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Plus ca change: Industrial R&D in the "third industrial revolution"

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The structure of industrial R&D has undergone considerable change since 1985, particularly in the United States. But rather than creating an entirely novel system, this restructuring has revived important elements of the industrial research "system" of the United States in the late 19th and early 20th centuries. In particular, many of the elements of the "Open Innovation" approach to R&D management are visible in this earlier period. This article surveys the development of industrial R&D in the United States during the postwar period. In addition to emphasizing continuity rather than discontinuity, this discussion of the development of US industrial R&D during the "Third Industrial Revolution" stresses the extent to which industrial R&D in the United States, no less than in other nations, is embedded in a broader institutional context. My discussion also highlights the extent to which its development has been characterized by considerable path dependency.

1. Introduction

The structure of industrial R&D has undergone considerable change since 1985, particularly in the United States. But rather than creating an entirely novel system, this restructuring has revived important elements of the industrial research "system" of the United States in the late 19th and early 20th centuries. In particular, many of the elements of the "Open Innovation" approach to R&D management (Chesbrough, 2003, 2006)[1] are visible in this earlier period. Indeed, the 1945–1985 period in the historical development of industrial R&D in the United States, which was characterized by large central corporate research facilities that sought to span the continuum from fundamental research to development, ultimately may prove to be a departure from a structure that for much of its existence included both inter-institutional linkages and a market for intellectual property to support industrial innovation.

[1]"...Open Innovation is the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation..." (Chesbrough, 2006, 1). See also Patit *et al.* (2006) for a discussion of the role of internal and external R&D in the early evolution of U.S. industrial R&D.

A major influence on the evolution of the US industrial R&D system during the past 125 years has been public policy, particularly antitrust policy. A second important public policy influence during the post-1945 period is public R&D spending, notably in defense-related areas and in biomedical research. Both information technology (IT) and biotechnology benefited from large federal R&D investments. These federal R&D programs, as well as defense-related procurement, influenced the growth of a postwar industrial R&D system that contrasted with those of other industrial economies and that differed significantly from its pre-1940 structure. Industrial R&D in the "Third Industrial Revolution" in the United States thus contains major elements of continuity as well as change, and the evolution of industrial R&D arguably has been less heavily determined by the new technologies of IT and biotechnology than by state policy. Indeed, these public policies underpinned some key innovations in IT and biotechnology.

This article surveys the development of industrial R&D in the United States during the postwar period. In order to establish the case for continuity, however, it is necessary to examine briefly the historical origins and early development of industrial R&D. Following this discussion of pre-1940 characteristics and trends, I discuss the sweeping changes associated with World War II and the Cold War that followed. I next examine a number of quantitative indicators of structural change in the industrial R&D system of the last quarter of the 20th century, relying on data from the National Science Foundation. Although I focus primarily on the United States, for which data are more complete during the postwar period, I highlight areas in which the evolution of US industrial research resembles or contrasts with trends in other industrial economies.

In addition to emphasizing continuity rather than discontinuity, this discussion of the development of US industrial R&D during the "Third Industrial Revolution" stresses the extent to which industrial R&D in the United States, no less than in other nations, is embedded in a broader institutional context. Other scholars have developed the concept of "National Innovation Systems" to capture the complex, inter-dependent institutional and policy context in which industrial innovation has evolved in the United States and other economies (Freeman, 1995; Nelson, 1993; Edquist, 2004). In addition to its emphasis on the "embeddedness" of US industrial R&D, my discussion also highlights the extent to which its development has been characterized by considerable path dependency.

2. The origins of industrial research in the "second industrial revolution"

A defining characteristic of the "new industries" of the Second Industrial Revolution, particularly chemicals and electrical machinery, was increased reliance on R&D within the firm. The pioneers in this organizational innovation were the large

German chemicals firms of the last quarter of the 19th century, whose growth was based on innovations in dyestuffs. By the first decade of the 20th century, a number of large US firms had established similar in-house industrial research laboratories. In both nations, the growth of industrial research was linked to a broader restructuring of manufacturing firms that transformed their scale, management structures, product lines, and global reach.

Many of the earliest US 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. The corporate R&D laboratory brought more of the process of developing and improving industrial technology into the boundaries of US manufacturing firms, reducing the importance of the independent inventor as a source of patents (Schmookler, 1957). But the in-house research facilities of large US firms were not concerned exclusively with the creation of new technology. Like the laboratories of the German dyestuff firms, these US industrial laboratories also monitored technological developments outside of the firm and advised corporate managers on the acquisition of externally developed technologies. Many of Du Pont's major product and process innovations during this period, for example, were obtained from outside sources, and Du Pont further developed and commercialized them within the US market (Mueller, 1962; Hounshell and Smith, 1988; Hounshell, 1995).[2] In-house R&D in US firms developed in parallel with independent R&D laboratories that performed research on a contract basis (see also Mowery, 1983a). But over the course of the 20th century, contract-research firms' share of industrial research employment declined.

The evolution of industrial research in the United States was influenced by another factor that was absent in Germany during the late 19th and early 20th centuries, competition policy. By the late 19th 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 one response to this new legal environment. Since informal and formal price-fixing and market-sharing

[2]The research facilities of AT&T were instrumental in the procurement of the "triode" from independent inventor Lee de Forest, and advised senior corporate management on their decision to obtain loading-coil technology from Pupin (Reich, 1985). General Electric's research operations monitored foreign technological advances in lamp filaments and the inventive activities of outside firms or individuals, and 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: 145–147).

agreements had been declared illegal in a growing number of cases, firms resorted to horizontal mergers to control prices and markets.[3]

The Sherman Act's encouragement of horizontal mergers ended with the Supreme Court's 1904 *Northern Securities* decision, but many large US firms responded to the new antitrust environment by pursuing strategies of diversification that relied on in-house R&D to support the commercialization of new technologies that were developed internally or purchased from external sources. George Eastman saw industrial research as a means of supporting the diversification and growth of Eastman Kodak (Sturchio, 1988: 8). 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, 1988: 57).

Although it discouraged horizontal mergers among large firms in the same lines of business, US antitrust policy through much of the pre-1940 period had little effect on efforts by these firms to acquire new technologies from external sources. The development of industrial research, as well as the creation of a market for the acquisition and sale of industrial technologies, benefited from reforms in US patent policy between 1890 and 1910 that strengthened patentholder rights (Mowery, 1995).

Judicial tolerance for restrictive patent licensing policies further increased the value of patents in corporate research strategies. Although the search for new patents provided one incentive to pursue industrial research, the impending expiration of these patents created another important impetus. Both American Telephone and Telegraph 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). 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.

Schumpeter argued in *Capitalism, Socialism and Democracy* (1943) that in-house industrial research had supplanted the inventor-entrepreneur (a hypothesis supported by Schmookler, 1957) and would reinforce, rather than erode, the position of dominant firms. The data on research employment and firm turnover among the 200 largest US manufacturing firms suggest that during 1921–1946 at least, the

[3]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 1895–1898 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 US merger wave, but her account (p. 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.

effects of industrial research were consistent with his predictions. Displacement of these firms from the ranks of the very largest was significantly less likely for firms with in-house R&D laboratories (Mowery, 1983b).

Many of the elements of the "Open Innovation" model, defined by its leading proponent as a new model for managing corporate innovation in which "firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as the firms look to advance their technology," are apparent in the early development of US industrial R&D. The in-house R&D facilities of leading industrial firms served as monitors of external technological developments that supported the purchase by their parent firms of important innovations from independent inventors and other firms.

These technology-acquisition strategies built on an active market for intellectual property that grew substantially during the 1880–1920 period. According to Lamoreaux and Sokoloff (1999), the development of a national market for intellectual property enabled independent inventors to specialize and thereby enhanced their productivity and the overall innovative performance of the US economy. As these scholars argue, the "golden age" of the independent inventor in the late 19th century US economy was brief, as the increased costs of inventive activity and greater demand for formal scientific and engineering training led to the supplanting of independent by corporate inventors (Lamoreaux and Sokoloff, 2005). The licensing and technology acquisition strategies that were supported by this domestic market for intellectual property, however, were an important component of the emerging network of corporate industrial R&D laboratories in the US economy of the early 20th century.

A final area in which the pre-1940 era in the development of industrial research resembles that of the past two decades is the evidence of collaborative linkages between industrial and academic research. Furman and MacGarvie (2005) show that pharmaceuticals industry R&D research facilities founded during 1927–1946 in the United States tended to locate nearby leading research universities, and provide other evidence of university–industry collaboration in pharmaceuticals during this period. Other scholars (Mowery *et al.*, 2004; Rosenberg, 1998) have emphasized the importance of university–industry collaboration during this period, not least in the development of such important fields of university research as chemical engineering.

University–industry collaboration in US higher education was facilitated by the unusual structure of the US higher education system (especially by comparison with those of other industrial economies) during the 20th century. The US higher education system was larger, included a heterogeneous collection of institutions (religious and secular, public and private, large and small, etc.), lacked any centralized national administrative control, and encouraged considerable inter-institutional competition for students, faculty, resources, and prestige (See Geiger, 1986, 1993; Trow, 1979, 1991, among other discussions). In addition, the reliance by many public universities on "local" (state-level) sources for political and financial support further enhanced their incentives to develop collaborative relationships with regional industrial and agricultural establishments.

Both the curriculum and research within US 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 US ethical drug firms that developed after World War I.[4] Hounshell and Smith (1988: 290–292) document a similar trend for the Du Pont Company, which funded graduate fellowships at 25 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, 1988: 295).

Still another university with strong ties with local and national firms was M.I.T., founded in 1862 with Morrill Act funds by the state of Massachusetts.[5] In 1906, MIT's electrical engineering department established an advisory committee that included 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 (Wildes and Lindgren, 1985: 42–43). 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. During the 1910–1940 period, M.I.T. also played an important role in the development of US chemical engineering, working closely with US chemicals and petroleum firms.[6]

[4]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% of Eli Lilly and Company's R&D budget. Swann cites similarly ambitious university research programs sponsored by Merck and Upjohn.

[5]The M.I.T. 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 1919 withdrawal by the Massachusetts state legislature of financial support for M.I.T., along with the termination of the Institute's agreement with Harvard University to teach Harvard engineering courses, led M.I.T. President Richard C. Maclaurin to establish the Division of Industrial Cooperation and Research. This organization was financed by industrial firms in exchange for access to M.I.T. libraries, laboratories, and staff for consultation on industrial problems. Still another institutional link between M.I.T. and a research-intensive US industry, the Institute's School of Chemical Engineering Practice, was established in 1916 (Mattill, 1991).

[6]As this discussion suggests, collaboration among at least two elements of the so-called "Triple Helix" (industry, universities, and government) was well-developed in some fields of research and among some firms and universities well before the popularization of the "Triple Helix" concept

Training by public universities of scientists and engineers for employment in industrial research also linked US universities and industry during this period. The PhD's trained in public universities were important participants in the expansion of industrial research employment during this period (Thackray, 1982: 211)[7]. The size of this trained manpower pool was as important as its quality; although the situation was improving in the decade before 1940, Cohen (1976) noted that virtually all "serious" US scientists completed their studies at European universities. Thackray *et al.* (1985) argue that American chemistry research during this period attracted attention (in the form of citations in other scientific papers) as much because of its quantity as its quality.

Federal expenditures for R&D throughout the 1930s constituted 12–20% of total US R&D expenditures, and industry accounted for about two-thirds of the total. The remainder came from universities, state governments, private foundations, and research institutes. One estimate suggests that state funds may have accounted for as much as 14% of university research funding during 1935–1936 (National Resources Planning Board, 1942: 178). Moreover, the contribution of state governments to nonagricultural university research appears from these data to have exceeded the federal contribution, in sharp contrast to the postwar period.

3. Industrial research and innovation: 1945–1985

3.1 The postwar transformation

The global conflict of 1939–1945 transformed the structure of R&D throughout the industrial economies. Global scientific leadership shifted from Western Europe to the Unites States. New industries, including those based on innovations in ICT and biomedical science, began to grow rapidly after the 1950s. As global trade and investment flows revived after the 1914–1945 period of war and depression, international flows of technology also expanded, and by the 1980s and 1990s economies such as Japan, South Korea, and Taiwan had emerged as sources of industrial innovation. In all of these economic regions, the state became a more important peacetime actor in the "national innovation system", especially through

in the 1990s (Etzkowitz and Leytesdorff, 1997; Etzkowitz *et al.*, 1998). As appears to be true of "Open Innovation," much of what is portrayed in these discussions as novel aspects of the "Triple Helix" have been present in the United States for decades.

[7]Hounshell and Smith (1988, 298) report that 46 of the 176 PhD'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% of the 184 PhD's overseen by Professor Roger Adams of the University of Illinois during 1918–1958 went directly into industrial employment. In 1940, 30 of the 46 PhD's produced by the University of Illinois chemistry department were first employed in industry.

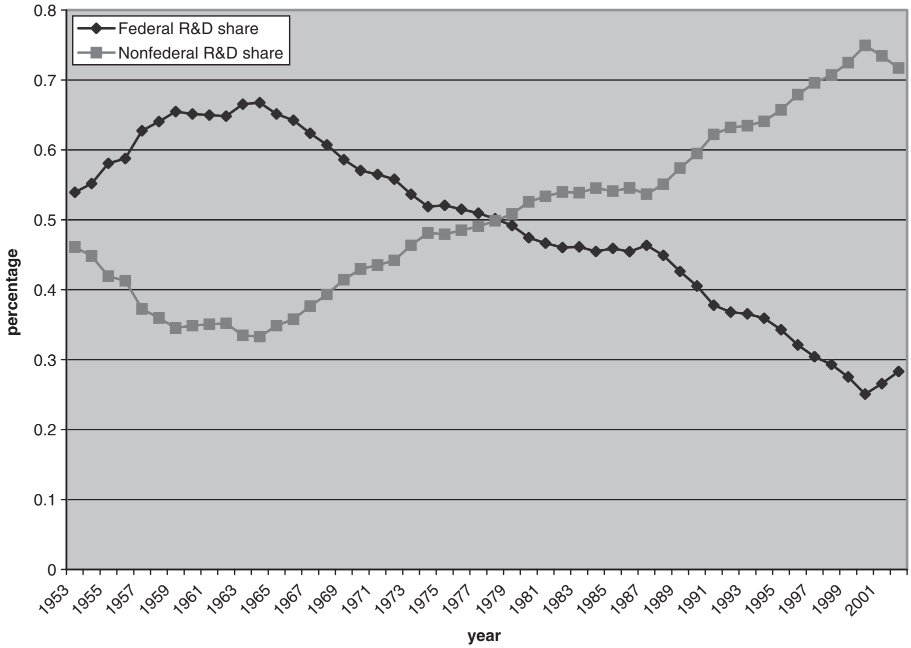

Figure 1 Federal and Nonfederally funded R&D, 1953–2002.

direct support of R&D in industry and elsewhere, and (in varying degrees) through procurement of the products of knowledge-intensive industries.

A central characteristic of the institutional transformation of the US national innovation system during 1941–1950 was increased federal support for R&D, most of which was defense-related. Defense-related R&D spending accounted for more than 80% of total federal R&D spending for much of the 1950s, and rarely has dropped below 50% of federal R&D expenditures during the entire 1949–2005 period (Figure 1; data from US Office of Management and Budget, 2005). Since federal R&D spending accounted for more than 50% of total national R&D spending during 1953–1978 (data for overall national R&D investment are available only after 1952), and only dropped below 40% in 1991 (its postwar low point of 25% appeared in 2000, as Figure 2 shows; data from National Science Board, 2006), the significance of the federal government's defense-related R&D investment is obvious—in some years during the postwar period (e.g. the late 1950s and early 1960s), defense-related R&D investment accounted for nearly one-half of total national R&D spending. Federal spending supported R&D activity in industry and universities, rather than being concentrated in federal government laboratories; as of 1980 (a date chosen arbitrarily as representative of the apogee of the "Cold War" US innovation system), 12.2% of R&D performance was located in the public sector, 13.2% took place in universities, and 71.1% was located in industry.

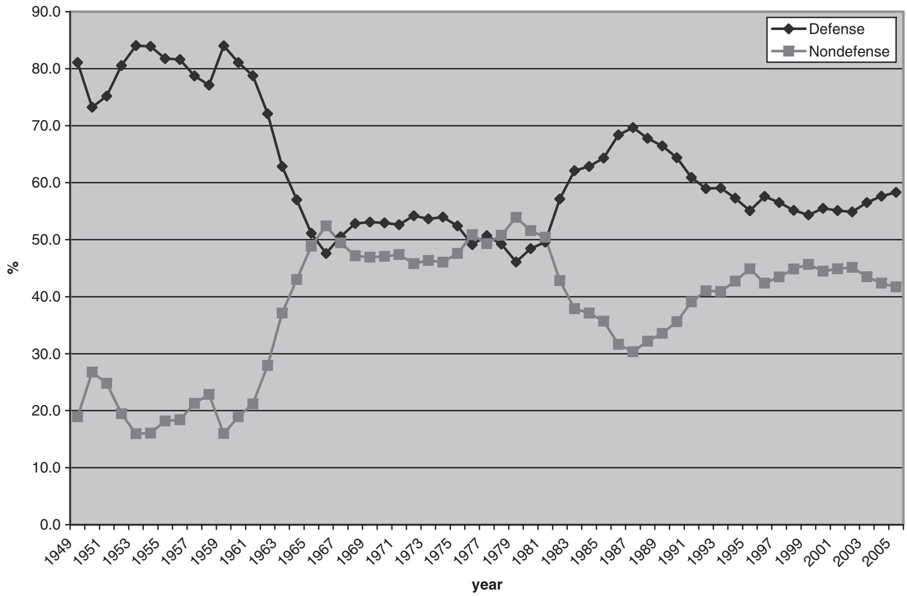

Figure 2 Defense & Nondefense share of total federal government R&D outlays, 1949–2005.

During this period, US science and technology "policy" was the product of loosely coordinated decisions made in diverse policy areas (including procurement policy) designed to further the missions of individual federal agencies. By far the most important of these missions throughout the postwar period, in terms of political consensus or budget, was national security. Indeed, the federal agency originally charged by Vannevar Bush in his famous 1945 report, *Science: The Endless Frontier* with responsibility for supporting nondefense basic research, the National Science Foundation (NSF, based on Bush's original conception of a National Research Foundation; see Bush, 1945), was established only in 1950. By that time, the major mission agencies (e.g. the military services, the Atomic Energy Commission, and the National Institutes of Health) had begun ambitious intramural and extramural R&D programs.[8] The NSF budget remains dwarfed by the research budgets of these other agencies.

[8]"In the absence of a National Science Foundation between 1945 and 1950, no comparable institutional sponsor of fundamental physical research for civilian needs had existed, nor had any comparable institutional mechanism to plan, if not to enforce, a research program in the physical sciences better balanced between civilian and military purposes. In retrospect, the delay in the establishment of the National Science Foundation was critically important in the evolution of postwar policy for research and development, not least because it cost the nation a program balanced between civilian and military patronage and purpose". (Kevles, 1977, 359–360).

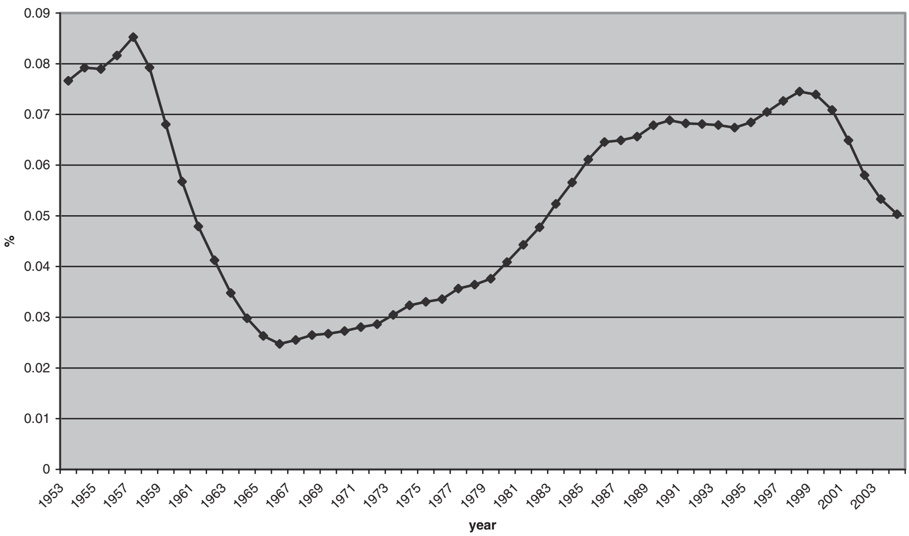

Figure 3 Industry-funded share of total university R&D, 1953–2003.

Increased federal R&D investment was associated with another shift in the postwar structure of the US innovation system. As Figure 3 (data from National Science Board, 2006) shows, the share of university research supported by industry declined during the 1950s from a peak of more than 8% of academic research in 1957 (a share than has not been achieved in any year since) to less than 3% in 1967. Bok (1982) among others has suggested that increased federal funding for academic research may have reduced the incentives of faculty and academic administrators to seek funding from industry.[9]

The structure (if not, necessarily, the scale) of the pre-1940 US R&D system resembled those of other leading industrial economies of the era, such as the UK, Germany, and France—industry was a significant funder and performer of R&D and central government funding of R&D was modest. But the postwar US R&D system differed from those of other industrial economies in at least three aspects: (i) US antitrust policy during the postwar period was unusually stringent; (ii) small, new firms played an important role in the commercialization of new technologies, especially in IT;[10] and (iii) defense-related R&D funding and procurement exercised a pervasive influence in the high-technology sectors of the US economy.

[9]"After 1950, however, the federal government rapidly increased its support of academic science, and corporate funding quickly declined in relative importance." (Bok, 1982, 139).

[10]Chandler and Hikino (1997) argue that established firms dominated the commercialization of new technologies in most sectors of the postwar US economy, with the significant exception of "...electronic data-processing technologies, based on the transistor and integrated circuit..." (p. 33).

During the late 1930s, US antitrust policy shifted from its relatively laissez-faire stance of the 1910s and 1920s to a much tougher posture that extended well into the 1970s (Hawley, 1966; Fligstein, 1990). Federal antitrust cases filed during the 1930s and 1940s against such firms as Du Pont, Alcoa, and AT&T, many of which were decided or resolved through consent decrees in the 1940s and early 1950s, transformed the postwar industrial research strategies of large US firms. This revised antitrust policy made it more difficult for large US firms to acquire firms in "related" technologies or industries, and increased their reliance on intrafirm sources for new technologies. In the case of Du Pont, the use of the central laboratory and Development Department to seek technologies from external sources was ruled out by senior management as a result of perceived antitrust restrictions on acquisitions in related industries. As a result, internal discovery (rather than development) of new products became paramount (Hounshell and Smith, 1988 emphasize the firm's postwar expansion in R&D and its search for "new nylons"[11]), in contrast to the firm's R&D strategy before World War II.

This shift in R&D strategy weakened the links between Du Pont's growing central research facilities, which concentrated their efforts on basic research, and its operating divisions.[12] 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, 1988: 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 global scientific community.

In other US firms, senior managers sought to maintain growth through the acquisition of firms in unrelated lines of business, creating conglomerate firms with few if any technological links among products or processes. Chandler (1990) and others (e.g. Ravenscraft and Scherer, 1987; Fligstein, 1990) argue that diversification weakened senior management understanding of and commitment to the development of the technologies that historically had been essential to the competitive

[11]Hounshell and Smith (1988) and Mueller (1962) both 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, which bore more than a passing resemblance to "open innovation". 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 of the fact that many senior Du Pont executives had direct experience with the nylon project. Hounshell (1992) argues that Du Pont had far less success in employing the "lessons of nylon" to manage such costly postwar synthetic fiber innovations as Delrin.

[12]Chandler (2001) argues that a similar weakening of links between central corporate R&D and operating divisions characterized the postwar R&D organization of RCA.

success, eroding the quality and consistency of decision-making on technology-related issues.[13]

The prominence of small firms in commercializing new electronics technologies in the postwar US contrasts with their more modest role in this sector during the inter-war period. In industries that effectively did not exist before 1940, such as computers, semiconductors, and biotechnology, new firms played important roles in the commercialization of innovations. These postwar US industries differ from their counterparts in Japan and most Western European economies, where established electronics and pharmaceuticals firms retained dominant roles in the commercialization of these technologies.

Several factors contributed to the importance of new firms in the postwar US innovation system. The large basic research establishments in universities, government, and a number of private firms served as "incubators" for the development of innovations that "walked out the door" with individuals who established firms to commercialize them. Although Klepper (2008) argues convincingly that a similar pattern of entrepreneurial exit and establishment within the same region of new firms also was characteristic of the US automobile industry in the early 20th century, the evolution of the postwar US biotechnology, microelectronics and computer industries was heavily affected by such "spinoffs". Indeed, high levels of labor mobility within regional agglomerations of high-technology firms served as an important channel for technology diffusion and as a magnet for other firms in related industries. Such labor mobility also aided in the transfer of knowledge and knowhow within many of these nascent high-technology industries.[14] The commercialization of these developments often relied on the extension to much

[13]Graham's discussion (1986) of the failure of RCA to commercialize its videodisk technology in the face of the firm's extensive diversification into such unrelated industries as automobile rental agencies and frozen food is an illustrative analysis of the failures of technology management that accompanied the conglomerate–diversification strategies of many US firms in the 1960s and 1970s.

[14]Discussing the development of laser technology, Bromberg (1991) highlights the importance of linkages among research funders and performers within the United States during the 1950s and 1960s that in turn were based on researcher mobility: "Academic scientists were linked to industrial scientists through the consultancies that university professors held in large and small firms, through the industrial sponsorship of university fellowships, and through the placement of university graduates and postdoctoral fellows in industry. They were linked by joint projects, of which a major example here is the Townes–Schawlow paper of (sic) optical masers, and through sabbaticals that academics took in industry and industrial scientists took in universities. Academic scientists were linked with the Department of Defense R&D groups, and with other government agencies through tours of duty in research organizations such as the Institute for Defense Analyses, through work at DoD-funded laboratories such as the Columbia Radiation Laboratory or the MIT Research laboratory for Electronics, and through government study groups and consultancies. They were also linked by the fact that so much of their research was supported by the Department of Defense and NASA." (Bromberg, 1991, 224).

smaller firms of the equity-based system of industrial finance that distinguishes the US economy from those of Germany and Japan.

4. Industrial R&D after 1985: "Open innovation" redux?

Beginning in the late 1970s, industrial R&D in the United States entered a period of structural change. Large corporations reduced or eliminated their central R&D laboratories, increasing their reliance on external sources of R&D and knowledge, such as universities, interfirm alliances, licensing transactions, and acquisitions of other firms. At the same time, the new firms that had been important sources of commercial innovations maintained and if anything expanded their importance as innovators, particularly in the IT and biotechnology sectors. Entry by new firms also benefited from and accelerated the evolution of "vertical specialization" in industries such as computers, pharmaceuticals, and semiconductors, in which specialist firms performed activities (e.g. drug discovery; semiconductor component design; computer software development; and marketing) that formerly were included within the boundaries of larger corporations. As new firms and new industries grew, the boundaries between the manufacturing and nonmanufacturing sectors became less distinct, and much of the growth in industry-funded R&D investment in the 1990s and early 21st century occurred in the nonmanufacturing sector. By the early 21st century, the landscape of US industrial R&D had been transformed from its structure of 30 years earlier. At the same time, however, many of the "new elements" of this 21st century structure resembled characteristics of the US industrial R&D structure of the early 20th century.

My discussion of structure change in US industry R&D after 1985, like the discussion of most of the 1945–1985 period, relies heavily on indicators of R&D investment collected and published by the US National Science Foundation. These data provide an imperfect picture of the economy-wide innovation process throughout the 1945–2005 period, but these imperfections may have increased significantly since 1985. As I discuss below, coverage of smaller firms by the National Science Foundation surveys of industrial R&D has always been problematic, and these coverage problems became more severe after 1985. Increased R&D investment by nonmanufacturing firms, as well as the conceptual and other difficulties involved in classifying diversified firms into one or the other category, also have created coverage and sampling problems for the NSF surveys and complicate the interpretation of longer-run trends in these data.

Change in the nature of the innovation process itself also means that the R&D statistics may fail to capture more and more of the central activities in this process. For example, many fast-growing firms in the US IT sector during the late 1990s relied on mergers and acquisitions to acquire technical expertise in new areas quickly. These mergers were motivated by a strategy of improving in-house innovative capabilities, but the investments by the acquiring firm do not appear in any R&D statistics. In other cases, the "outsourcing" of knowledge–intensive activities that formerly were included in large firms' reported R&D spending (e.g. management of clinical trials by independent firms for large pharmaceuticals firms) may no longer be reported by these large firms as part of their R&D spending. The licensing payments that large pharmaceuticals firms disburse to biotechnology "research boutiques" as part of the large firms' "open innovation" strategies also may not be reported as R&D expenditures consistently by all respondent firms in the National Science Foundation surveys. The very restructuring of the innovation process that is the focus of this section, therefore, complicates the measurement of structural change. And the source of these difficulties is more deeply rooted than "mere" problems of survey design or sampling.

4.1 The changing roles of large and small firms in financing R&D, 1984–2001

The changing roles of large and smaller firms in industrial R&D during the period of restructuring are revealed in Figure 4, which depicts trends in the share of industry-funded R&D investment performed by different segments of the firm size

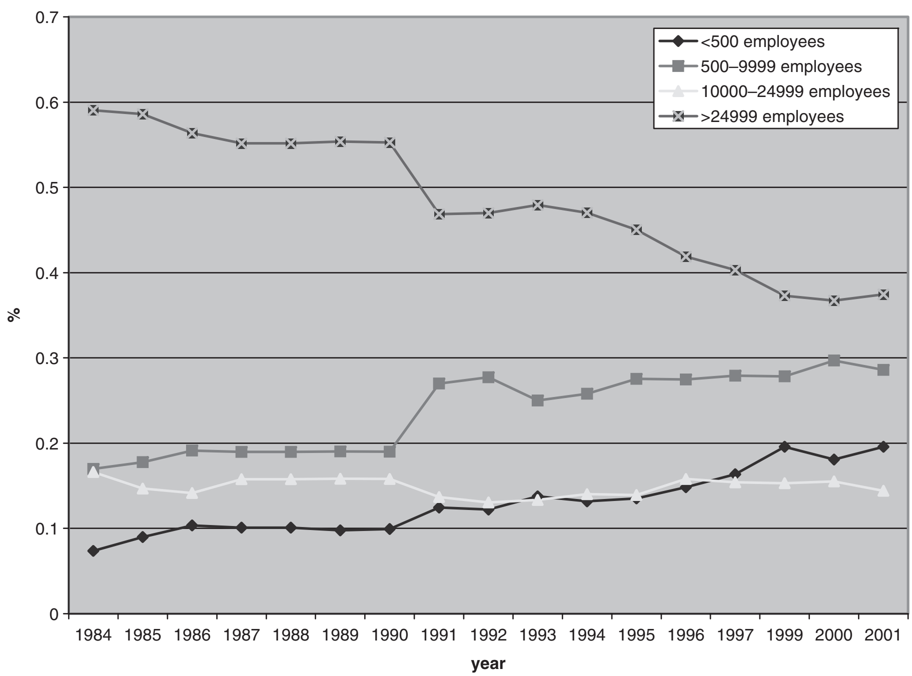

Figure 4 Firm-size class shares of industry-performed R&D (nonfederally funded), 1984–2001.

distribution in the United States during 1984–2001.[15] The share of industry-funded R&D investment performed by firms with 25,000 or more employees dropped from nearly 60% in 1984 to less than 40% by 2001. Firms employing 10,000–24,999 employees also witnessed a more modest decline in their performance share of industry-funded R&D, from almost 17% to slightly more than 14%. Smaller firms (500–9,999 employees), however, increased their share of R&D performance from 17% to almost 29%, and the smallest employee size class, firms with fewer than 500 employees, increased their performance share from 7% in 1984 to almost 20% by 2001. One of the few studies of the private returns to R&D investment during the 1980s, Hall (1993), found that the sharpest declines in the private rate of return on R&D investment occurred in the electronics and electrical equipment industries (both prominently represented in the aggregate data in Figure 4), particularly among large firms. It is at least plausible that some of the shifts in R&D investment depicted in Figure 4 may reflect such change in the relative rates of return to R&D investment in large and smaller firms. The trends depicted in Figure 4 also are consistent with a shift by large firms to "outsourcing" a larger share of their self-financed R&D through contracts with other, smaller firms.

These changes in the R&D performance shares of different firm size classes are associated with modest shifts in the structure of industry-funded R&D investment (as measured, imperfectly, by the National Science Foundation). The share of "basic" research within industry-funded R&D was essentially unchanged, "growing" from 49.5% in 1984 to 50.1% in 2001, and the share of "basic and applied" research investment also changed very little, declining from 27.5% in 1984 to 26.9% in 2001 (Figures 5 and 6). Although both Figures 5 and 6 suggest that the share of "long-term" R&D within industry-financed R&D investment has indeed fallen from its levels of the 1950s and early 1960s, the most significant declines in the share of "long-term" research within industry-funded R&D investment appears to predate the widely remarked cutbacks in central corporate research laboratories that occurred during the late 1970s and 1980s. Indeed, the bulk of the declines in the share of long-term research occurred during the second-half of the 1960s and early 1970s.

[15]The US National Science Foundation was forced to alter its survey sampling procedures in 1990 because of serious problems of coverage and representativeness. The changes in survey construction and sampling produced increases of as much as $14 billion (nearly 20%) in estimates of industry R&D investment funded by nonfederal sources, including industry, by 1991 (National Science Foundation, 1995b). Much (but not all) of the increase in estimated R&D resulted from improved coverage by the NSF surveys of non-manufacuring industry. The pre- and post-1991 data in Figures 4–7 thus are not strictly comparable, and caution should be exercised in drawing conclusions about trends covering the entirety of the time period covered in each Figure.

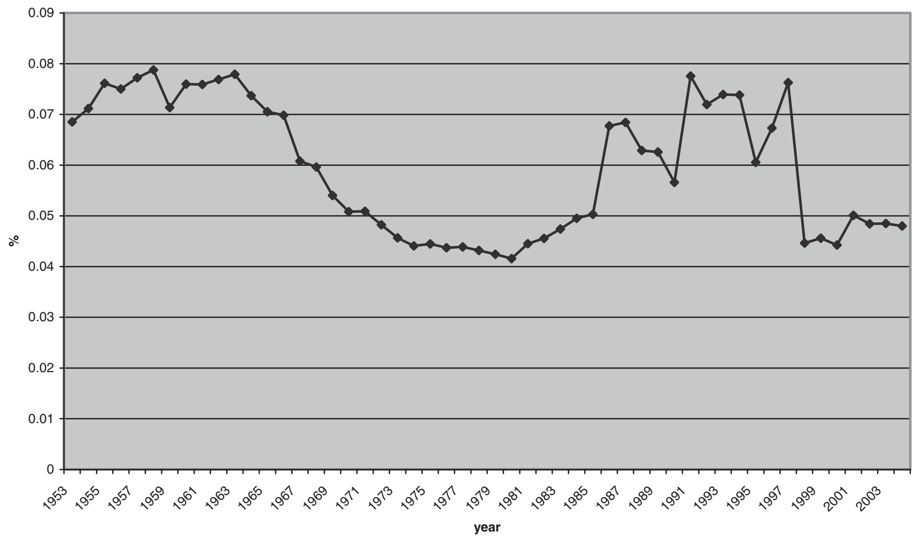

Figure 5 Industry-funded basic percentage of total industry-funded R&D, 1953–2003.

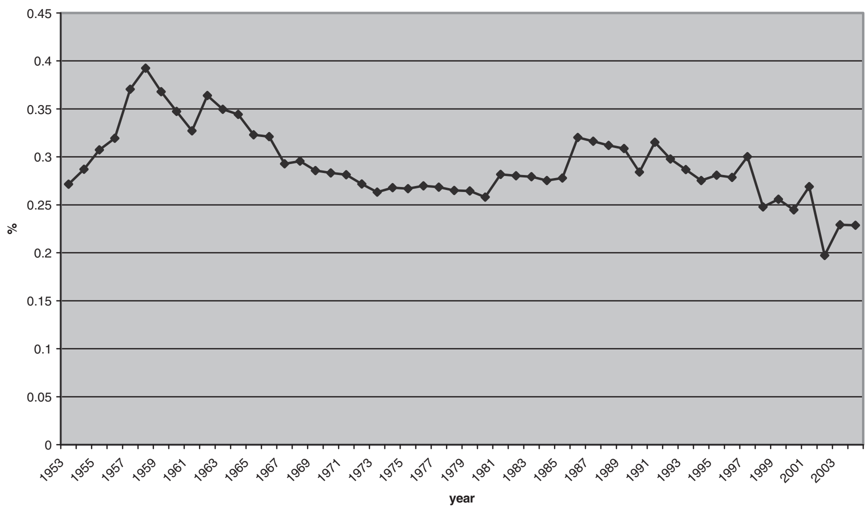

Figure 6 Industry-funded "basic + applied" share of total industry-funded R&D, 1953–2003.

4.2 Manufacturing and nonmanufacturing R&D investment, 1990–2003

Another manifestation of structural change in US industrial R&D is displayed in Figure 7, which depicts trends in industry-funded R&D (in constant dollars) for "manufacturing" and "nonmanufacturing" firms during 1990–2003. As in the previous figures, comparison of pre- and post-1992 data is hazardous, because of changes instituted by the National Science Foundation in sampling procedures

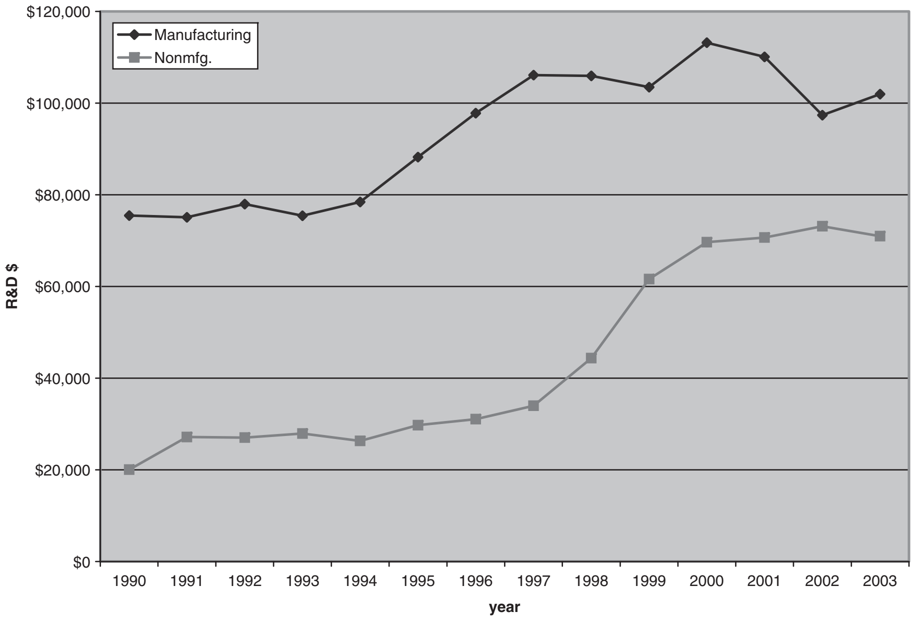

Figure 7 Industry-funded R&D investment, manufacturing and nonmanufacturing, 1990–2003 (2000$$).

that expanded the NSF R&D survey's coverage of nonmanufacturing industries. Nevertheless, the figure indicates that R&D investment by nonmanufacturing firms increased more rapidly than in manufacturing firms thoughout the 1990–2003 period and that growth in nonmanufacturing firms' R&D investment accelerated during the last half of the 1990s. Nonmanufacturing R&D investment grew from roughly 25% of manufacturing R&D investment in 1990 to nearly 70% by 2003. Unfortunately, these time trends also reflect the reclassification of a few large US firms from the "manufacturing" to the "nonmanufacturing" categories during the period.[16] Nonetheless, a substantial portion of the narrowing gap between manufacturing and nonmanufacturing R&D investment is not spurious but real,

[16]The National Science Foundation noted in 1995 that "It is difficult to determine precisely how much of this expansion resulted from changes in the R&D activity of firms that have remained within the nonmanufacturing sector and how much resulted from movement of firms formerly classified as manufacturers into the nonmanufacturing classifications. By comparing sales (not shown here) and R&D figures from the 1993 survey with those from the 1992 survey, it appears that an undetermined number of firms shifted out of the industry classifications for machinery, which include manufacturers of office, computing, and accounting machines, and into services. Consistent with this shift, reported R&D for machine manufacturing firms dropped from $15 billion for 1992 to $8 billion for 1993." (National Science Foundation, 1995a, 1–2). Among the firms that shifted from the "manufacturing" to "nonmanufacturing" categories at roughly this time was IBM.

and reflects the blurring of the distinction between these two sectors in the US economy, particularly the growth of "knowledge-intensive business services" in fields such as IT and financial services.

4.3 Vertical specialization and "open innovation" in IT and biotechnology

The changing roles of large and smaller firms in the US R&D system during the 1980s and 1990s also reflected increased vertical specialization in a number of knowledge-intensive industries. The development of vertically specialized industry structures in IT and biotechnology, for example, was associated with the entry by numerous smaller firms into these industries that specialized in narrower segments of these industries' "value chain". In IT, the growth of vertical specialization can be traced to at least the 1960s, although this form of structural change and associated displacement of incumbent firms appears to have accelerated after 1985. By contrast, vertical specialization was a hallmark of the industrial exploitation of biotechnology from the inception of this technology, although the displacement of incumbent (pharmaceutical) firms by entrants thus far is less apparent. But in these and other industries, vertical specialization involved a greater reliance on market relationships for the governance of the innovation process, as well as an increased role for firms specializing in the "upstream" phases of the innovation process. Both of these characteristics of the emergent industry structures once again echo elements of the late 19th-century world described by Lamoreaux and Sokoloff (2005), underscoring the extent to which "open innovation" itself may not be an entirely novel phenomenon.

4.3.1 Vertical specialization in IT

For the first two decades of the computer and semiconductor industries, large integrated producers such as AT&T and IBM designed their own solid-state components, manufactured the majority of the capital equipment used in the production process and utilized internally produced components in the manufacture of electronic computer systems that were leased or sold to their customers (Braun and MacDonald, 1978). During the late 1950s, "merchant" manufacturers entered the US semiconductor industry and gained market share at the expense of firms that produced both electronic systems and semiconductor components. Specialized producers of semiconductor manufacturing equipment began to appear by the early 1960s, and hundreds of so-called "fabless" semiconductor firms that design and market semiconductor components have entered the global semiconductor industry since 1980. These firms rely on contract manufacturers (so-called "foundries") for the production of their designs (Macher *et al.*, 1999, 2006). Contract manufacturers include "pure-play foundries" that specialize in semiconductor manufacturing, as well as the foundry subsidiaries of established integrated device manufacturers seeking to fully utilize excess fabrication capacity. Almost all of these "pure-play" foundries are based in Taiwan and elsewhere in East Asia. Fabless semiconductor firms serve a variety of fast-growing industries, especially computers and communications, by offering more innovative designs and shorter delivery times than integrated semiconductor firms.

Commercialization of microelectronics and computer hardware and software innovations by new firms was aided by a domestic intellectual property regime that facilitated technology diffusion and reduced the burden on young firms of litigation over inventions that originated in part within established firms. In microelectronics and computers, liberal licensing and cross-licensing policies were byproducts of antitrust litigation, illustrating the tight links between these strands of US government policy. The 1956 consent decrees that settled federal antitrust suits against IBM and AT&T both mandated liberal licensing of these technologies, lowering barriers to entry by new firms into the embryonic computer and semiconductor industries. (Flamm, 1988).

The entry and growth of new, specialized IT firms benefited from yet another postwar federal policy, military procurement. Military procurement policies contributed to the growth of a number of new firms in microelectronics and contributed to high levels of technology spillovers among these firms. Partly because of the greater size of the US defense budget, US procurement programs involved competition for R&D contracts and for purchases—Western European defense programs more frequently awarded contracts on a noncompetitive basis to "national champions".[17] New computer and semiconductor firms competed successfully in a number of US defense-related R&D and procurement programs, and the availability of defense contracts was a powerful magnet for the entry of new firms into both US industries. The commercial consequences of military procurement policies were heightened further by the technological spillovers that flowed from military to civilian products during the early development of computers and semiconductors.

Entry by new firms into emerging segments of the IT sector, such as computer software and new segments of the computer hardware industry, displaced many established firms. The leading producers of semiconductor components in the late 1950s bore little resemblance to a list of the leading producers in 1975, and by the end of the 1980s, nearly all of the firms that dominated the hardware industry in the 1950s, with the exception of IBM, had been displaced. Moreover, the entry

[17]Bromberg's history of the early years of laser technology development in the United States argues that in the early 1960s, "Small electronics businesses enjoyed a special advantage (in procurement competitions) at this time. The Kennedy administration believed in using government procurement practices, as well as fiscal policy, to reinvigorate the economy and was committed to giving small businesses a bigger piece of the defense pie. This reinforced the tendencies already resulting from the fact that the Department of Defense was procuring small lots of sophisticated electronic equipment". (Bromberg, 1991, 114).

of new firms in many segments of IT was associated with growing "vertical specialization" in this sector.

A similar process of vertical specialization fostered the growth of independent software vendors in the United States during the 1980s. Aided by the settlement of a federal antitrust suit against IBM in the late 1960s that separated pricing for computer hardware and software, as well as the emergence of a huge market for software complements to the desktop computer in the 1980s, software "specialist" firms such as Microsoft grew rapidly during the 1980s. These firms focused on producing software for mass markets, in contrast to the custom software and computer services that had made up the majority of the business activities of the software firms of the 1970s.

These tendencies toward vertical specialization seem to have been strongest in the United States. Major Japanese computer manufacturers, such as Hitachi, NEC, and Fujitsu, all produce electronic components and software, and large Western European electronics firms, such as Philips and Siemens, have until recently been more highly vertically integrated than their US competitors. During the late 1990s and since 2000, however, considerable restructuring within these large European and Japanese electronics firms has resulted in the creation of vertically specialized "spinoff" firms that specialize in production of semiconductor components, such as Infineon and NXP in Europe.

Increased vertical specialization, of course, means that the process of technological innovation in IT relies more heavily on market-mediated transactions in intellectual property, as well as other complex contracting relationships. Such transactions in turn benefit from relatively stable interfaces among the components (both hardware and software) of the complex systems that are developed. For this reason, among others, vertical specialization in IT hardware (including semiconductor components) is less significant in the most advanced segments of such industries as semiconductors. Nonetheless, the restructured IT industry value chain bears more than a passing resemblance to the late 19th-century environment described by Lamoreaux and Sokoloff (2005), although the fabless design specialist firms also are responsible for marketing their products. The specialist individual inventor has to some extent been replaced by a specialist firm.

4.3.2 Vertical specialization in biotechnology and pharmaceuticals

The postwar period also witnessed a remarkable expansion of federal support for biomedical research through growth in the budget of the National Institutes of Health. Between 1950 and 1965, the NIH budget for biomedical research grew by no less than 18% per year in real terms. By 1965, the federal government accounted for almost two-thirds of all spending on biomedical research. Although NIH funding grew rapidly through 2004, it has been outstripped by privately funded R&D since the 1960s. The US Pharmaceutical Manufacturers Association estimated that foreign and US pharmaceuticals firms invested more than $26 billion in R&D in the United

States in 2002, substantially above the $16 billion R&D investment by the National Institutes of Health in the same year (See Pharmaceutical Manufacturers Association, 2003, for both estimates).

The rapid growth of federal expenditures for university-based biomedical research, combined with slower growth in defense-related funding for academic research during the 1970s, transformed US universities. By 2000, fully two-third of federally supported university research in the United States came from a single agency, the National Institutes of Health. Beginning in the 1970s, NIH-supported university research produced a series of major scientific advances that formed the foundation for the biotechnology industry. The prominent role of US universities in this research had several important effects. A number of new biotechnology firms were founded to exploit these scientific advances. Similarly to the situation in IT, many of these firms specialized in drug discovery or early-stage development, forming alliances and licensing agreements with established pharmaceutical firms (Galambos and Sturchio, 1999; Henderson *et al.*, 1999). These new firms, as well as a large number of established pharmaceutical firms, sought to license the results of academic research in biotechnology, and the prospect of significant licensing revenues led US universities to lobby Congress for a new set of policies governing such licensing, culminating in the Bayh-Dole Act of 1980 (see below and Mowery *et al.*, 2004 for further discussion).

The entry by new, vertical specialist biotechnology firms that were largely financed by the equity investments of venture capital firms resembled the earlier development of many segments of the IT sector. Just as was true of IT, the biotechnology industry now relies extensively on contractual and market relationships in the innovation process.[18] And to an even greater extent than is true of semiconductors, vertical specialization in biotechnology and pharmaceuticals involves considerable corporate specialization in invention. In contrast to IT, however, new firms in biotechnology by and large have not displaced dominant pharmaceutical firms.

The reasons for these different patterns of displacement are complex, but are related to the important role of regulation in pharmaceuticals. The expertise of established firms in managing the costly processes of drug development and clinical trials appears to have formed an important entry barrier for new firms seeking to enter into the commercial production of biotechnology-based pharmaceuticals. Nevertheless, a few biotechnology firms, such as Chiron and Genentech, have entered the commercial production of pharmaceuticals. In addition, specialist firms now are playing more important roles in managing clinical trials, potentially weakening another element of these entry barriers. Overall, however, the displacement effects

[18]Pisano (2006) argues that the growth of vertical specialization within the biotechnology industry has in fact produced rather disappointing innovative and financial results, because of the unusual characteristics of the underlying knowledge and technologies in this field, as well as the failure of arms'-length contracting in a "market for ideas" to transfer less well-codified knowhow effectively.

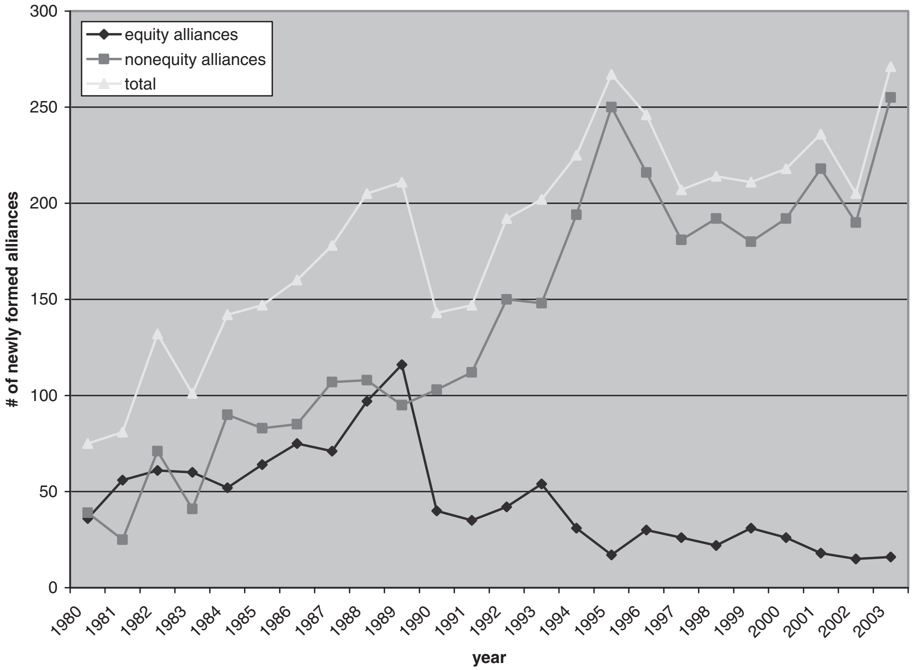

Figure 8 Alliances between US and non-US firms, 1980–2003.

of the entry by new firms in biotechnology thus far have been far less significant than in IT.

4.4 Interfirm R&D and technology development alliances

Partly because of the entry of vertically specialized firms discussed above, domestic and international collaboration among firms in R&D and related activities, i.e. "alliances," has grown since 1980. Data from the MERIT-CATI database depicting rates of formation during 1980–2003 of new alliances involving R&D and product development for all alliances between US and non-US firms (Figure 8) and for alliances among US firms only (Figure 9)[19]. These data track only announcements of the formation of alliances, and lack any information on rates of dissolution of these alliances, which are high.[20] These data also do not report the size (measured in terms

[19]The MERIT/CATI database excludes alliances and consortia that are publicly funded (Hagedoorn, 2002). Since a substantial portion of the NCRA filings depicted in Figure 9 involve consortia for which ATP and other federal programs have contributed some funds, it is likely that some but by no means all of these NCRA alliances are included in the Figure 13 data.

[20]The survey of research alliances between biotechnology and pharmaceutical firms administered by Reuer and Zollo (2005) found a dissolution rate of more than 36% over an unspecified period; Park and Russo (1996) found that nearly 94 of the 204 joint ventures in their dataset, more than

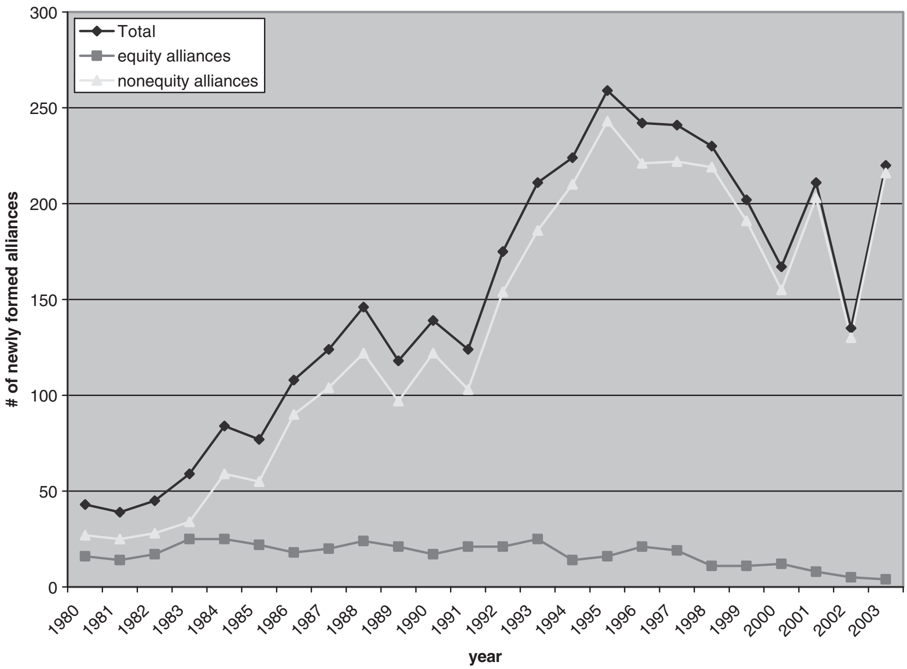

Figure 9 Alliances among US firms, 1980–2003.

of assets, sales, or other indicators) of these alliances, preventing any evaluation of change over time in the scale or economic significance of alliance activity. Nevertheless, the MERIT-CATI database, which is based on announcements in various business and trade publications, is widely accepted as the most comprehensive tabulation of global alliance activity since 1980.

More than 250 alliances were formed between US and non-US firms in 2003, more than three times the number of alliances (75) announced in 1980. The growth trend for domestic alliances involving US firms is similar to that for international alliances, growing from 53 alliances announced in 1980 to more than 200 in 2003. In contrast to international alliances, however, formation rates for those involving only US firms have declined since their peak of more than 250 new alliances announced in 1995.

In his survey of trends in alliance formation since 1960, Hagedoorn (2002) notes that the most R&D-intensive industries in the MERIT/CATI database, IT, pharmaceuticals, and aerospace, dominated growth in alliances during 1960–1998. The data in Figure 10, which displays trends in the number of new domestic or

46%, had been terminated within five years of formation; and Kogut (1989) found that 32 of the 92 joint ventures in his sample, nearly 35%, had been terminated within 5 years of formation.

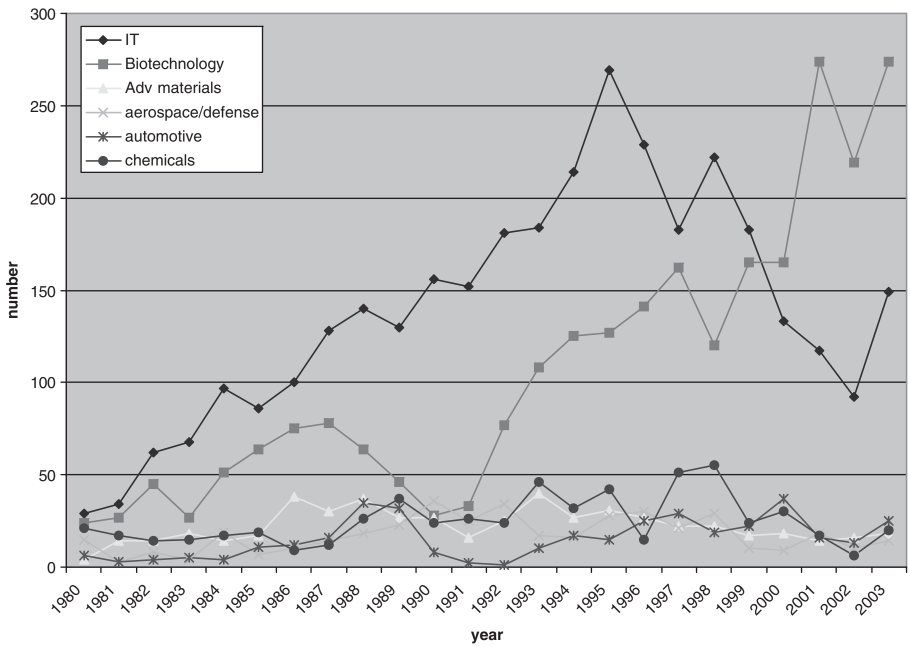

Figure 10 Alliances involving US firms, 1980–2003, by industry.

international alliances formed each year that involve US firms (thus combining the data from Figures 8 and 9), show that IT and biotechnology dominated alliance formation during 1980–2003.

An interesting feature of the data in Figures 8 and 9 is the growth in the share of alliances based on contracts. The reasons for this trend have not been explored in detail by scholars, many of whom have emphasized the importance of alliance governance forms in which shared equity aligns the incentives of alliance participants and reduces opportunistic behavior. Although equity-based alliances incorporate strong defenses against opportunism, they often are more complex and more difficult to adjust to changing market environments than contract-based alliances. Stronger intellectual property rights may facilitate greater reliance by alliance participants on contractual rather than equity-based governance, since some forms of opportunistic behavior can be discouraged by legal enforcement of IP rights. As Hagedoorn (2002) points out in his survey of trends in alliance formation, firms in knowledge-intensive industries disproportionately rely on contractual rather than equity-based forms of alliances, and the divergence between "medium" or "low-tech" and "high-tech" industries' reliance on contractual as opposed to equity-based alliances has grown during the 1980–2000 period. This apparent shift in governance forms within the expanding population of interfirm alliances may be yet another manifestation of the revival of contract-based forms of collaboration (perhaps aided by stronger patentholder rights and markets in intellectual property) that is a hallmark of the "open innovation" framework.

4.5 Globalization

Another widely remarked characteristic of the post-1985 evolution of R&D is internationalization, or "globalization," in the innovation process. Expanded cross-border flows of goods, technology, and capital have been associated with the internationalization of innovation-related activities. In some cases, internationalization has involved the growth of innovation-related activities in regions, such as South and Southeast Asia, which have become significant exporters of technologically advanced products or sites for R&D investment since 1980. Other examples of such internationalization include the growth in cross-border R&D investment by multinational firms, expanded formation of international alliances among firms from different nations, and "outsourcing" of some types of technology development (e.g. software development) by firms in one nation (e.g. the United States) to firms elsewhere (e.g. India). In other cases, such as the reliance by US "fabless" semiconductor firms on foreign "foundry" firms for production, contractual relationships involve a great deal of cross-border knowledge and technology exchange. Advances in information and communications technologies, hallmarks of the "Third Industrial Revolution," have played a critical role in facilitating these cross-border flows of information and data.

Like many other "new phenomena" in the evolution of industrial R&D, however, "globalization" is not unprecedented. Cross-border technology transfer and related activities, like other forms of "globalization," flourished in the late 19th and early 20th centuries, before the political and economic convulsions of war, depression, and fascism. Even during the 1930s, as Cantwell and Barrera (1998) and other scholars have shown, large US and European multinationals operated extensive international networks for technology acquisition, licensing, and R&D investment. Many of these firms invested heavily in the development of international R&D networks during the early postwar period as part of their overall international foreign investment and production strategies, highlighted in the "product cycle" work by Vernon (1966) and others.

Moreover, the extent and characteristics of post-1985 "globalization" of R&D may be overstated. In particular, the inventive activities of global firms appear to be much less "globalized" that conventional wisdom or R&D statistics suggest. The "homebound" nature of their inventive activities in turn reflects the dependence of these activities on "local" (domestic) sources of scientific and technological knowledge. Different indicators yield different conclusions on the extent and nature of globalization of R&D.

Both inward and outward foreign R&D investment have grown since the mid-1980s within US industry-funded R&D investment. Inward foreign investment

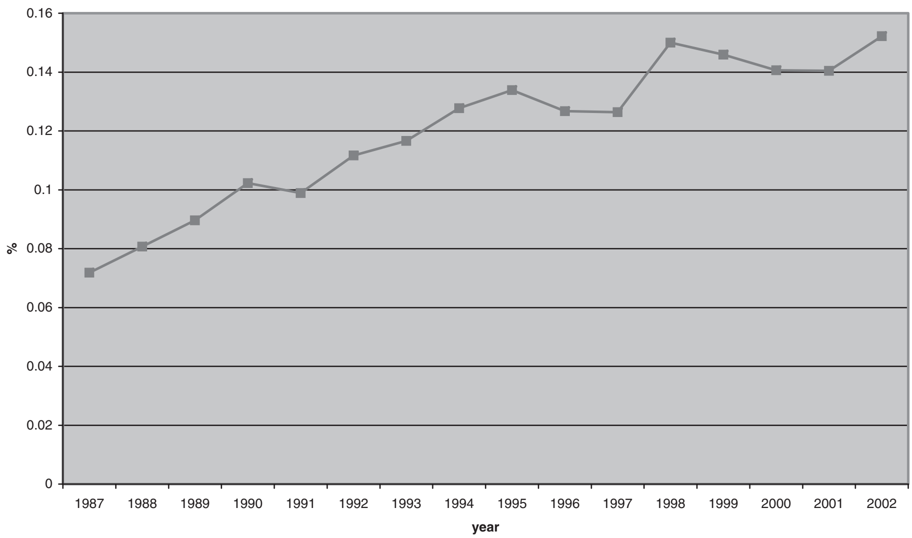

Figure 11 Share of US industry-financed R&D from foreign firms, 1987–2002.

in US R&D, measured as the share of foreign-financed R&D within total US industry-financed R&D has increased from roughly 7% in 1987 to more than 15% in 2003 (Figure 11). Similar growth in the "offshore" share of US industry-funded R&D investment is apparent in Figure 12, which depicts growth in the share of foreign-performed R&D within overall US industry-funded R&D from 6.3% in 1985 to 15.4% in 2003. Interestingly, however, much of the increase in offshore R&D investment is attributable to rapid growth in the share of nonmanufacturing R&D performed offshore during the period. The share of manufacturing R&D performed offshore grew from slightly more than 6% in 1985 to 9.3% in 2003. But the share of offshore R&D within industry-funded nonmanufacturing R&D increased from essentially nothing in 1985 to more than 6% by 2003.

Since much of the apparent growth in nonmanufacturing R&D reflects reclassification and better coverage of the sector by the NSF R&D surveys that began in the early 1990s, the comparison of trends in offshore R&D for the manufacturing and nonmanufacturing sectors is more meaningful for the 1992–2003 period. The share of offshore R&D investment remains essentially flat for manufacturing during this period, actually declining slightly, while that for nonmanufacturing grows from slightly less than 1% in 1995 to 6% by 2003. These two figures suggest little change in offshore R&D investment within US manufacturing, considerable growth in offshore R&D investment from US nonmanufacturing firms, and significant growth in R&D investment by foreign firms in the United States.

The share of offshore R&D investment within industry-funded R&D spending also varies a great deal across US industries, as the data in Figure 13, covering 1981–2003, suggest. Although this measure of globalization of their R&D fluctuates

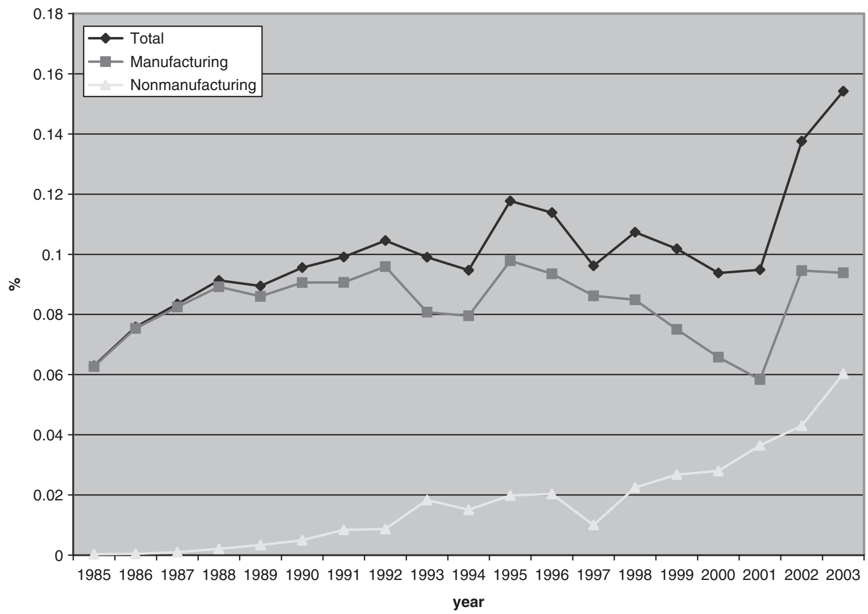

Figure 12 US industry-funded offshore R&D percentage of total US industry-funded R&D, 1985–2003.

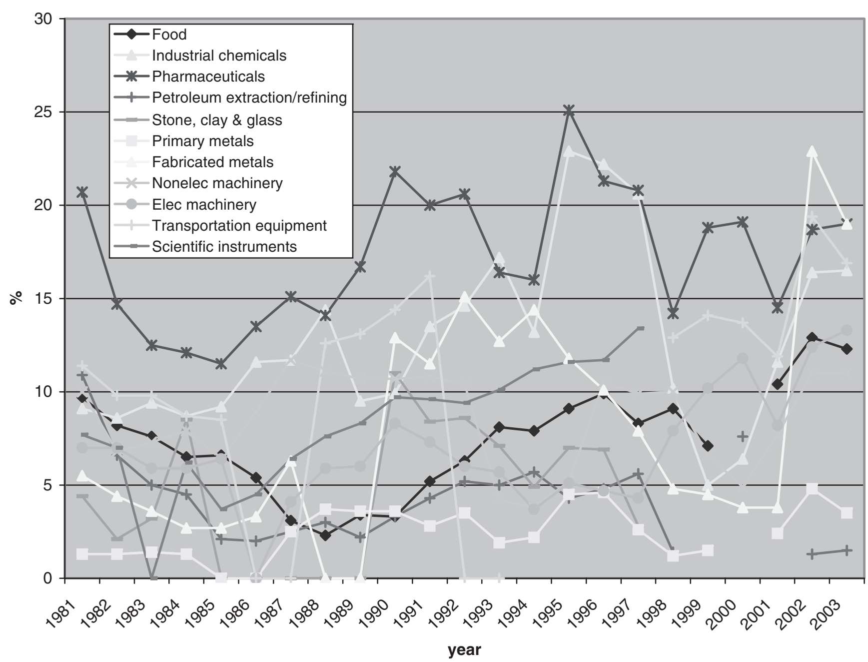

Figure 13 Share of industry-financed R&D invested offshore, by industry, 1981–2003.

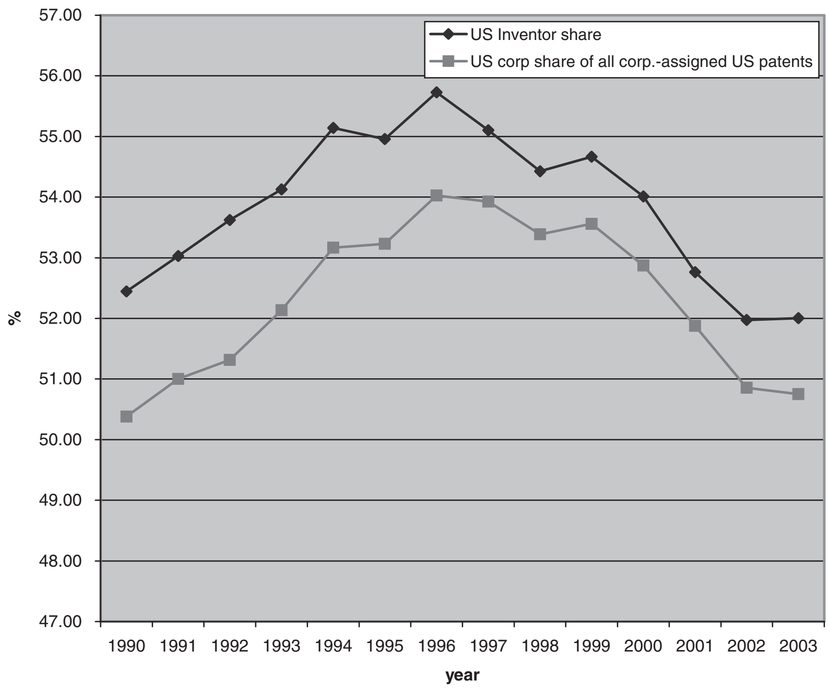

Figure 14 US inventor and US corp share of US patents, 1990–2003.

considerably during the period, chemicals and pharmaceuticals invest most heavily throughout the period in offshore R&D, while petroleum and primary metals are the least "globalized" in their industry-funded R&D. Few if any of the industry-specific timeseries display significant upward or downward trends during the more than 20 years covered by these data. Keeping in mind that the data in Figure 13 exclude nonmanufacturing industries, which display significant growth in offshore R&D spending during this period, the trends depicted in the figure once again do not support a characterization of rapid globalization overall after 1980 for industrial R&D in manufacturing. Instead, one observes fairly consistent inter-industry differences in the extent of offshore R&D investment and surprisingly little upward trend within these industry-specific data.

Other indicators of the "globalization" of the innovative activities of US and non-US firms in the US R&D system can be developed from patent data. Patents are most appropriately conceptualized as an input to the innovation process, rather than an output. Moreover, the economic and technological value of patents varies widely, and any distribution of patents by value is highly skewed. Nevertheless, US patents list both the inventor(s) and their location(s), as well as the characteristics (individual, nonprofit organization, industrial firm) and nationality of the assignee. Figure 14 depicts the share of US patents during 1990–2003 for which the first inventor listed on the patent is a US resident, a rough indicator of the location of the inventive activity that resulted in the patent, regardless of whether the patent is owned by a US or non-US entity. The figure also displays the share of US patents assigned to US corporations within all corporate patents issued during 1990–2003. Both time series display remarkably similar trends, which is to say that the share of US inventors and US corporations within US patenting in 2003 is almost identical to their shares in 1990, following similar increases and declines during the 1990s. Once again, there is little compelling evidence of significant expansion in the presence of foreign invention sites or foreign patent assignees within industrial patenting in the United States during the 1990s.

Yet another patent-based analysis of R&D "globalization" examines the share of firm patents that are accounted for by patents for which the site of the invention lies outside of the "home country" of the patenting firm. One of the first scholars to utilize this measure of "globalization," Patel (1995), found that "home-based" inventive activity accounted for more than 85% of the patenting of large multinational firms based in the United States, Italy, Japan, France, and Germany. A similar analysis of more recent patent data from a single industry, semiconductors (Macher *et al.*, 2006) reached similar conclusions for the 1992–2004 period—more than 90% of US semiconductor firms' patents were based on inventive activity in the United States, and the US patents held by firms from Western Europe, Japan, and Taiwan were similarly dominated by "home country" inventive activity.

One reason for the apparently "homebound" nature of industrial patenting is the prominent role of home-country "public" R&D in such patenting. The analysis by Narin *et al.* (1997) of "nonpatent" references (generally, references to relevant scientific and technical papers or publications) in patent applications resulting in issued patents found that a substantial majority of the papers cited in such patents were produced by "public" research institutions (government, university, or nonprofit laboratories) rather than by industrial R&D. Moreover, the number of scientific papers cited per patent had grown during the 1985–1995 decade, suggesting that the "science-intensity" of patenting had increased during this period. Even more interesting for the study of "globalization" in R&D was the finding that inventors in a given industrial economy tended disproportionately to cite "domestic" scientific papers, i.e. those authored by residents of the same nation.

4.6 Public policy and the post-1985 restructuring of industrial R&D

US public policy, which exercised considerable influence on the early evolution of industrial R&D, retained its importance in the restructuring of industrial R&D after 1985. Particularly in the antitrust and IP policy areas, federal policy shifted considerably from its previous postwar stance. In a number of respects, post-1985 initiatives moved policy closer to the posture of the 1920s and 1930s, with significant effects on industrial R&D that are still manifesting themselves. Many of the policy shifts of the 1980s and 1990s responded to the environment of slower growth in US productivity and incomes, coupled with stronger foreign competition in manufacturing, that characterized the period. These factors also influenced the efforts of US firms to restructure their internal R&D operations, and affected their political activities in support of or opposition to the policy shifts described below.

4.6.1 Federal R&D spending, 1985–2005

Two of the most significant trends of the post-1985 period represented a response to positive political news, the end of the Cold War, in a period during which much of the economic news was dismal. As Figure 1 shows, following its buildup during the early years of the Reagan Administration, the defense-related share of federal R&D spending peaked in 1987 at nearly 70% (still considerably lower than its post-1949 peak of 84% in 1959), and began a decline that reached a low point of 54% in 1999, followed by an increase in response to the 11 September 2001 tragedy that increased the defense share to 58% by 2005. Because of the enormous size of the federal defense R&D budget, declines in federal defense-related R&D spending were reflected in a simultaneous decline in the share of national R&D investment accounted for by federal funds from 46% in 1987 to a low point of 25% in 1999 (Figure 2).

Since federal defense-related R&D spending was particularly important in a number of fields of engineering and the physical sciences, accounting for as much as 35% of federally funded research in fields such as computer science, the declining share of defense-related R&D within the overall federal R&D budget contributed to a shift in the disciplinary composition of federal R&D spending away from the physical sciences in favor of biomedical fields of research. Figure 15 reveals the rapid growth in federal biomedical R&D spending during the post-1985 period, a growth trend that accelerated during the 1990s. As I noted earlier, the rapid growth in the NIH budget shifted the sources of support for academic research; by 2006, at most US universities with academic medical centers, the NIH had become the largest single source of funding for research.

The post-2001 growth in defense-related spending has been concentrated in the "development" portion of the defense R&D budget, which is likely to limit the types of knowledge spillovers that played a role in the US IT industry in the early postwar period. Interestingly, increased R&D spending on "homeland security" remains dominated by biomedical R&D, and therefore has done little to increase the share of physical sciences and engineering in the federal R&D budget (Mowery, 2005).

4.6.2 Antitrust policy

The Reagan and Bush Administrations reduced antitrust restrictions on collaboration in research and improved enforcement of intellectual property protection. Justice Department guidelines and review procedures for mergers were relaxed somewhat, and major federal antitrust suits against high-technology firms were

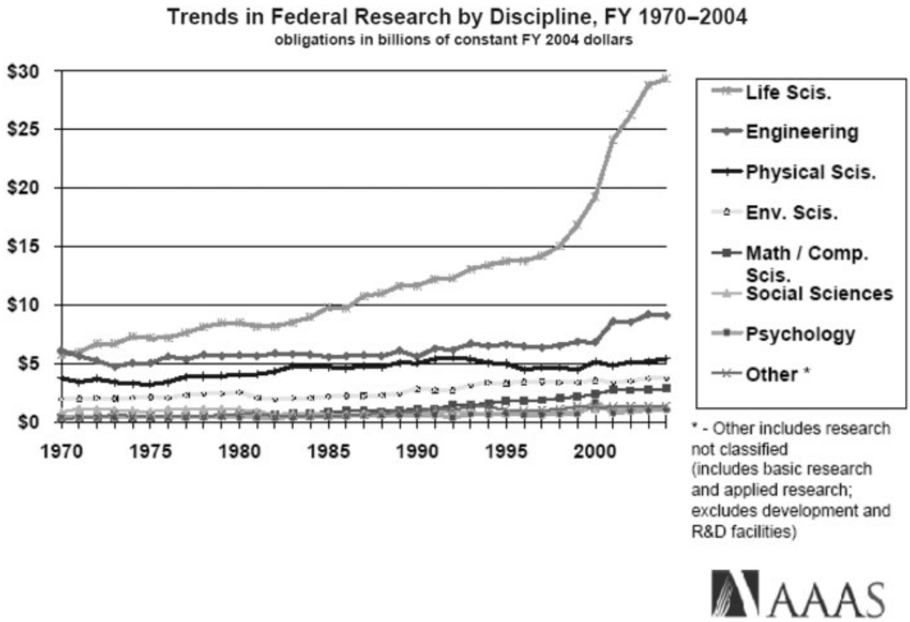

Figure 15 Trends in Federal Research by discipline, FY 1970–2004. Obligations in billions of constant FY 2004 dollars.

Source: National Science Foundation, Federal Funds for Research and Development FY 2002, 2003, and 2004. FY 2003 and 2004 data are preliminary. Constant-dollar conversions based on OMB's GDP deflators. OCTOBER '04 © 2004 AAAS.

dropped or settled in the early 1980s. Following a brief revival of aggressive enforcement under the Clinton Administration, exemplified by the filing of the federal antitrust case against Microsoft, the Bush Administration once again relaxed antitrust enforcement, and shifted away from a "structural" remedy in the Microsoft case.

The Reagan Administration also supported the 1984 National Cooperative Research Act, which reduced the antitrust penalties for collaboration among firms in precommercial research. The NCRA has been credited with facilitating the early growth and operation of the Microelectronics and Computer Technology Corporation, a research consortium involving US computer and electronics firms. In 1993, the NCRA was extended to cover joint production ventures.

In spite of the considerable support for these cooperative R&D statutes from US industry, the number of collaborative R&D and/or production ventures registered by US firms under the NCRA declined substantially through the 1990s and early 21st century (Figure 16). This decline in NCRA filings occurred against a backdrop of increased R&D collaboration among US firms and between US and non-US firms, discussed above (Figures 8–10). The lack of filing activity under the NCRA may reflect a perception by US firms of reduced risks from private

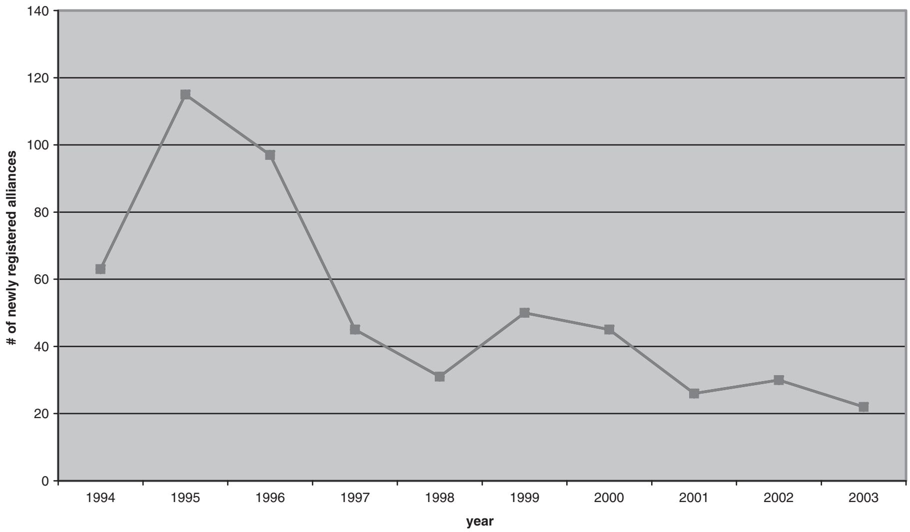

Figure 16 NCRA alliances registered by US firms, 1994–2003.

antitrust suits against collaborative ventures, but the reduction in NCRA filings has received surprisingly little attention and remains poorly understood.

4.6.3 The "pro-patent era" and its consequences, 1985–2005

Intellectual property rights policy was an important influence on the development of industrial R&D in the United States, as I noted earlier. Judicial tolerance for restrictive licensing schemes during the early 20th century encouraged the use by firms of industrial R&D and patenting as means of building up or retaining market power. The marked shift in US antitrust policy that began in the late 1930s was accompanied by increased hostility toward patent-based market power, and for much of the 1945–1980 period, federal judicial and antitrust enforcement philosophies were relatively hostile to patentholder rights. All of this changed significantly during the 1980s, inaugurating what has come to be called the "pro-patent era" in US IP policy.

One of the most important foundations for the "pro-patent era" was the 1982 legislation that established the Court of Appeals for the Federal Circuit, which strengthened the protection granted to patentholders. As the court of appeal for patent cases throughout the federal judiciary, the CAFC soon emerged as a strong champion of patentholder rights. According to Katz and Ordover (1990), the CAFC upheld patent rights in roughly 80% of the cases argued before it, a considerable increase from the pre-1982 rate of 30% for the Federal bench. But even before the establishment of the CAFC, the 1980 U.S. Supreme Court decision in *Diamond v. Chakrabarty* upheld the validity of a broad patent in the new industry of biotechnology, facilitating the patenting and licensing of inventions in this sector.

Other important judicial decisions in private patent litigation resulted in damages awards of unprecedented scale (the Kodak-Polaroid case, which resulted in a damages award of one billion dollars and forced Kodak to close its instant camera line of business in 1986) and extended the scope of patentable intellectual property to include "business methods" (the *State Street* case). The US government also pursued stronger international protection for intellectual property rights in the Uruguay Round trade negotiations and in other bilateral venues.

The consequences of the "pro-patent era" for US economic performance have been the subject of a wide-ranging and inconclusive debate since the early 1990s. One consequence on which there is little debate is the surge in patenting during 1980–2005. Between 1967 and 1984, US patent applications grew by roughly 0.3% per year; after 1984, the rate of growth increased to nearly 7% per annum (Hall, 2004). The sharp increase is attributable largely to filings from individual, corporate, and institutional inventors residing in the United States, and it is concentrated mainly in computing and electronics (Hall, 2004). Other scholars have suggested that this surge in patent applications, particularly those involving relatively new fields of inventive activity such as computer software, has taxed the review capabilities of the U.S. Patent Office, leading to an increase in low-quality patents (Merges, 1999).

The effects of stronger patentholder rights on industrial R&D and innovative behavior are less clear. On the one hand, the "pro-patent" environment should strengthen markets for intellectual property, leading to an increase in licensing transactions and facilitating the financing and entry of new firms that have a small number of (reputedly) valuable patents. In addition to supporting the entry of new firms, such a market for intellectual property may support the development of vertical specialization within industries such as biotechnology and pharmaceuticals or semiconductors, since firms are able to specialize in certain activities and license the results to other firms. Indeed, a market for intellectual property is a precondition for many of the strategies and transactions described by Chesbrough (2003) in his discussion of "open innovation".[21] It seems likely that some portion of the increased vertical specialization that has been observed in industries such as semiconductors or biotechnology is attributable to the strengthening of patentholder rights since 1980.

[21]The links between vertical specialization and the strengthening of patentholder rights are difficult to substantiate empirically. Although the development of vertical specialization in semiconductor design and fabrication during the 1980s followed the legislative and judicial changes of the early 1980s, and the industry itself experienced an upsurge in patenting (Hall and Ziedonis, 2001), the evidence for vertical specialization in the computer hardware and software industries is much weaker. Entry and growth by independent software vendors largely preceded the rise in patenting within the US software industry (Graham and Mowery, 2005). Pisano (2006) also argues that the IP environment in biotechnology remains filled with uncertainties that have impeded the effectiveness of vertical specialization in biotechnology in both innovation and financial performance.

Considerable evidence supports the argument that markets for intellectual property have grown rapidly since the early 1980s. Arora *et al.* (2001) estimate that the value of licensing transactions in US manufacturing and nonmanufacturing industries more than doubled (in constant-dollar terms) between 1990 and 1994, increasing from $24.2 billion in 1990 to more than $50 billion in 1994 (the estimated volume of licensing transactions subsequently declined to less than $22 billion by 1997). Hall's analysis (2004) of the "patent explosion" of the 1980s and 1990s concluded that the market value of patents held by entrant firms in industries such as electronics and computing increased significantly during the 1980s, reflecting the higher valuation assigned to entrant-firm patent firms by the capital markets.

On the other hand, the high costs, time-consuming nature, and risks of litigation mean that established firms with "deep pockets" and substantial portfolios of patents may be able to challenge would-be entrants or competitors, limiting entry and competition. Lerner's study (1995) of patenting by incumbent and entrant firms in the biotechnology industry indicates that entrants avoid patenting in areas of inventive activity in which incumbent firms are heavily represented, consistent with the argument that patenting by incumbents can deter entry. Still another possibility is the accumulation of large portfolios of low-value patents by established firms that seek to use these patents in cross-licensing bargains to insulate themselves against the effects of patent litigation or infringement judgments.

Work by Hall and Ziedonis (2001) and Hall (2004) provides some support for the argument that a portion of the increased patenting since 1980 in the United States reflects such strategic motives. In semiconductors, where patents are widely reported to be of limited value for appropriating the returns to innovation, Hall and Ziedonis (2001) show that firms with particularly high levels of capital investment in production facilities were especially likely to increase their rate of patenting relative to R&D investment during the 1980s, partly as a means of accumulating large portfolios of patents to use in cross-licensing negotiations to resolve patent disputes without the risk of a court injunction that would shut down these costly production facilities. Hall (2004) similarly finds that the increased patenting of larger firms in the electronics and computer industries does not affect the market value of these firms, consistent with a "strategic patenting" argument.

The expansion in patentable subject matter, which has extended "upstream" to cover the results of fundamental research and various inputs to the scientific research process, may create impediments to scientific research by increasing the complexity and transaction costs associated with licensing and otherwise obtaining research tools and materials. The expansion of patentable subject matter to include life forms that resulted from the Supreme Court's *Diamond v. Chakrabarty* decision also contributed (along with other policy initiatives, such as the Bayh–Dole Act, that are discussed below) to increased patenting by US universities, another development whose consequences for national innovative performance and welfare are uncertain.

The faith in intellectual property rights as a critical policy tool in improving US competitiveness was exemplified the Bayh-Dole Patent and Trademark Amendments Act of 1980 (sponsored by a leading Democratic and Republican senator), which permitted federal agencies to grant licenses to small businesses and nonprofit institutions, including universities, for patents based on research funded by federal agencies at federal and contractor-operated laboratories. The Federal Technology Transfer Act of 1986 and amendments passed in 1989 authorized federal laboratories to conduct cooperative research and development agreements (CRADAs)[22] with private firms. Because the Bayh-Dole Act has attracted considerable attention as both a significant shift in US policy and a great success, I discuss it in greater detail in the next section.

5. The Bayh-Dole Act and growth in university patenting and licensing, 1980–2005

The Bayh-Dole Act of 1980 sought to strengthen US innovative and competitive performance by simplifying federal policy toward intellectual property resulting from federally funded R&D in US universities and government laboratories. According to the Act's supporters, too many important inventions from federally funded research in US universities and federal laboratories were not commercialized because of the difficulties would-be commercializers faced in gaining clear rights to the intellectual property. Strengthening and clarifying the intellectual property rights associated with these inventions, the argument claimed, would facilitate commercialization of these inventions.

Although the Bayh-Dole Act is frequently portrayed as a transformative policy initiative that (among other things) contributed to improved US innovative and economic performance during the 1990s (see the *Economist, 2002*), the Act's origins and effects must be placed in a broader context. The Act was in part a response to increased patenting and licensing of intellectual property by US universities, rather than an exogenous cause. In addition, the Act's effects on university patenting and technology transfer are easily exaggerated, inasmuch as its passage coincided with a number of other developments, including the *Diamond v. Chakrabarty* Supreme Court decision, the overall strengthening of patentholder rights discussed earlier, and the breakthroughs in fundamental research in fields such as molecular biology that created scientific advances with great commercial potential. Rather than inaugurating a "new era" in US university–industry relationships, then,

[22]A CRADA specifies terms under which a private organization provides personnel, equipment, or financing for R&D activities that are consistent with a specific laboratory's broader mission. Most CRADAs include provisions that cover the sharing of intellectual property rights to any technologies resulting from the project.

the Bayh-Dole Act may be more accurately portrayed as one of a series of developments in the 1980s that deepened and extended a long-established collaborative relationship between US academic and industrial research.

The number of US universities establishing technology transfer offices and/or hiring technology transfer officers began to grow in the late 1960s, well before the passage of the Bayh-Dole Act of 1980. The institutional ambivalence that prevented many universities from direct involvement in management of patenting for much of the post-1945 period subsided after 1970, for reasons that are not well understood, and a number of universities entered into direct management of patenting and licensing. Private universities in particular expanded their patenting and licensing during this decade—their share of university-assigned patents grew from 14% in 1960 to 45% in 1980. US universities' share of overall US patenting more than doubled during the decade (albeit from a very low level, increasing from 0.2% to 0.5% of US patents), and biomedical technologies' share of US university patents also more than doubled, increasing from 17% in 1970 to 30% in 1980. The increased share of biomedical disciplines within overall federal academic R&D funding, the dramatic advances in biomedical science that occurred during the 1960s and 1970s, and the strong industrial interest in the results of this biomedical research, all affected the growth of biomedical patenting by US universities during the 1970s.

Although universities had been allowed to patent and license the results of federally funded research under the terms of "Institutional Patent Agreements" (IPAs) well before the Bayh-Dole Act, these Agreements had to be negotiated between individual federal funding agencies and universities. Moreover, federal agencies retained considerable powers of oversight concerning the terms of licenses, and in some cases, federal agencies' concerns over the prices of pharmaceuticals contributed to some reluctance on the part of the NIH to approve exclusive licensing agreements between universities and pharmaceutical firms.

US research universities active in patenting and licensing, as well as other institutions seeking to enter into this activity, grew dissatisfied with the complexity of the IPA system and sought a reduction in the power of federal agencies to influence the terms of licensing agreements. Legislation was introduced in 1979 by Senators Birch Bayh (D-IN) and Robert Dole (R-KS) to address their concerns. A number of universities, including Harvard University, Stanford University, the University of California,[23] and the Massachusetts Institute of Technology, lobbied for passage of the bill. Witnesses from universities active in patenting (including

[23]As Kevles (1994) points out, the University of California also filed an *amicus curiae* brief in the *Diamond v. Chakrabarty* case, in which the US Supreme Court ruled that patents on life forms were valid. Had the Chakrabarty patent not been upheld as valid, the Reimers patenting and licensing strategy for the Cohen–Boyer invention would have been utterly useless. Indeed, much of the post-1980 growth in university licensing rests on an array of other policy initiatives and judicial decisions

Stanford, Purdue, and Wisconsin) testified in support of the bill, as did representatives from various university associations (including the American Council on Education, the Society for University Patent Administrators, and the National Association of College and University Business Officers) and the Research Corporation. The prominent role of research universities already active in patenting in supporting passage of the Act highlights the extent to which the Bayh-Dole Act was a response to increased university patenting during the 1970s, rather than an exogenous "cause" of the post-1980 growth in patenting and licensing.

The Bayh-Dole Patent and Trademark Amendments Act of 1980 provided blanket permission for performers of federally funded research to file for patents on the results of such research and to grant licenses for these patents, including exclusive licenses, to other parties. The Act facilitated university patenting and licensing in at least three ways. First, it replaced the web of Institutional Patent Agreements (IPAs) that had been negotiated between individual universities and federal agencies with a uniform policy. Second, the Act's provisions expressed Congressional support for the negotiation of exclusive licenses between universities and industrial firms for the results of federally funded research. Third, the Act weakened the authority of federal research funding agencies to oversee the terms of licenses covering patents resulting from federally funded research. The Act granted "march-in" rights to federal funding agencies to be exercised in the event that a licensee fails to act in good faith to develop a patented invention, as well as the power to deny a license to a given firm, but federal funding agencies have invoked only the latter provision in one case since the Act's passage.

Figure 17 depicts US research university patenting as a share of domestically assigned US patents during 1963–1999, in order to remove the effects of increased patenting in the United States by foreign firms and inventors during the late 20th century. Universities increased their share of patenting from less than 0.3% in 1963 to nearly 4% by 1999, but this share began to grow before 1980. Increased university patenting reflected growth in patenting by institutions with considerable pre-1980 experience in patenting and licensing, as well as entry into this activity by universities with little experience.[24] As Figure 18 shows, by 1992 universities that had received 10

during the 1980s that strengthened patentholder rights overall and in such new areas as computer software and biotechnology (see below and Mowery *et al.*, 2004 for further discussion).

[24]The Bayh–Dole Act did not dramatically affect the patenting and licensing activities of universities that had long been active in this area, such as Stanford University and the University of California. Indeed, the biomedical patents and licenses that dominated these institutions' licensing revenues during the 1980s and 1990s had begun to grow before the passage of the Bayh–Dole Act. Columbia University, an institution with little experience in patenting and licensing before 1980 (and an institution that prohibited the patenting of inventions by medical faculty until 1975), also had filed for its first "blockbuster" patent before the effective date of the Act. Nevertheless, the Act did increase patenting of faculty inventions at both Stanford and the University of California, although

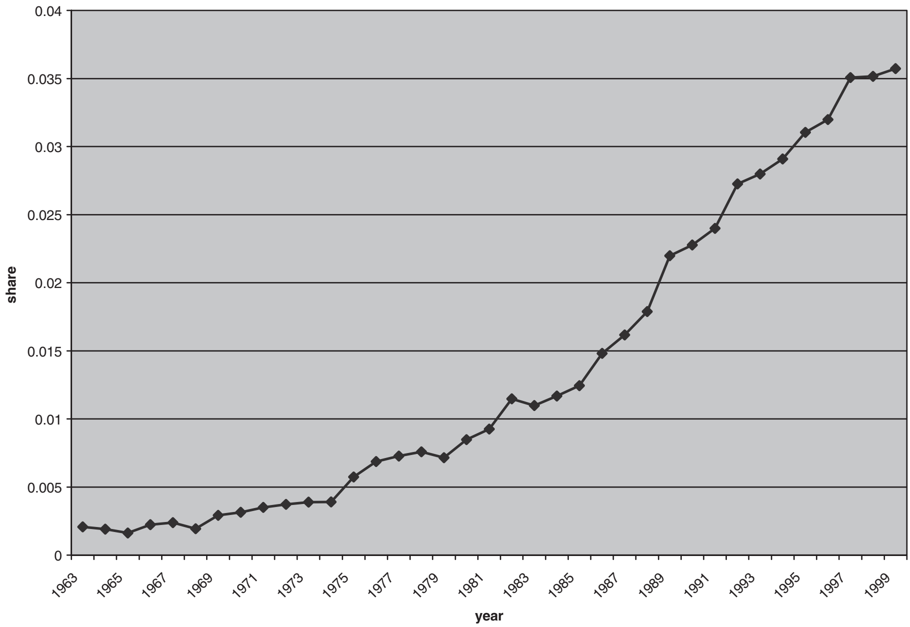

Figure 17 US research university patents percentage of all domestic-assignee US patents, 1963–1999.

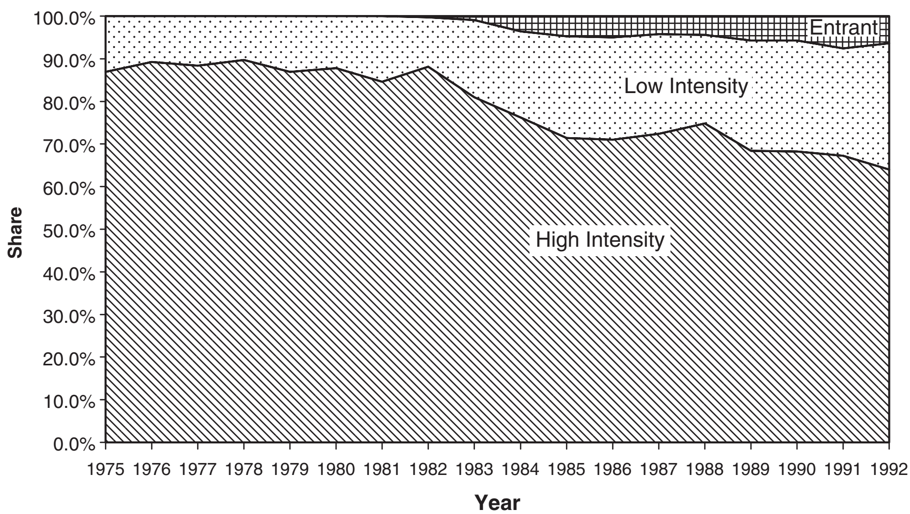

Figure 18 Shares of all US Universtity patents by "High intensity", "Low intensity", and "Entrant" University patenters, 1975–1992.

or more patents during the 1970s accounted for 64% of total patenting, down from their share of nearly 85% in 1975. Universities with little or no experience in patenting had increased their share from slightly more than 13% in 1975 to 36% in 1992.

By 2002, according to the Association of University Technology Managers (2003), gross licensing revenues for all US universities exceeded $1.2 billion. Licensing data from the University of California 9-campus system, Stanford University, and Columbia University, all of which have ranked among the institutions reaping the highest gross licensing income, show that biomedical patents accounted for more than 66–85% of the gross licensing revenues of these academic institutions for much of the 1980s and 1990s (Mowery *et al.*, 2004). Even for these relatively successful academic licensors, however, licensing revenues (especially net licensing revenues that flow to the institution) represent a remarkably small share of overall academic operating budgets. To cite only one example, the annual net licensing revenues of the University of California system after deduction of operating expenses and payments to inventors averaged roughly $16 million during fiscal 2001–2004, less than 0.5% of the system's annual research expenditures of nearly $3 billion and well below the $235 million in industry-sponsored research at the University of California in fiscal 2003. Inasmuch as the UC system reports relatively high gross licensing revenues (averaging nearly $76 million annually during FY2001—2004), it seems likely that the financial contributions to most university operating budgets from patent licensing are modest at best, and negative for a great many institutions. Moreover, these financial inflows appear to be dwarfed by those associated with industry sponsorship of academic research.

Although this growth in university patenting and licensing has raised concerns over the potential effects of "increasing commercialism" on the research mission of US universities, US university researchers have for decades collaborated with industrial researchers. Moreover, university patenting and licensing is heavily concentrated in a few fields, mainly in the biomedical sciences. In addition, little evidence that faculty who are active in patenting their inventions reduce their publishing productivity—indeed, the most prolific patenters tend to be the most productive sources of published research (Agrawal and Henderson, 2002).

Nevertheless, some evidence suggests that patenting and related IP policies may affect the direction of faculty research. Both Murray and Stern (2007) and Sampat (2005) show that citations to publications that cover research advances that are patented tend to decline after the issue of the patent. Other evidence, however (Walsh *et al.*, 2005) indicates that faculty do not search for patents in prospective research areas, and that the real IP-related obstacles to research are associated with

many of these patents covered inventions of marginal industrial value and did not yield significant licensing royalties.

difficulties in gaining access to research materials under the terms of Materials Transfer Agreements (MTAs). Still other research (Fabrizio, 2005) suggests that the speed with which US firms cite university patents has declined, pointing to still other potential impediments associated with patenting under the post-1980 regime. Although the evidence thus does not suggest an imminent crisis, there is reason for concern over the effects of patenting and licensing of academic research results on the diffusion and exploitation of these results within the broader economy.

In nonbiomedical fields of research characterized by a long history of close collaboration between US university and industry researchers, the recent emphasis by universities on patenting and licensing of research results appears to have created friction in university–industry research relationships. Dr R. Stanley Williams of Hewlett Packard, a firm with a long history of close research collaboration with US universities, stated in testimony before the US Senate Commerce Committee's Subcommittee on Science, Technology and Space that

> Largely as a result of the lack of federal funding for research, American Universities have become extremely aggressive in their attempts to raise funding from large corporations. ... Large US based corporations have become so disheartened and disgusted with the situation they are now working with foreign universities, especially the elite institutions in France, Russia and China, which are more than willing to offer extremely favorable intellectual property terms." (September 17, 2002; statement reproduced at http://www.memagazine.org/contents/current/webonly/webex319.html; accessed April 2, 2005).

These critical comments have triggered considerable discussion between large industrial firms (many of which are in the IT sector) and US research universities over intellectual property policies and licensing guidelines. In December 2005, four large IT firms (Cisco, Hewlett Packard, IBM, and Intel) and seven universities—Carnegie Mellon University; Renssellaer Polytechnic; UC Berkeley; Stanford University; University of Illinois at Champaign-Urbana; and University of Texas-Austin) agreed on a "statement of principles" for collaborative research on open-source software that emphasizes liberal dissemination of the results of collaborative work funded by industrial firms.[25]

[25]The "Open Collaboration Principles" cover "...just one type of formal collaboration that can be used when appropriate and will co-exist with other models, such as sponsored research, consortia and other types of university/industry collaborations, where the results are intended to be proprietary or publicly disseminated." According to the "Principles," "The intellectual property created in the collaboration (between industry and academic researchers) must be made available for commercial and academic use by every member of the public free of charge for use in open source software, software related industry standards, software interoperability and other publicly available programs as may be agreed to be the collaborating parties..." (http://www.kauffman.org/pdf/open_collaboration_principles_12_05.pdf; accessed February 20, 2006). These principles

In the nature of the case, most of the tensions that have received considerable press and some attention from policymakers involve relationships between established firms and universities—indeed, in some respects, the economic interests of established firms with large patent portfolios may differ from those of small startup firms that are owners or licensees of far fewer patents. Moreover, most of the major conflicts have involved firms outside of the biomedical sector, reflecting the fact that the value of individual patents in industries such as IT typically is lower than is true of biomedical research. Nevertheless, the current controversies and discussions among US industrial firms (some of which, as was noted earlier, contrast US university IPR policies unfavorably with those of universities outside of the United States) and US research universities may result in a rethinking by universities of the value of patents in efforts to sustain collaborative research relationships with US industry.

Industry criticism of the patent and licensing policies of some US universities notwithstanding, the Bayh-Dole Act has been the subject of extensive discussion by other OECD governments, several of which have developed similar policies that seek to encourage the patenting and licensing of university inventions. Many of these initiatives cite the Bayh-Dole Act as a policy model (See Mowery and Sampat, 2004, for further discussion). Since the new policies have been implemented only within the last five years in nations such as Japan or Denmark, it is too early to evaluate their effects; but in many cases, these policies overlook the long history of university–industry collaboration in the United States that predates the Bayh-Dole Act and is rooted in the unusual structure of the US higher education system. In addition, these policies tend to overlook the importance for US universities' technology transfer activities of institutions external to the university, such as venture capital finance and the relatively high mobility of scientific and engineering talent between US universities and industry. More than emulation of the Bayh-Dole Act is needed to encourage closer university–industry relationships in these other nations, but a broader restructuring of higher education is politically difficult. The exercises in emulation of Bayh-Dole underscore the limits to institutional convergence among the innovation systems of industrial economies that are closely interconnected through trade, investment, and other relationships.

6. Conclusion

Industrial R&D in the United States has undergone considerable change in structure since 1985. Data on R&D investment suggest that large firms now play a smaller role,

originated in an August 2005 "University and Industry Innovation Summit" in Washington DC organized by the Kauffman Foundation of Kansas City and IBM (http://www.kauffman.org/items.cfm?itemID=662; accessed February 20, 2006).

that nonmanufacturing firms are far more important sources of R&D investment, and that US firms are increasing their offshore R&D activities at a modest pace. We also observe some growth in "strategic alliances" among firms in R&D and related technology-development activities, and considerable growth in both patenting and licensing activity. New firms continue to play a more important role in the commercialization of innovations, especially in fields such as IT and biotechnology, than appears to be true elsewhere in the industrial economies or in the US economy before 1940. The growth of these new firms and the declining importance of large firms as R&D performers both are associated in complex ways with increased vertical specialization in these and other industries.

Whether and how this restructuring is an effect of a "Third Industrial Revolution", especially by comparison with other factors, is unclear. For example, much of the unusual structure of the "new industries" of IT and biotechnology in the postwar United States is the result of public policy in the lavish funding of federal R&D in defense-related and biomedical fields, the large-scale procurement of the products of this publicly funded R&D in IT, the cost-insensitive healthcare system that provided enormously profitable markets for biomedical innovators, and changes in federal policy in antitrust and intellectual property. The restructuring of industrial R&D that we observe since 1985 is a response to the same forces that supported the development and commercial exploitation of IT in the United States during the 1945–2005 period, rather than a response to the technological artifacts resulting from this commercial exploitation.

It is also interesting to consider the extent to which the "New Wave" of industrial R&D that is captured in the term "Open Innovation" is itself entirely novel. As I have argued throughout this essay, one can point to a number of aspects of US industrial R&D in the 1920s and 1930s, such as the use by large firms of their in-house R&D operations to monitor innovation outside of their boundaries and guide the acquisition of technologies from external sources, or the efforts by both industrial firms and US universities to form closer research collaborations, that anticipate much of what is associated with "Open Innovation".

I have devoted the vast bulk of this article to a discussion of trends before and after 1985 in the structure of US industrial R&D, making only brief references to developments elsewhere in the industrial economies and (as they once were known) newly industrialized economies. Do developments in the structure of industrial R&D in the United States prefigure developments elsewhere in the global economy, i.e. are we likely to observe strong tendencies toward "convergence" in the structure of the R&D systems of the United States and these other economies? Some such convergence does appear likely, not least through the efforts of other governments to emulate the policies (such as the Bayh-Dole Act) that are correctly or incorrectly believed to underpin developments in the United States. But the resistance of such central influences on industrial R&D and innovation as systems of corporate governance, labor markets, and national systems of higher education to the forces of "convergence" unleashed by global economic integration is noteworthy. These critical institutional components of "national innovation systems" remain national in the face of powerful forces of globalization and homogenization. Although some tendencies toward convergence thus are likely in the structure of the industrial systems of the United States and other high-income industrial economies, the countervailing forces remain strong. In a dynamic economic and technological environment, convergence is less likely than continued structural change.

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