)	2,849 (26.38)	4,750 (28.79)
Rubber products	207 (2.04)	361 (2.56)	564 (5.65)	1,000 (8.35)	1,069 (5.2)
Leather	25 (0.09)	35 (0.11)	67 (0.24)	68 (0.21)	86 (0.25)
Stone/clay/glass	96 (0.38)	410 (1.18)	569 (3.25)	1,334 (5.0)	1,508 (3.72)
Primary metals	297 (0.78)	538 (0.93)	850 (2.0)	2,113 (3.13)	2,460 (2.39)
Fabricated metal products	103 (0.27)	334 (0.63)	500 (1.53)	1,332 (2.95)	1,489 (1.81)
Nonelectrical machinery	127 (0.25)	421 (0.65)	629 (1.68)	2,122 (3.96)	2,743 (2.2)
Electrical machinery	199 (1.11)	732 (2.86)	1,322 (8.06)	3,269 (13.18)	6,993 (11.01)
Transportation equipment	83 (0.204)	256 (0.52)	394 (1.28)	1,765 (3.24)	4,491 (4.58)
Instruments	127 (0.396)	234 (0.63)	581 (2.69)	1,318 (4.04)	2,246 (3.81)
Total	2,775	6,320	10,927	27,777	45,941

Source: Mowery 1981.

Note: Figures in parentheses represent research intensity, defined as employment of scientists and engineers per one thousand production workers.

during this period exhibits similar stability. Five states (New York, New Jersey, Pennsylvania, Ohio, and Illinois) contained more than 70 percent of the professionals employed in industrial research in 1921 and 1927; their share declined modestly, to slightly more than 60 percent, by 1940 and 1946. The major prewar research employers remained among the most research-intensive industries well into the postwar period, despite the growth in federal funding for R&D in industry. Chemicals, rubber, petroleum, and electrical machinery accounted for more than 53 percent of industrial research employment in 1940 and represented 40.3 percent of research employment in industry in 1984 (National Science Foundation 1987).

The stable rank ordering of industries by research intensity may be attributable to enduring differences among industries in "technological opportunity," higher levels of which are associated with greater R&D investment (Scherer 1965; Levin, Cohen, and Mowery 1985). An additional factor contributing to such intertemporal stability is that the development of firm-specific innovative capabilities through R&D investment requires considerable time. The resulting high levels of serial correlation in longitudinal firm-level R&D investment data may influence these industry-level data.

Stability in the geographic concentration of R&D employment over long time periods suggests that the regional concentration of high-technology firms and R&D activities within the United States is not an exclusively postwar phenomenon. This intertemporal stability in the geographic distribution of industrial R&D activity is also consistent with Patel and Pavitt's observation (1991) that the widely remarked postwar globalization of manufacturing activity has not been accompanied by a similar international spread in the location of R&D activity, insofar as patent data are reliable indicators of such activity. In domestic as well as international markets and operations, proximity to a network of other firms, universities, and support services remains critical to innovation. The development or decay of such a regional or national infrastructure takes considerable time. The in-house R&D facilities of firms benefit from the regional agglomeration effects pointed out by Marshall (1910, chap. 10). These effects derive in part from the ability of labor and ideas to move among research facilities, reflecting the porousness of firms' boundaries in R&D.

5.3.1 U.S. Antitrust Policy and the Origins of Industrial Research

The development of U.S. industrial research was closely linked with the emergence of large-scale corporations during the late nineteenth and early twentieth centuries (Chandler 1977, 1990). Technically trained managers, a central office staff that focused on strategic rather than operating decisions, and the integration within the firm of functions such as marketing were necessary conditions for the development of in-house R&D. This relationship between the internal organization of the firm and in-house industrial research meant that the mergers and corporate reorganizations of the late nineteenth and early twentieth centuries hastened the growth of industrial research.

The structural change in many large U.S. manufacturing firms that underpinned investment in industrial research was influenced by U.S. antitrust policy. By the late nineteenth century, judicial interpretations of the Sherman Antitrust Act had made agreements among firms for the control of prices and output targets of civil prosecution. The 1895–1904 merger wave, particularly the surge in mergers after 1898, was in part a response to this new legal environment. Finding that the legality of informal and formal price-fixing and market-sharing agreements was under attack, firms resorted to horizontal mergers to control prices and markets.[10]

The incentives created by the Sherman Act for horizontal mergers were reduced by the Supreme Court's 1904 *Northern Securities* decision. But the influence of antitrust policy on the growth of industrial research extended beyond its effects on corporate mergers and remained important long after 1904. Justice Department opposition to horizontal mergers caused large U.S. firms to seek alternative means for corporate growth. For some firms, the threat of antitrust action created by their dominance of a single industry led to efforts to diversify into other areas. The commercialization of new technologies, developed internally or purchased from external sources, supported corporate diversification and growth. Threatened with antitrust suits from state as well as federal agencies, George Eastman saw industrial research as a means of supporting the diversification and growth of Eastman Kodak (Sturchio 1985, 8). Facing a similarly hostile political environment during the first decade of this century, the Du Pont Company used industrial research to diversify out of the black and smokeless powder businesses even before the 1913 antitrust decision that forced the divestiture of a portion of the firm's black powder and dynamite businesses (Hounshell and Smith 1989, 57).

Although it discouraged horizontal mergers among large firms, U.S. antitrust policy through much of the pre-1940 period did not discourage efforts by these firms' research laboratories to acquire new technologies from external sources. Du Pont obtained many of its major product and process innovations during this period, for example, from outside sources and proceeded to further develop and commercialize them within the U.S. market (Mueller 1962; Hounshell and Smith 1989). The research facilities of AT&T were instrumental in the procurement of the "triode" from independent inventor Lee De Forest, and also were involved in the corporation's decision to obtain loading-coil technology from Pupin (Reich 1985). General Electric's research operations inten-

10. See Stigler 1968. The Supreme Court ruled in the *Trans Missouri Association* case in 1898 and the *Addyston Pipe* case in 1899 that the Sherman Act outlawed all agreements among firms on prices or market sharing. Data in Thorelli 1954 and Lamoreaux 1985 indicate an increase in merger activity between the 1895–98 and 1899–1902 periods. Lamoreaux (1985) argues that other factors, including the increasing capital intensity of production technologies and the resulting rise in fixed costs, were more important influences on the U.S. merger wave, but her account (109) also acknowledges the importance of the Sherman Act in the peak of the merger wave. Lamoreaux also emphasizes the incentives created by tighter Sherman Act enforcement after 1904 for firms to pursue alternatives to merger or cartelization as strategies for attaining or preserving market power.

sively monitored foreign technological advances in lamp filaments and the inventive activities of outside firms and individuals, and aggressively pursued patent rights to innovations developed all over the world (Reich 1985, 61). The Standard Oil Company of New Jersey established its Development Department precisely to carry out development of technologies obtained from other sources, rather than for original research (Gibb and Knowlton 1956, 525). Alcoa's R&D operations also closely monitored and frequently purchased process innovations from external sources (Graham and Pruitt 1990, 145–47). To the extent that federal antitrust policy motivated industrial research investment by large U.S. firms before and during the interwar period, the policy paradoxically may have aided the survival of these firms and the growth of a relatively stable, oligopolistic market structure in some U.S. manufacturing industries.[11]

Historians are virtually unanimous in concluding that the stringency of U.S. antitrust policy was unique among the industrial economies during this period.[12] This antitrust climate contrasted with that of Great Britain, the only foreign industrial economy for which comparable R&D employment data are available for even a part of the 1900–1950 period. In Great Britain, weak antitrust policies allowed the establishment of informal cartels and market-sharing agreements that reduced firms' incentives to merge and prevented the rationalization of the internal structure of the firms created by these mergers (Hannah 1979). British antitrust policy was associated with levels of industrial R&D intensity that were lower than those of U.S. firms during much of the 1900–1950 period (Mowery 1984; Chandler 1990).[13] Even in large British firms that did invest significantly in R&D, such as Imperial Chemical Industries, historians have suggested that the weakness of the firm's central management structure reduced the returns to this investment (Reader 1975).

Since a weak antitrust climate in Germany was associated with what are widely believed to have been high levels of industrial research (no direct measures of German industrial R&D investment are available for the pre-1940 period), one cannot assert a simple cause-and-effect relationship between tough antitrust policy and high levels of intrafirm R&D. Although it was an important element of U.S.-U.K. contrast, antitrust policy was only one of several factors

11. During 1921–46, the growth of intrafirm industrial research was associated with a decline in turnover among the largest U.S. manufacturing firms (Mowery 1983b; Edwards 1975; Kaplan 1964; Collins and Preston 1961). Interestingly, and in contrast to the usual formulation of one of the Schumpeterian "hypotheses," these results suggest that firm conduct (R&D employment) was an important influence on market structure (turnover). They are also broadly consistent with the results of studies of more recent data on the market structure-R&D investment relationship that suggest that structure and R&D investment are jointly determined (Levin, Cohen, and Mowery 1985).

12. The argument is elaborated in Keller 1990, 23; Freyer, chap. 6 in this volume; McCraw 1981; Fligstein 1990; and Chandler 1977, 1990.

13. Cantwell's analysis of U.S. patenting during the interwar period by European firms (1991) also concludes that corporate R&D in Great Britain and France lagged behind the level of corporate R&D observed in the United States and Germany during this period.

affecting the unique path of development of U.S. corporate structure and industrial research. Nevertheless, the pre-1940 antitrust environment created strong incentives for U.S. firms to establish in-house research facilities and to use their internal R&D operations to exploit external sources of technology.

5.3.2 The Role of Patents in the Origins of U.S. Industrial Research

The effects of U.S. antitrust policy on the growth of industrial research were reinforced by other judicial and legislative actions in the late nineteenth and early twentieth centuries that strengthened intellectual property rights. The congressional revision of patent laws that took effect in 1898 extended the duration of protection provided by U.S. patents covering inventions patented in other countries (Bright 1949, 91). The Supreme Court's 1908 decision (*Continental Paper Bag Company v. Eastern Paper Bag Company*) that patents covering goods not in production were valid (Neal and Goyder 1980, 324) expanded the utility of large patent portfolios for defensive purposes. Other congressional actions in the first two decades of this century increased the number of Patent Office examiners, streamlined internal review procedures, and transferred the office from the Interior to the Commerce Department (Noble 1977, 107–8). These changes in Patent Office procedures and organization were undertaken in part to improve the speed and consistency of procedures through which intellectual property rights were established, while shifting the office to an agency charged with representing the interests of U.S. business.

Stronger intellectual property protection expanded the appropriability of the returns from innovation, increasing incentives for the establishment of industrial laboratories. In addition, stronger and clearer intellectual property rights facilitated the development of a market for the acquisition and sale of industrial technologies. Judicial tolerance for restrictive patent licensing policies (see below) further increased the value of patents in corporate research strategies.

Although the search for new patents provided one incentive to pursue industrial research, their imminent demise formed another important impetus for the establishment of industrial research laboratories. The impending expiration of patents protecting core technologies, as well as the growth of competing technologies, led to the establishment or expansion of in-house research laboratories. Both AT&T and General Electric, for example, established or expanded their in-house laboratories in response to the intensified competitive pressure that resulted from the expiration of key patents (Reich 1985; Millard 1990, 156). In both of these firms, intensive efforts to improve and protect corporate technological assets were combined with increased acquisition of patents in related technologies from other firms and independent inventors.

Patents also provided a mechanism for some firms to retain market power without running afoul of antitrust law. The 1911 consent decree settling the federal government's antitrust suit against General Electric left GE's patent licensing scheme largely untouched, allowing the firm considerable latitude in setting the terms and conditions of sales of lamps produced by its licensees, maintaining an effective cartel within the U.S. electric-lamp market (Bright 1949, 158). Patent licensing provided a legal basis for the participation by GE and Du Pont in the international cartels of the interwar chemical and electrical equipment industries. U.S. participants in these international market-sharing agreements took pains to arrange their international agreements as patent licensing schemes, arguing that exclusive license arrangements and restrictions on the commercial exploitation of patents would not run afoul of U.S. antitrust enforcement (Taylor and Sudnik 1984, 126).

Change in the structure of the U.S. intellectual property system in the early twentieth century, as well as the treatment of intellectual property by the judiciary, thus enhanced firms' incentives to internalize industrial research and to invest in the acquisition of technologies from external sources. Against the backdrop of tougher federal enforcement of antitrust statutes, judicial decisions affirming the use of patents to create or maintain positions of market power also created additional incentives to pursue in-house R&D. Stronger, more consistent intellectual property rights also improved the operation of a market for intellectual property, making it easier for firms to use their in-house research facilities to acquire technology and contributing to the porousness of their boundaries in R&D.

5.3.3 U.S. Universities and Industrial Research before 1940

University-based research and education also influenced the growth of U.S. industrial research. The reliance of many U.S. universities on state government funding, the modest scope of this funding, and the rapid expansion of their training activities all supported the growth of formal and informal linkages between industry and university research. U.S. universities formed a formal point for the external monitoring activities of many U.S. industrial research laboratories before 1940. In some cases, these university linkages involved industrial development and commercialization of new technologies or products. But most of these relationships appear to have supported industrial firms' observation of emerging developments in scientific and technological research.

Linkages between academic and industrial research were powerfully influenced by the decentralized structure and funding of U.S. higher education, especially the public institutions within the system. Public funding created a U.S. higher education system that was substantially larger than those of European nations such as Great Britain.[14] The source of this public funding, however, was equally important. The prominent role of state governments in fi-

14. In the early 1920s, roughly 42,000 students were enrolled in British universities; the figure rose to 50,000–60,000 by the late 1930s. By contrast, American institutions of higher learning awarded over 48,000 *degrees* in 1913 and more than 216,000 in 1940. With a total population 35 percent that of the United States, Britain had only about 6 percent as many students in higher education in the late 1930s. See Briggs 1982; U.S. Bureau of the Census 1975.

nancing the prewar U.S. higher education system led public universities to seek to provide economic benefits to their regions through formal and informal links to industry (Rosenberg and Nelson 1992).

Both the curriculum and research within U.S. higher education were more closely geared to commercial opportunities than was true in many European systems of higher education. Swann (1988) describes the extensive relationships between academic researchers, in both public and private educational institutions, and U.S. ethical drug firms that developed after World War I.[15] Hounshell and Smith (1989, 290–92), document a similar trend for the Du Pont Company, which funded graduate fellowships at twenty-five universities during the 1920s and expanded its program during the 1930s to include support for postdoctoral researchers. During the 1920s, colleges and universities to which the firm provided funds for graduate research fellowships also asked Du Pont for suggestions for research, and in 1938 a leading Du Pont researcher left the firm to head the chemical engineering department at the University of Delaware (Hounshell and Smith 1989, 295).

Many state university systems introduced new programs in engineering, mining, and metallurgy in response to the requirements of local industry. Although they never received federal financial support, the first engineering experiment stations were established early in the twentieth century, and by 1938 there were thirty-eight. These installations focused mainly on applied, rather than basic, research.[16] The University of Minnesota's Mines Experiment Station, equipped with a blast furnace and foundry, conducted research that led to techniques for the commercial exploitation of the state's vast taconite deposits (Mowery and Rosenberg 1989, 95). Purdue University maintained a testing facility for locomotive engines. Levine (1986, 52) notes that, during the 1920s, the University of Illinois offered degrees in disciplines ranging from architectural engineering to railway civil engineering and railway electrical engineering, and stated that virtually every Illinois industry or government agency was served by a department at the university.

Still another example of strong ties with local and national government is provided by the Massachusetts Institute of Technology, founded by Massachusetts in 1861 with Morrill Act funds.[17] In 1906, according to Wildes and Lind-

15. According to Swann (1988, 50), Squibb's support of university research fellowships expanded (in current dollars) from $18,400 in 1925 to more than $48,000 in 1930, and accounted for one-seventh of the firm's total R&D budget for the period. By 1943, according to Swann, university research fellowships amounting to more than $87,000 accounted for 11 percent of Eli Lilly and Company's R&D budget. Swann cites similarly ambitious university research programs sponsored by Merck and Upjohn.

16. The contribution of universities to U.S. technological performance is particularly interesting in view of the fact that for much of the pre-1940 period, there were few areas of scientific research in which U.S. universities or scholars could be described as substantially stronger than their European counterparts. This portion of the historical record suggests that the linkage between excellence in scientific research and growth in U.S. national income or productivity is tenuous, a point consistent with postwar evidence and with the conclusions of Nelson (1990) and Wright (1990).

17. The MIT example also illustrates the effects of reductions in state funding on universities' eagerness to seek out industrial research sponsors. Wildes and Lindgren (1985, 63) note that the

gren (1985, 42–43), MIT's electrical engineering department established an advisory committee that consisted of Elihu Thomson of General Electric, Charles Edgar of the Edison Electric Illuminating Company of Boston, Hammond V. Hayes of AT&T, Louis Ferguson of the Chicago Edison Company, and Charles Scott of Westinghouse. The department's Division of Electrical Engineering Research, established in 1913, received regular contributions from General Electric, AT&T, and Stone and Webster, among other firms.

Another important linkage between higher education and industrial research operated through the training by public universities of scientists and engineers for employment in industrial research. The Ph.D.'s trained in public universities were important participants in the expansion of industrial research employment during this period (Thackray 1982, 211).[18] The sheer scale of the U.S. higher educational system meant that it served as a device for the diffusion and utilization of advanced scientific and engineering knowledge by established firms. The foundation of entirely new firms by university-based researchers does not appear to have been prominent in the prewar period, in part because of the forbidding economic climate of the 1930s and in part because federal government programs and policies were so much less supportive of new, R&D-intensive firms than was true of the post-1945 era (see below).

5.3.4 Summary

Industrial research laboratories were a key part of a prewar U.S. R&D system in which federal funds played a modest role (accounting, according to one estimate, for 12–20 percent of total national R&D expenditures during the 1930s). Moreover, 39 percent of the federal R&D budget in 1940 was devoted to the Department of Agriculture. Industry, on the other hand, accounted for roughly two-thirds of total national expenditures on R&D (see Mowery and Rosenberg 1989, 93, and National Resources Planning Board 1942, 178). The remainder of national R&D spending was drawn from state, university, and private philanthropic sources.

The industrially funded R&D that loomed so large in the prewar period's R&D spending was conducted mainly within the boundaries of U.S. firms. Although located within the firm, these novel entities also looked outside the

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1919 withdrawal by the Massachusetts state legislature of financial support for MIT, along with the termination of the institute's agreement with Harvard University to teach Harvard engineering courses, led MIT president Richard C. Mclaurin to establish the Division of Industrial Cooperation and Research. This organization was financed by industrial firms that gained access to MIT libraries, laboratories, and staff for consultation on industrial problems. Still another institutional link between MIT and a research-intensive U.S. industry, the institute's School of Chemical Engineering Practice, was established in 1916 (Mattill 1992).

18. Hounshell and Smith (1989, 298) report that 46 of the 176 Ph.D.'s overseen by Carl Marvel, longtime professor in the University of Illinois chemistry department, went to work for one firm, Du Pont. According to Thackray (1982, 221), 65 percent of the 184 Ph.D.'s overseen by Professor Roger Adams of the University of Illinois during 1918–58 went directly into industrial employment. In 1940, 30 of the 46 Ph.D.'s produced by the University of Illinois chemistry department were first employed in industry.

firm, monitoring the external environment of research in universities and industry, and supporting the technology acquisition strategies that played an important part in the development of large U.S. manufacturing firms during this period. By 1940, all of the components of this research system were about to undergo a dramatic transformation that would in less than a decade produce a very different national R&D system.

5.4 The Postwar Transformation

World War II and the cold peace that followed changed the roles of the three institutional pillars of the pre-1940 U.S. R&D system—universities, government, and industry. All of the influences that molded the pre-1940 industrial research laboratory, including antitrust policy, university research, and (to a lesser extent) intellectual property rights were affected by the postwar transformation. World War II propelled the federal government into a central role as research funder within both academia and industry.[19] The dramatic increase in federal defense-related spending on R&D and weapons procurement, which had no pre-1940 analogue, also exerted a strong influence on the development of industrial R&D.

U.S. antitrust policy continued to influence U.S. industrial research and innovation during the postwar period, but both the policy and the nature of its influence changed. The appointment of Thurman Arnold in 1938 to head the Antitrust Division of the Justice Department, combined with growing criticism of large firms and economic concentration (e.g., the investigations of the federal Temporary National Economic Committee), produced a much tougher antitrust policy that extended well into the 1970s. The cases filed by Arnold and his successors, many of which were decided or resolved through consent decrees in the 1940s and early 1950s, changed the postwar industrial research strategies of many large U.S. firms.

This revised antitrust policy made it more difficult for large U.S. firms to acquire firms in "related' technologies or industries,[20] and led them to rely more heavily on intrafirm sources for new technologies. In the case of Du Pont, the use of the central laboratory and Development Department to seek technologies or firms for acquisition was ruled out by senior management as a result of the perceived antitrust restrictions on acquisitions in related industries. As

19. According to Hounshell and Smith (1989, 331–32), the expanded wartime role of federal funding, the operation by competitor firms of large-scale chemical plants, and the sale of government-financed production plants after the war weakened the dominant technological position of Du Pont within the chemicals industry. Graham and Pruitt (1990, 239–42 and chap. 6) note that World War II had a similar effect on Alcoa's technological and economic dominance of the U.S. aluminum industry.

20. Hawley (1966) analyzes the shifting antitrust policies of the New Deal. Arnold took office in 1938, and during 1938–42 filed 312 antitrust cases, considerably more than the 46 filed during 1932–37 or the 70 filed during 1926–31 (Fligstein 1990, 168).

a result, internal discovery (rather than development) of new products became paramount (Hounshell and Smith [1989] emphasize the firm's postwar expansion in R&D and its search for "new nylons"),[21] in contrast to the firm's R&D strategy before World War II.

This shift in Du Pont's R&D strategy weakened the links between the growing central corporate research facilities, which increasingly concentrated their efforts on basic research, and the operating divisions of the firm. The R&D efforts of the established business units focused on increasingly costly improvements in existing processes and products, and the overall productivity of Du Pont R&D suffered (Hounshell and Smith 1989, 598). The inward focus of Du Pont research appears to have impaired the firm's postwar innovative performance, even as its central corporate research laboratory gained a sterling reputation within the scientific community.

A similar inward orientation developed within the R&D operations of Alcoa, according to Graham and Pruitt (1990, chap. 7), as a result of the federal antitrust suit against the firm and the creation of competitors through the sale of government-owned wartime production plants.[22] For Alcoa, however, the effects of this inward orientation were rather different than for Du Pont. The links between Alcoa researchers and external research institutions weakened to such an extent that both the scientific and technological contributions of the firm's laboratory declined.

Where large firms made acquisitions, they frequently did so in unrelated lines of business, creating conglomerate firms with few if any technological links among products or processes. In a number of instances, this extensive diversification led to a decline in the innovative performance of firms that prior to World War II had been leaders in R&D and innovation (see Chandler 1990; Ravenscraft and Scherer 1987; Fligstein 1990). RCA, for example, pursued a conglomerate diversification strategy while maintaining its large fundamental research "campus" near Princeton, New Jersey, which made important research contributions to military and consumer electronics technologies. But RCA found it difficult to reap the commercial returns to its research capabilities, pursuing the hugely expensive and unsuccessful videodisc project (Graham

21. Hounshell and Smith (1989) and Mueller (1962) argue that discovery and development of nylon, one of Du Pont's most commercially successful innovations, was in fact atypical of the firm's pre-1940 R&D strategy. Rather than being developed to the point of commercialization following its acquisition by Du Pont, nylon was based on the basic research of Carothers within Du Pont's central corporate research facilities. The successful development of nylon from basic research through to commercialization nevertheless exerted a strong influence on Du Pont's postwar R&D strategy, not least because many senior Du Pont executives had direct experience with the nylon project. Hounshell (1993) argues that Du Pont had far less success in employing the "lessons of nylon" to manage such costly postwar synthetic fiber innovations as Delrin.

22. Graham and Pruitt (1990, 270–71) also argue that patents played a much less prominent role in Alcoa's postwar R&D strategy, because of corporate concerns over the disclosure of technical information to competitors. Instead, process-related know-how, not subject to disclosure through patent applications, became central to the firm's R&D efforts.

1986), while failing to maintain its dominant position in color television receivers.

At the same time that established firms were shifting the R&D strategies that many had employed since the early twentieth century, new firms began to play an important role in the development of the technologies spawned by the postwar U.S. R&D system. The prominence of small firms in commercializing new electronics technologies in the postwar United States, for example, contrasts with their more modest role in this industry in the interwar period. In industries that effectively did not exist before 1940, such as computers and biotechnology, major innovations were commercialized largely through the efforts of new firms.[23] The postwar U.S. differs in this respect from both Japan and most western European economies, where established firms in electronics and pharmaceuticals dominated the commercialization of these technologies.

In semiconductors, the activities of new firms in the commercialization of new technologies often built on the R&D investments and patents of larger firms (Tilton 1971, 69). In a near-reversal of the prewar situation, the R&D facilities of large firms provided the basic technological advances that were commercialized by new firms. Small-firm entrants' contribution to semiconductor-industry patents grew steadily during 1952–68, but their most significant role was in introducing new products, reflected in their often-dominant share of markets in new semiconductor devices.[24] In mainframe computers, established firms, such as IBM, Burroughs, and NCR, retained important roles. In other emerging segments, however, such as minicomputers and supercomputers, new firms, including CDC, DEC, Data General, and Cray, achieved dominant positions, a point overlooked in Chandler's analysis (1990). Microcomputers also saw an influx of new firms, such as Compaq and Apple, along with established enterprises such as IBM. In the U.S. biotechnology industry, new firms have played an even more important role in developing and patenting new techniques and products than was true of semiconductors (Pisano, Shan, and Teece 1988, 189).

The arguments made by Chandler (1990) and Pavitt (1990) about large

23. This is not to deny the major role played by large firms such as IBM in computers and AT&T in microelectronics. In other instances, large firms have acquired smaller enterprises and applied their production or marketing expertise to expand markets for a new product technology. Nonetheless, it seems apparent that start-up firms have been far more active in commercializing new technologies in the United States than in other industrial economies. Malerba (1985) and Tilton (1971) stress the importance of new, small firms in the U.S. semiconductor industry; Flamm (1988) describes their significant role in computer technology; and Orsenigo (1989) and Pisano, Shan, and Teece (1988) discuss the importance of these firms in the U.S. biotechnology industry. Bollinger, Hope, and Utterback (1983) survey some of the literature on the "new technology-based firm."

24. The contribution of new firms to major innovations increased substantially after 1960, the era of integrated circuits that combined in a single chip the functions formerly performed by discrete semiconductor components. Levin (1982, 55) noted that only one of the firms (Motorola) identified as having produced major innovations or new product families during 1960–77 had been active in the electronics industry before the invention of the transistor.

firms' dominance of new technologies thus require some qualification when applied to these high-technology industries in the postwar United States. The significant technological contributions made by large firms in semiconductors, for example, have not been matched by their role in commercializing these technologies. In biotechnology, small firms have played a more important role in expanding the technology pool and in commercializing its contents. Moreover, in both semiconductors and computers, new small firms grew rapidly to positions of considerable size and market share.

Several factors have contributed to the prominent role of new, small firms in the postwar U.S. innovation system. The basic research establishments of universities, government, and large corporations served as important sources of scientific and technological knowledge that "walked out the door" with individuals who established firms to commercialize the innovations based on this knowledge. High levels of labor mobility and a supportive legal climate in intellectual property and antitrust policy facilitated the incubator role of universities and large firms.

The foundation and survival of vigorous new firms also depended on a sophisticated private financial system to support these firms during their infancy. The U.S. venture capital market played an important role in the establishment of new firms in microelectronics, computers, and biotechnology. According to the Office of Technology Assessment (1984, 274), the annual flow of venture capital into industrial investments ranged between $2.5 and $3 billion during 1969–77. Roughly $500 million in venture capital funds annually flowed into new firms during the 1980s (Florida and Smith 1993). Western European economies have yet to spawn similarly abundant sources of risk capital for new enterprises in high-technology industries (Sharp 1989, 9–10). Okimoto (1986, 562) estimated that Japanese venture capital firms provided no more than $100 million in financing in 1986.
firms provided no more than $100 million in financing in 1986.

U.S. antitrust policy also contributed to the importance of start-up firms in postwar high-technology industries, reducing patent-based entry barriers. The 1956 settlement of the AT&T case significantly improved the environment for start-up firms in microelectronics, because of the liberal patent licensing terms of the consent decree and because of AT&T's decision following the decree to avoid commercial activities outside of telecommunications. As a result, the firm with the greatest technological capabilities in microelectronics chose not to enter the commercial production of microelectronic components, enhancing the opportunities for entry by start-up firms. The 1956 consent decree that settled a federal antitrust suit against IBM also mandated liberal licensing by this pioneer computer firm of its punch-card and computer patents at reasonable rates (Flamm 1988, 223).

These antitrust consent decrees contributed to the development of an unrestrictive intellectual property regime in both semiconductors and computers, in which patent licensing at low royalty rates was common and patent enforce-

Table 5.2 **Sources of Funds for Research and Development, by Sector, 1953–91 (millions of 1982 dollars)**

	Total	Federal Government	Industry	Universities and Colleges	Other Nonprofit
1953	19,744	10,590	8,671	276	208
1954	21,445	11,895	9,023	303	224
1955	22,760	12,923	9,282	326	229
1956	29,822	17,311	11,910	344	257
1957	33,641	21,035	11,923	376	307
1958	36,076	22,826	12,494	406	350
1959	40,598	26,432	13,351	440	375
1960	43,648	28,191	14,591	479	387
1961	45,764	29,553	15,226	525	460
1962	48,176	31,011	16,039	578	548
1963	52,585	34,519	16,839	635	591
1964	57,202	38,023	17,877	711	591
1965	59,351	38,532	19,384	791	643
1966	62,589	40,047	20,962	875	706
1967	64,406	40,057	22,654	960	735
1968	65,458	39,788	23,869	1,049	752
1969	64,672	37,660	25,166	1,071	775
1970	62,405	35,636	24,851	1,111	807
1971	60,385	33,966	24,387	1,212	820
1972	61,414	34,146	25,190	1,246	832
1973	62,427	33,478	26,837	1,268	844
1974	61,467	31,726	27,578	1,298	865
1975	59,883	30,986	26,679	1,302	916
1976	62,134	31,813	28,058	1,305	959
1977	63,653	32,152	29,176	1,325	1,001
1978	66,769	33,172	31,087	1,446	1,064
1979	70,077	34,271	33,198	1,538	1,071
1980	73,255	34,557	36,065	1,574	1,059
1981	76,641	35,690	38,257	1,667	1,027
1982	80,018	36,578	40,692	1,731	1,017
1983	85,753	39,251	43,568	1,851	1,083
1984	93,790	42,286	48,456	1,945	1,102
1985	102,462	46,870	52,252	2,130	1,209
1986	104,866	47,555	53,639	2,436	1,235
1987	106,616	49,201	53,341	2,711	1,364
1988	110,166	50,635	55,181	2,856	1,495
1989	111,129	49,553	56,815	3,115	1,646
1990[a]	110,470	48,591	56,757	3,376	1,746
1991[b]	110,277	47,991	56,799	3,596	1,890

Source: National Science Foundation 1991.

[a]Preliminary.

[b]Estimated.

Table 5.3 Defense R&D as a Share of Federal R&D Spending, 1960–92

Year	%	Year	%	Year	%
1960	80	1971	52	1982	61
1961	77	1972	54	1983	64
1962	70	1973	54	1984	66
1963	62	1974	52	1985	67
1964	55	1975	51	1986	69
1965	50	1976	50	1987	69
1966	49	1977	51	1988	68
1967	52	1978	49	1989	65
1968	52	1979	48	1990	63
1969	54	1980	51	1991[a]	59
1970	52	1981	54	1992[a]	60

Source: National Science Board 1991.
[a]Estimated.

ment was relatively lax.[25] The postwar intellectual property rights environment in these industries that resulted from federal antitrust policy contrasts sharply with that of the early decades of industrial research, when large firms used patenting to maintain positions of market power that would not attract antitrust prosecution.

Defense spending on R&D and procurement, another element of the postwar U.S. R&D system that greatly increased in importance from pre-1940 levels, also benefited new firms in some industries. The share of national R&D spending accounted for by federal funds expanded to 40–50 percent of national R&D expenditures during the postwar period (table 5.2), although in contrast to other industrial economies, a large fraction of federally financed research was performed in nongovernment research laboratories. The military services have dominated this large federal R&D budget since the early 1950s, falling below 50 percent of federal R&D obligations in only three years during 1960–92 (table 5.3). But many of the most significant effects of postwar defense spending resulted from Department of Defense procurement, rather than R&D.[26] The U.S. military market in the 1950s and 1960s provided an important springboard for start-up firms in microelectronics and computers, who faced relatively low marketing and distribution barriers to entry into this market (Tilton 1971, 91; Flamm 1988, 78–79). The willingness of U.S. military

25. In biotechnology, according to Pisano, Shan, and Teece (1988), aggressive enforcement of patents has been discouraged somewhat by uncertainty over the breadth and strength of intellectual property protection.

26. The interaction of defense procurement spending and R&D investment is in fact more complex than this statement suggests; Lichtenberg's empirical estimates (1988) on the effects of federal defense procurement during 1979–84 indicate that federal procurement competitions induce increases in private R&D spending. Lichtenberg concluded that more than one-half of the increase in private R&D spending during 1979–84 could be attributed to the effects of increased defense spending.

policymakers to channel procurement contracts to relatively new firms contrasts with the military procurement policies of European governments, which tended to favor established firms (Flamm 1988, 134). The benefits of the military market were enhanced further by the substantial possibilities for technological spillovers from military to civilian applications in a broad array of high-technology industries.

The role of universities within the U.S. research system, including the interaction between U.S. industry and academic research, also was transformed by World War II. The wartime Office of Scientific Research and Development (OSRD) relied heavily on universities as research performers. The largest single recipient of OSRD grants and contracts during wartime (and the inventor of institutional overhead charges) was MIT, with seventy-five research contracts that amounted to more than $116 million. The largest corporate recipient of OSRD funds, Western Electric, accounted for only $17 million (Pursell 1977, 364).

Federal financial support for U.S. university research continued to grow during the postwar period, as Department of Defense support for university research was supplemented by funds from such agencies as the Atomic Energy Commission, the National Institutes of Health, and, more modestly, the National Science Foundation. Combined with increased reliance by large U.S. industrial firms on their internal R&D laboratories for new technologies, the upsurge in federal funding of university research appears to have weakened some of the prewar links between corporate and university research (Leslie [1993] presents a similar view of the effects of defense-related research funding on the postwar research activities of MIT and Stanford University). Universities no longer sought industrial research sponsors as aggressively as they had before 1940, since abundant research funding was available from federal sources. Du Pont's research director argued in 1945 that the firm no longer could rely as heavily on university research as it had before World War II (Hounshell and Smith 1989, 355), in part because the firm's competitors, strengthened by World War II, were equally capable of exploiting such research. No longer able to use its superior ability to commercialize the results of basic research performed outside the firm, Du Pont found another reason to rely more heavily on internal sources of new scientific and technical knowledge. Swann (1988, 170–71) also argues that research links between U.S. universities and the pharmaceuticals industry weakened significantly in the immediate aftermath of World War II by increased federal research funding for academic research in the health sciences.

The structure of the U.S. national innovation system, of which industrial R&D was a central component, underwent dramatic change during the 1940s, largely as a result of World War II and its aftermath. The huge expansion in the federal government's role as research funder and as a purchaser of the products of research-intensive industries changed the relationship between U.S. corporate research laboratories and universities, and created new markets with relatively low entry barriers for producers of innovative electronic components and systems. The antitrust policy of the late 1930s, which came to fruition in the 1940s, also led large U.S. corporations to reduce their use of in-house R&D facilities to seek out and acquire technologies from outside the firm, and aided the entry and growth of start-up firms. The overall effect of these changes was to reduce the relative importance of large U.S. firms as sources of R&D funding by comparison with their pre-1940 position. Large firms attempted to rely more heavily on their in-house R&D facilities as the exclusive source of new technologies. The boundaries of these firms in R&D effectively became less porous.

Two elements of the postwar transformation are noteworthy. First, the large federal role in R&D funding, the tough antitrust policies that accompanied it, and the importance of new firms in technology commercialization all were characteristics of the postwar U.S. that had no counterpart in the R&D systems of other industrial economies. In Japan and Germany, for example, public and defense-related R&D accounted for a much smaller share of national R&D investments, and established firms dominated the commercialization of new technologies in electronics and biotechnology. Second, this discussion suggests that much if not most of the postwar shift in the role of corporate R& D reflected change in the public policy environment within which U.S. firms operated, rather than originating either from technological factors or intrafirm developments.

5.5 Conclusion

U.S. firms were among the earliest investors in industrial research within the firm, as part of the late-nineteenth-century processes of corporate restructuring that extended the boundaries and range of products manufactured by industrial firms. Although intrafirm R&D substantially outstripped the importance of independent contract services, the two forms of R&D organization complemented one another. Before 1940, the in-house R&D facilities of major corporations monitored the external technological environment and guided the acquisition of new technologies from outside sources, which were then developed to the point of commercialization by the acquiring firm.

After 1945, changes in government policy transformed the role of R&D within many large firms. Rather than using it as a source of in-house innovations and a "listening post" for external technological opportunities, U.S. firms came to rely on intrafirm R&D to create new technologies for the firm. This shift toward an "inward orientation" in R&D strategy contributed to the important role of new firms as agents of technology commercialization in the postwar United States.

These observations on the changing role of corporate R&D need much more research, especially on the history of individual corporations and their R&D facilities, to be corroborated. Nevertheless, the evidence suggests that the emphasis in Chandler's comparative analysis (1990) on the continuity of the pre- and post-World War II corporate U.S. economy may be overstated. The consequences for corporate or national economic performance of these changes in the role of U.S. industrial research also require additional research. These effects are confounded with those of many other variables, and their identification is further hampered by the lack of reliable models linking innovative performance to internal corporate structure. Nevertheless, some evidence suggests that the changes discussed in this paper impaired the innovative performance of at least some large U.S. firms that had pioneered in industrial research.

Hounshell and Smith's historical account of Du Pont's R&D program (1989) concluded that the firm's postwar search for "new nylons" impaired its innovative and competitive performance. As was noted earlier, other scholars have argued that many of the conglomerate mergers and acquisitions of the 1960s and 1970s produced disappointing economic results. Recent empirical evidence suggests that the competitive strength of at least some Japanese manufacturing firms is associated with their ability to rapidly commercialize technologies based on external sources of knowledge (see Mansfield 1988). To the extent that large U.S. firms' shift to internal sources for innovations weakened their ability to exploit external sources of industrial technology, it may have weakened their ability to deal with new competitors that were especially adept at exploiting these sources.

Considerable uncertainty also remains about the consequences for national competitive performance of the large role played by new, small firms in postwar U.S. high-technology industries. Long hailed as a dynamic source of new technologies, entrepreneurial verve, and employment opportunities, the start-up firm has more recently been criticized for being unable to move from the creation and commercialization of a new product to the sustained competitive improvement of a portfolio of products and processes (see, e.g., Florida and Kenney 1990; Gomory 1992).

Comparative studies of the U.S. and Japanese semiconductor industries, for example, have argued that the greater size and higher level of vertical integration in many Japanese electronics firms have strengthened their ability to compete against a U.S. industry populated largely by smaller firms (the descendants of start-ups) with much lower levels of vertical integration (Steinmueller 1988; Borrus 1988). But this debate has not reached a satisfactory conclusion. As of early 1993, at least, the putative advantages of large size and vertical integration have not prevented erosion in the profits and market share of these large Japanese firms, nor have they prevented a significant downturn in the performance of the largest, most highly vertically integrated U.S. producer of semiconductors, IBM.

Nelson (1988, 325) has referred to the industrial research laboratory as the "heart of the [innovation] system" in the United States. Even this pillar of the U.S. system, however, is undergoing change. Faced with escalating costs and intensified competitive pressures, many U.S. firms are exploring alternatives to exclusive reliance on intrafirm sources of innovation; their search is being supported by new state and federal government policies.[27] Alternatives include university-industry research partnerships, alliances with other domestic and foreign firms, and publicly sponsored cooperative research programs. These and other changes in the structure of the U.S. innovation system may revive several of the characteristic elements of the pre-1940 period, including state government funding of applied research and collaborative research relationships between universities and industry. These initiatives represent a partial revival of earlier relationships that were sundered by the dramatic changes in the structure of the U.S. national research system during and after World War II.

Since these changes also will affect several features of the postwar U.S. national innovation system that have distinguished it from those of other industrial economies, they may also reduce the structural differences between the U.S. and other national innovation systems.[28] As U.S. defense spending declines, the federal government's share of national R&D spending is likely to shrink to levels that more closely resemble those of other industrial economies. Some evidence also suggests that the civilian technological spillovers historically associated with postwar defense spending have shrunk (Rosenberg 1987; Mowery and Rosenberg 1989; Chinworth and Mowery forthcoming). The declining role and weaker civilian spillovers of defense procurement spending, along with tougher domestic protection of intellectual property rights, may raise the entry barriers faced by new firms in many R&D-intensive industries, reducing the important role of start-up firms in technology commercialization that has been unique to the postwar United States among the major industrial economies.

The seminal work of Chandler (1977, 1990) on the development of the modern corporation has drawn on and influenced the work of Williamson (1975, 1985) on market-based and intrafirm approaches to the organization of economic activity. This discussion of the development of industrial research, however, suggests that the distinction between "markets" and "hierarchies" should not be overstated. Market-based and intrafirm forms of governance of the industrial innovation process have coexisted throughout this century. Although the historical transformation in the boundaries of the firm is an important

27. Examples of such supportive public policies include changes in antitrust policy, public funding for industry-university research linkages, and state government support of industrial technology development.

28. Even as some historically unique characteristics of the U.S. national innovation system may be declining in importance, debate has intensified in other industrial economies (e.g., Japan) about the wisdom of developing R&D organizations and institutions that in some respects resemble those that were long important in the United States. Thus, Japanese policymakers and managers are considering policies to strengthen university research, industry-financed basic research, and military-financed research in ways that may reduce the salience of some of the unique structural characteristics of the Japanese innovation system (see Mowery and Rosenberg 1989, chap. 8, for further discussion).

development in modern economic history, the fact remains that, at least within corporate R&D, these boundaries have been porous to varying degrees during the development of U.S. industrial research. Moreover, changes in the porousness of U.S. firms' boundaries in R&D during the past seventy-five years probably have been more heavily affected by public policy than any other single factor. In R&D, no less than in other areas, many of the key influences on the evolution of the boundaries of the U.S. firm lie outside the corporation.

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Comment Joel Mokyr

Mowery's paper deals with the location of the source of technological progress. Specifically, it asks whether that location is within the boundaries of the firm that ends up using it, or whether it is purchased from other firms, either R&D labs or possibly competitors. Mowery provides a useful historical survey of the location of R&D, that is, whether most of it will be carried out in-house or purchased from other firms, and surveys the changes in its location as a result of government policy and other environmental factors. His paper, however, does not connect this question to some deeper and highly relevant issues in the theory of the firm and the theory of technological change and thus falls short of an altogether persuasive account of the issue.

The question of what economic activity will take the place *within* the firm as opposed to transacted *among* firms is not new, of course, and was first posed in its starkest form by Ronald Coase in his celebrated 1937 paper on the nature of the firm. Mowery's paper basically constitutes an extension of Coase's question to the realm of R&D (oddly without direct reference to Coase), clearly an important and timely issue.

Coase asked when activities will occur within the firm as opposed to when they will occur through the market by means of an explicit transaction. The answer is now quite obvious and well understood: firms will integrate and produce things for themselves in-house rather than buy them in the market when the costs of transaction between firms are higher than the gains from specialization that necessitate this transaction. The in-house production of inputs thus substitutes for the market, and internal decision rules are substituted for obeying price signals. The coexistence of conscious in-house decision making and spontaneous, decentralized market allocations was described by D. H. Robertson in an appetizing if mixed metaphor, cited with approval by Coase as follows: "we find islands of conscious power in this ocean of unconscious cooperation like lumps of butter coagulating in a pail of buttermilk."

Coase was thinking of intermediate products and inputs, not that elusive thing called new technological knowledge. As Mowery stresses, R&D is in many ways different from other inputs. There are obvious and well-understood contracting difficulties that come up in the market for technology (Teece

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1988). Thinness of markets, the specificity of technical knowledge, the uncertainty involved in generating it, asymmetric information, the moral hazards of cost-plus contracts, and above all the pitfalls of intellectual property rights and public-good properties of technology—all are good reasons why obvious and well-undersood contracting difficulties come up in these markets. Opportunistic behavior is likely to be rampant, and markets of technical knowledge are often said to be deficient and incomplete. Yet they do exist, and licensing agreements, consultant firms, interfirm technological consortia, and other forms of contracting for technologies exist. After all, as Coase said, the firm is a "supersession of the price mechanism." When the price mechanism becomes expensive to use, vertical integration and in-house R&D are more likely to occur. The more tacit and firm-specific the knowledge, the more likely firms are to develop their technologies in-house. Yet there are clearly enormous advantages in specialization and interfirm trade in new technological ideas.

The basic microeconomic rule that governs the in-house versus outside purchase in technological progress is this: industrial R&D will be purchased from the outside the higher the gains to specialization and the lower the market transactions cost. In technological change, transactions costs may have been very high, but so were the gains from specialization. Comparative advantage is never more pronounced and powerful than when it comes to development and engineering of new products and processes, because that is where inspiration and expertise, intuition and experience come together as nowhere else. The lack of discipline and freedom in search for new ideas have always made universities and pure research-oriented think tanks more effective at developing new departures, and firms have traditionally recognized that. "Universities are much better at the basic sciences and discovery than we are," argues Joseph Patterson of Hoechst Celanese, after awarding $1 million each to three research schools (*Wall Street Journal* 22 October 1992). Comparative advantage patterns thus differ, and there are gains from a division of labor in R&D.

Theory, therefore, predicts a less than perfect specialization pattern. R&D will involve some modicum of cooperation and transaction between firms that will eventually use the technology and those that research the first stages of it, as well as a fair amount of in-house work. That still leaves a lot of slippage in the middle, and clearly the history of R&D in the United States indicates changing weights between in-house research and market transactions in new technology. The boundaries of the firm will be quite porous to relatively radical new technologies, where they will continue to rely on outsiders. If this relation gets very cozy, the firms might change from a market to a nonmarket relationship and merge or perhaps hire the consultant firm on a permanent retainer. Some of these mergers, like the GM-EDS fusion, were intended from the outset to revolutionize production methods in the firm. The fact that this happens proves there are transactions costs in using the market. The fact that it does not happen *invariably* proves that there are offsetting advantages to specialization and market transactions.

Unfortunately, explaining this process over time is difficult. Transactions costs are not measurable with any degree of accuracy, and so there is no way of knowing whether the growing dependence on in-house research after 1945 was the result of increasing difficulties in buying and selling components of an ever more complex technology or declining gains from interfirm trade in technology. Moreover, it is not clear whether the ratio of transactions costs to gains from specialization changed in one direction or another in the period under discussion. In the absence of any direct clues, the search for an explanation must remain tentative. Furthermore, unrecognized by the simple Coasian framework, there are transactions costs of doing business *within the firm* as well. In large corporate bureaucracies, information is generated in large quantities in part because there are economies of scale in information. All the same, the fact that it exists *somewhere* within a firm does not mean that it automatically flows from one branch of the bureaucracy to another and that it is accessible by those who need it. To judge from what Ross Perot had to say about GM, clearly intrafirm information is not all it is cracked up to be and does not flow necessarily better than interfirm. Indeed, it is often said of large firms that "the left hand does not know what the other left hand is doing." The incentive structure to *share* and *dispense* knowledge within the firm is not always as strong as it is in a market environment where the quid pro quo is more immediate. Much depends on the quality of top management. In the long haul, the obvious problems of appropriability, intellectual property rights, and opportunistic behavior notwithstanding, the competitive forces that lead to the sharing of information between firms may be more reliable.

One way of making some progress is to look not at the inputs of the innovation process (that is, R&D budgets or the number of employees in the research sector) but at the nature of the product that is generated. Teece and others do not distinguish sufficiently between R&D (essentially an input) and new technological knowledge, whether it qualifies as "inventions" or whether it is more in the nature of "product development," which is an output of inventive activity. Mowery treats technology more or less as an undifferentiated outcome of R&D input. Yet to answer his question about the locus of technological change, the *nature* of the technology generated may be quite crucial. Ever since Usher, we have understood that major breakthroughs create a new technique or a new industry, and constitute a shift *of* the marginal product curve of R&D rather than a shift *along* it. Following such a macroinvention, we observe a wave of smaller inventions (microinventions) that refine, debug, and perfect the new technique and make it workable. Many of those microinventions are part of experience and learning by doing or learning by using and often are so tacit and specific that they cannot be marketed. Others may be sold or licensed to other firms. Things are quite different with respect to major breakthroughs. On the whole, macroinventions are rarely made in-house, that is, by a firm that could use them best. The classic account of Jewkes, Sawers, and Stillerman (1969) provides a long list of examples and much of the rationale for this phenomenon: truly radical inventions require an uncommitted and unconventional mind, which is rarely welcome in the corporate world of conformist team-players. When they emerge, they are either licensed out, the inventing firm itself is acquired by the user, or it adapts its structure to accommodate the new technology. At times, what seems an ex ante invention ready to be licensed and traded becomes an ex post in-house invention as the inventing firm decides to go into the business itself. Aspartame was invented by G. D. Searle, which had no way of using it under its existing structure, not by Coca Cola, which did. To pick another example, when an in-house R&D lab at a German dye-making concern, Bayer's, stumbled upon the most successful analgesic in history, the firm diversified into pharmaceutics. Leo Godowski and Leopold Mannes, the two musicians who invented Kodachrome, received both financial support and necessary assistance from Eastman Kodak but did not work for it. Downstream inventions, determined by users and customers, may well be of critical importance in the overall picture, but few macroinventions were generated that way. In an age of technological consolidation rather than radical new departures, then, we would expect in-house R&D to become more important. In an age of fundamental innovations, such as the 1980s, interfirm trade in new knowledge seems more likely.

One testable hypothesis, then, that derives directly from this analysis is that in-house R&D will be more successful in older industries in which there have been few major breakthroughs, and that interfirm transactions in technology are more common in industries in which recent technological breakthroughs have occurred. Although this picture is confused by the fact that firms buy up other firms, the evidence presented in Mowery's paper bears it out. A single heroic inventor in the Jewkes, Sawers, and Stillerman tradition might be counted ex post as doing his work "in-house" when a large corporation acquires him, his lab, and his ideas in a package deal. All the same, really big and successful technological ideas are sufficiently rare that if a firm comes up with one, either through luck or through hard work, it is more likely to license or sell it, and thus it will enter the market rather than be counted as a purely in-house type of invention. As an invention becomes "smaller" this likelihood declines, other things equal.

A separate issue is whether existing and old firms are more suitable at innovating and carrying out industrial R&D or whether new firms entering are essential for continuous industrial progress. Mowery rightly takes issue with Chandler's exaggerated beliefs in the flexibility of big corporations, and points to "new firms" as indispensable loci where much of the R&D takes place. Yet at the same time some old corporations were able to rejuvenate themselves, with IBM, NCR, Motorola, Ford, and Du Pont the classic examples. Perhaps, then, firm "age" is not the only important variable in determining whether a firm will be innovative and engage heavily in industrial R&D, and whether it will get its new technology by doing its own research or buy the ideas from others. Instead we should look at the technology at stake itself: How novel is it? What is the appropriability of further advances? How firm-specific are microinventions that make it advance? Is the nature of the innovations highly patentable and licensable? Does it involve processes than can be kept secret and thus best developed and kept in-house?

A further issue is the quality of management and its openness to new ideas. On the whole, it seems to me that all we know about the long-term dynamics of bureaucracies suggests that within the same firm R&D departments tend to go stale unless they are subject to radical overhauls from time to time. Perhaps the strongest argument against in-house research then is that big corporations, like all bureaucracies, tend to become ossified and conservative, and so their managements may become hostile to innovations that make waves and threaten the stability of the status quo (Kuran 1988). Such sclerotic firms may not be able to generate much innovation themselves, but when faced with tighter conditions in the marketplace, the new technology is presented to them by their competitors rather than by their employees, and so their options are limited. Their large R&D departments then become scouting agencies, searching for new inventions on the markets that threaten the firm. Once identified, however, it is still an open question whether management will buy into the new technology. Mowery implicitly assumes that firms that cannot generate new technology will buy it from others if available. But management may not welcome new ideas at all. To be sure, competitive markets tend to deal summarily with firms that suffer from the "not-invented-here" syndrome and its more malignant relative "if it were possible we would have done it long ago." Yet in practice firms make these mistakes all the time. It is easier to dismiss a new idea when it comes from your own employee. When Henry Ford III was faced with radial tires, he contemptuously dismissed them. He then reluctantly had to purchase them from Michelin despite his distaste for "frog tires" (Frey 1991). Serious pockets of resistance in other parts of the corporation may block the introduction of new techniques, as the example provided by John Sutton regarding the introduction of polyester-based tires at Du Pont amply demonstrates. Firms that resist innovation might be clay-footed bureaucratic giants, or one-man empires in which a brilliant but erratic entrepreneur makes the decisions himself. Either way, they have three options: generate the new technology themselves, buy it from others, or languish and (perhaps) perish.

The recent work by Daniel Shiman (1992) on technological progress in Victorian Britain has found that a key variable in technological progress is the ability of the firm to delegate authority within its own hierarchy to the people in charge of R&D. British family firms, run by, through, and for old-boy networks, trusted few underlings, and management rarely lent the R&D departments, insofar that these existed at all, a free hand. Effective in-house research requires that management leave technical issues to its in-house specialists. In practice, this rarely happens, and the same scientist will produce very different results depending on whether he is working for a large firm that plans to use his invention or a smaller one (including himself) that will sell it. Yet continuous pressure on such labs to produce profitable results quickly mean that in-house and specialist research labs do not produce the same kinds of new knowledge. Only if the firm's management is fully committed to let its research lab do what it wants will they produce similar results.

An important element, allegedly, in the interpretation of the development of the U.S. R&D industry is the existence of antitrust laws. Antitrust policies, on balance, are said to have enchanced in-house research. A simple test of this proposition is to look at imperial Germany, where it flunks quite spectacularly. The hypothesis also implies that when antitrust legislation was loosely enforced, firms should have switched from in-house R&D to market-supplied new technologies. Yet one could argue that the reverse is equally plausible: firms that do a lot of in-house research might fear that their competitive advantage would become so overwhelming that the antitrust enforcers would attribute it to price-fixing rather than to technological superiority. If they are worried about intervention of this kind, they do not *have* to merge with the firms that generated the new technologies, and could license or rent it in some form. The market provides enough flexibility to overcome such fears. Moreover, in the vast bulk of technological mergers in which a large user company bought out a small but innovative supplier, the difference in size between the two companies was such that it can hardly have mattered to the authorities. In any event, if the antitrust policies had this effect, the outcome may have been the reverse of the intended one if intrafirm research tended to weaken competition as successful firms acquired technological niches in the products they developed and thus fostered a stable oligopolistic market. This hypothesis is never put to an exact test, and we have another tantalizing suggestion that makes sense, but is not directly confronted with the evidence. It is, of course hard to prove anything when the main variable to be explained (the proportion of new technology produced by in-house industrial research labs) is neither quantifiable nor directly observable.

Neoclassical economic theory is quite good in pointing out its own failures and carefully delineating when markets fail, and it is standard fare in any course in the economics of technological change to point out why markets involving technology are incomplete and unreliable. When they are, they can be superseded by mechanisms internal to the firm. But where do these internal procedures come from, what constraints are they subject to, and can they adapt over time to a changing environment? And, above all, are they capable of generating that flow of innovations that is necessary for a dynamic capitalist system to sustain itself? Many of the papers in this volume are making an effort to provide alternatives. An analysis in terms of the *nature* of the hierarchies involved and their tendency toward conservatism seems to me necessary to complement the emphasis on external environment, especially government policies. What happens when management is faced with a radical novel approach from its own R&D department? Will the firm willingly accept innovations that will make much of its physical and human capital obsolete? Does the R&D department anticipate management's response? To what extent does the R&D lab itself become a bureaucracy with entrenched vested interests?

On these issues we look in vain to standard theory for answers. To bend a hackneyed aphorism about the drunk looking for his keys a bit more: we have searched under the streetlight, and the keys we are looking for are not there. We can either go home without our keys, or try to get another source of light. In the new institutional economics, with its emphasis on transactions costs, its capability to characterize conventions and customs as Nash equilibria in bargaining models and coordination games, and its analysis of the internal dynamics of power structures and hierarchies, we may be in the process of erecting a new streetlight. I am not sure whether our keys are there either, but it is worth a look.

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