Explaining Industrial Leadership

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I. Introduction

This paper summarizes the findings of a multi-author study of the development of seven industries in the United States, Japan, and Western Europe. The industries are machine tools, organic chemical products, pharmaceutical biotechnology, medical devices, computers, semiconductors, and software. Each industry study analyzes the similarities and differences in the development of these industries among the different countries and considers the factors that seem to explain the differences. We are especially interested in understanding the factors that led to industrial leadership in these industries.

The term “Industrial Leadership” denotes our focus on industries in which being ahead of one’s competitors in product or process technology, or in production and marketing, gives firms an advantage in world markets. But the term also is intended to convey our concern with the translation of technological expertise into commercial success, rather than solely with technological innovation.

Some economists use the term "comparative advantage" to refer to much the same thing as industrial leadership. We prefer our term in this context because it explicitly denotes performance in industries where technological sophistication and innovative performance are key factors. Scholars of business history and strategy often use the term "competitive advantage" for this purpose; but most studies of competitive advantage focus on factors internal to the firm. The term "industrial leadership" avoids this presumption. Indeed, we take no stand as to whether industrial leadership is determined by strengths that

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1 The study was published as The Sources of Industrial Leadership: Studies of Seven Industries (Cambridge University Press, 1999). This paper summarizes the introductory and concluding chapters of Mowery and Nelson, which in turn drew on chapters written by: Timothy Bresnahan and Franco Malerba (Computers), Roberto Mazzoleni (Machine Tools), Rebecca Henderson, Luigi Orsenigo, and Gary Pisano (Pharmaceuticals), Richard Langlois and Edward Steinmueller (Semiconductors), Annette Gelyin and Nathan Rosenberg (Medical Devices) and Ashish Arora, Ralph Landau, and Nathan Rosenberg (Chemical Products). In addition to the chapters and comments of these contributors, we are indebted to the participants in this project who did not contribute chapters: Giovanni Dosi, Luigi Orsenigo, Steven Klepper, Sidney Winter, Richard Rosenbloom, Keith Pavitt, Robert Merges, David Teece, and Ralph Landau. Support for this project was provided by the Center for Economic Policy Research at Stanford University; the Institute for Management, Innovation and Organization at the Haas School of Business, U.C. Berkeley; Columbia University; the Harvard Business School; the Alfred P. Sloan Foundation; the U.S. Air Force Office of Scientific Research; and the Andrew Mellon Foundation.
firms build for themselves, by their national environment, or by something in between (e.g., regional factors, institutions or other factors that are specific to an industry, etc.).

The choice of these seven industries was motivated by our wish to cover an array of diverse industries in which technological innovation has played an important role. Several of these industries, such as semiconductors and computers, trace their birth to the opening of a major new technology. Technological advance in some of these industries, particularly organic chemical products, semiconductors, and computers, has had a profound impact on the products and processes of a wide range of downstream industries. In turn, the technology employed in some of these industries, such as machine tools and computers, has been powerfully influenced by upstream innovation.

At one time or another in the history of virtually all of these industries, firms located in one or a small number of countries developed superior product or process technologies, ways of organizing production, or marketing strategies, that gave them significant advantages over firms based in other countries. The identity of leading firms sometimes changed, in several cases more than once, over the course of the histories of several of these industries. In some cases this shift in the locus of firm leadership involved a shift of leadership among different nations, but in others, shifts in firm leadership produced new leading firms of the same nationality as the old leaders. Each industry study attempts to identify the key factors that led to the emergence of national leadership, and the reasons behind the shifts that occurred.

The individual industry studies have much in common with some earlier work in which cross-national differences in technology, management, and competitive performance in a particular industry was the central focus (see e.g. Beer, 1959, on dyestuffs, or Malerba, 1985, on semiconductors). Such studies often have explored national differences in competitive performance. But most of these previous studies focus on an individual industry or a small number of industries, and thus do not illuminate significant differences in the sources of industrial leadership across industries and eras.

We believe that this study is unique in 1) considering the evolution of a number of
technology-intensive industries in different countries and attempting to explain the factors behind national differences; 2) exploring a number of different explanations of the sources of industrial leadership; and 3) considering the possibility that these explanations differ from industry to industry and from era to era.

II. **Summaries of the Industry Studies**

This section briefly summarizes the historical evolution and explanations for the characteristics and stability of industrial leadership in each of these seven industries. We defer a discussion of the implications of these historical accounts for the understanding of industrial leadership and public policy to subsequent sections of this paper.

In his historical analysis of shifts in the locus on industrial leadership in machine tools, Mazzoleni emphasizes the differences among the United States, Western Europe, and Japan in the character of domestic demand for machine tools. In the early 19th century British firms were leaders in the design and production of machine tools, reflecting Britain’s overall lead in manufacturing activity. By contrast, American manufacturing firms adopted mass production techniques in the late 19th and early 20th centuries, well before their widespread diffusion within Western Europe and Japan. The widespread use of mass production methods in the United States created a large domestic market for machine tools that was dominated by U.S. firms.

After World War II, the emergence of numerical control opened up new possibilities for machine tool design, and Mazzoleni’s study focuses on this era. The different profiles of domestic demand in the U.S. and Japanese markets led Japanese machine tool producers to develop low-cost CNC machine tools. This market segment turned out to be very large, and Japanese firms continue to dominate it. Japanese machine tool firms also benefitted from the establishment of a standard for electronic controllers by the Japanese firm FANUC, the dominant global designer and supplier of these components.

A different set of factors explains the shifting locus of industrial leadership in the
chemical products industry (Arora, Landau, and Rosenberg) from British dominance in the mid-19th century to the emergence of U.S. firms as global competitors in the 1940s and 1950s. German universities’ research strength, together with the ability of German firms to export their products, lay behind the rise to dominance by German firms of this “high-technology” manufacturing industry from the 1870s through the early 1920s. The farsighted strategies of German chemicals firms reinforced these institutional advantages, as these firms pioneered in the development of in-house R&D facilities to take advantage of the new scientific opportunities. During the 1920s, U.S. firms began to develop petrochemical-based products and processes, aided by the abundance of cheap domestic petroleum and rapid growth in the American market for organic chemical products.

The rise of U.S. chemical firms also relied on important contributions from U.S. universities to the development of these petroleum-based manufacturing technologies. Their development of petroleum-based processes for the production of organic chemical products enabled American firms to establish a strong position in global production and innovation after World War II, one that was shared with firms in Germany and Great Britain. The last two decades have seen the erosion of American leadership and the spread of the industry to many corners of the world. In some respects, the postwar evolution of this industry is consistent with the pattern outlined in the Vernon (1966)-Posner (1961) product cycle model of international competition and investment. As the technology became more routinized, it diffused more widely, and U.S. and European firms lost competitive advantage in “commodity” products to countries with lower labor costs.

German and Swiss producers of fine chemicals (notably, dyestuffs) were early entrants into the pharmaceuticals industry and largely dominated the industry until the 1930s. The dominant position of German and Swiss firms in early 20th-century pharmaceuticals rested on the same factors that underpinned German and Swiss competitive strength in dyestuffs--close links between corporate and university research, as well as an abundant supply of skilled scientists and production personnel. Following World War II, American pharmaceuticals firms, none of whom were based in the chemicals industry, and some
British firms (including the dominant British chemicals firm) joined the German and Swiss as leading innovators and exporters. The postwar rise to leadership of American pharmaceutical firms benefited from massive U.S. government investments during this period in biomedical research that enabled U.S. firms to exploit the new scientific basis for pharmaceuticals development that resulted from the revolutionary breakthroughs of the 1930s.

The study of this industry (Henderson, Orsenigo, and Pisano) focuses on the effects of new biotechnology-based techniques for drug discovery, development, and production on both incumbent and new pharmaceuticals firms. These new techniques challenged the drug development practices of established pharmaceuticals firms in the United States, Great Britain, Japan, and other Western European nations. The same factors that supported their entry into pharmaceuticals in the 1940s and 1950s also enabled U.S. firms to exploit advances in biotechnology for pharmaceutical applications. Close links between U.S. firms and university research became even more important during this period in supporting U.S. leadership in pharmaceutical biotechnology. The abundant domestic supply of venture capital for the formation of new biotechnology firms also contributed to rapid technological advance, although these entrants did not displace incumbent U.S. pharmaceutical firms. The unusual characteristics of domestic demand for pharmaceuticals also benefited U.S. firms, who faced a large, price-insensitive domestic market for drugs.

Our study of medical devices (Gelijns and Rosenberg) focuses mainly on the period after World War II, although the medical diagnostic devices industry traces its origins to the early 20th century. As was true of pharmaceuticals, the influence of regulatory controls, along with demanding requirements for national and global marketing and product support networks, enabled early entrants from the United States and Germany to maintain dominance, although other firms frequently were the first to design and market new products. The strength of their national university systems in physics and medical research also contributed to the leadership of German and U.S. medical device firms.

The post-1945 entry into endoscopy and imaging by Japanese optics and camera firms
drew on their close interaction with domestic users and their ability to apply their optical competences to this new area. During this period, American firms, European firms, and Japanese firms came to dominate different parts of the industry. Companies' reputations for producing high quality equipment, their mastery of complex marketing and regulatory environments, and their connections with the relevant user communities became more important during this period.

The computer industry (Bresnahan and Malerba), the semiconductor industry (Langlois and Steinmueller), and the software industry (Mowery), all were born after World War II, and American firms soon came to dominate all three industries. U.S. firms benefited from the procurement and R&D programs of the Department of Defense. Defense-funded university research and training proved especially important in expanding a domestic pool of skilled scientists and engineers for these industries in the United States. The large domestic market for commercial mainframe computers in the United States aided the growth of firms in both semiconductors and computer hardware. A large U.S. domestic market of demanding and innovative users, as well as strong antitrust policy, also contributed to the emergence of independent U.S. software firms. The sophisticated venture capital industry in the United States provided financing for new firms in the computer hardware industry and in semiconductors.

The dominant position of U.S. semiconductor firms in particular was challenged during the 1980s by Japanese firms in products such as memory chips (i.e., DRAMs), which were (inaccurately) characterized at the time as indispensable products for the advancement of semiconductor manufacturing technology. Since the late 1980s, however, Japanese firms have been challenged by Korean firms in these product areas, and U.S. firms have re-established their dominance of semiconductors through product innovation and have largely ceded such market segments as DRAMs to non-U.S. firms. Japanese and Taiwanese computer firms also have developed considerable strength in certain niches, such as laptop computers and computer components. Nevertheless, American firms continue to dominate much of the semiconductor industry, and retain a leading position in
most types of computers. And throughout the history of the computer software industry, American firms have dominated global markets in packaged software.

The rise of Japanese memory chip production and the subsequent growth of South Korean output of these components appear to be consistent with the Vernon-Posner product cycle theory. U.S. competitive advantage has declined in these “commodity” products and more recent entrants from South Korea have challenged Japanese dominance. In the personal computer industry, Taiwan and other Asian industrializing economies (e.g., Singapore) have entered the production of systems and critical peripherals (e.g., disk drives), a trend that also appears to be broadly consistent with the product cycle models.

III. Factor Endowments, Institutions, and Industrial Leadership

Economists have long sought to explain the locus of comparative advantage in terms of differential access to critical inputs. To what extent do our authors' explanation for industrial leadership emphasize differences in the domestic supply of critical inputs? What aspects of these differences in supply conditions were most influential?

Differences in the availability of natural resources seldom played an important role. The original location of the German chemicals industry along the Rhine was influenced by proximity to domestic coal deposits, but prior to 1914, German firms imported much of their feedstock coal from the United Kingdom. During the 1920s and 1930s, abundant deposits of petroleum encouraged American chemical and petroleum firms to develop manufacturing technologies and products that relied on petroleum as a feedstock. But these U.S. firms’ innovative efforts were motivated in large part by the large size of the American market, which increased the profitability of continuous-flow production technologies that relied on petroleum. In addition, the U.S. natural resource endowment was partly endogenous, since exploitation of the large domestic petroleum deposits relied on advances in exploration and production technologies.

On the other hand, international differences in the availability of high-level skilled
labor have affected the development of virtually all of these industries. An abundant domestic supply of scientists and engineers contributed to the entry and growth of German and U.S. firms in chemicals and pharmaceuticals, to U.S. firms’ leadership in computer software and computer hardware, and to the emergence of new U.S. firms in pharmaceutical biotechnology.\(^2\) In some cases, such as machine tools, the development of a domestic pool of skilled labor resulted from the growth of the machine tool industry itself and did not rely on institutions external to the industry.\(^3\) But in most of the other industries for which scientific and engineering talent have proven to be essential, domestic university systems have played an important training role.

Differences in the domestic availability of capital also contributed to international differences in the pace and structure of growth of such industries as semiconductors, computer hardware, and pharmaceutical biotechnology. Increased international integration of the domestic capital markets of the industrial economies since 1970 has not removed the strong influence of purely national elements on domestic capital markets.

For example, the rapid growth of the Japanese semiconductor industry during the early 1980s at the expense of U.S. firms benefited in part from U.S.-Japanese differences in the sources and costs of investment capital for this industry. The size and strength of the venture capital market in the postwar United States, and its relative weakness in the other industrial economies considered here, was important in several of our industry histories. Venture capital facilitated the entry by new U.S. firms into semiconductors, computer hardware, software, and pharmaceutical biotechnology, among other industries, leading to the development of industry structures in the U.S. that contrast with those observed elsewhere. And in several of these industries, the firms supported by venture capital became industrial leaders, albeit not always enduring leaders.

\(^2\)As we noted earlier, the growing presence of South Korean and Taiwanese firm in the semiconductor and personal-computer industries during the 1980s and 1990s may reflect a decline in the importance of advanced degree holders, relative to middle-skill labor (e.g., bachelor’s degreeholders), consistent with the product-cycle model.

\(^3\) Indeed, the failure of U.S. universities to develop a more effective research and training base for the postwar U.S. machine tools industry may have contributed to this industry’s decline.
This relatively abundant supply of venture capital, which was unique to the United States through most of the postwar period, rested on significant differences between the United States and other industrial economies in the institutions of corporate governance and industrial finance. The U.S. venture capital industry was founded on the strong U.S. market for public offerings of new and young firms. Moreover, the equity-dominated system of corporate finance (one that contrasts with those of Japan and Germany, to name two polar cases) that underpinned the U.S. venture capital industry also affected the development of firms in more mature industries examined in this study. The U.S. “market for corporate control” during the 1970s and 1980s appears to have enforced greater flexibility and responsiveness by U.S. firms to changes in market demand or technological opportunities.4 During the 1980s in particular, U.S. financial markets forced rapid restructuring in such industries as chemicals.

As the example of venture capital suggests, many of the significant cross-national differences in the availability of highly skilled and specialized labor and capital reflected differences in the structure of domestic institutions affecting a broad swath of economic activity. To cite another example, national university systems are important factors in many of our seven industry histories. The importance of university-based research and training varies among our industries, but the strength or weakness of national universities influenced the locus of industrial leadership in virtually all of them.

German university research aided German firms’ rise to leadership in the new dyestuffs industry of the 1870s and 1880s. Subsequently, American university research paved the way for American firms’ development of petrochemicals technology, by creating the new field of chemical engineering. University research in the U.S. and Europe has been a source of strength for national firms in medical diagnostics and in pharmaceuticals, particularly in the age of biotechnology.5

4 The disciplinary function of the equities markets does not operate flawlessly. The U.S. equities markets of the 1960s arguably overvalued the “synergies” created by conglomerate mergers (Shleifer and Vishny, 1991; Ravenscraft and Scherer, 1987), and other scholars (e.g., Chandler, 1990; Dertouzos, et al., 1989) have argued that the U.S. system of corporate governance tends to penalize long-term investments.

5 Interestingly, however, domestic university research has proven to be of little importance in the
Academic researchers in Great Britain and the United States were directly involved in the development of electronic computers in the immediate aftermath of World War II. After this early involvement, however, the contributions of university research to computer hardware development lay more in the area of basic research and in the training of engineers and scientists. This role was fulfilled most effectively by U.S. universities, with the aid of generous public funding for defense-related research. In computer software, U.S. universities remain important sources of technology and fundamental research, in addition to training computer scientists. In all of these areas, the strength of American university research has contributed to the leadership of American firms. The university systems of most Western European economies and Japan have proven less responsive to the research and training needs of these industries. The weaker links between industry and universities in these regions have impeded their attainment or maintenance of leading positions in many high-technology industries.

IV. The Role of Domestic Market Demand in Industrial Leadership

As Porter (1990) and Lundvall (1992) have argued more generally, the key role of users and international differences in the profile of domestic demand are central to understanding the evolution of many of the industries included in our study. Although leading German chemical products firms catered largely to foreign markets from the early years of the industry’s development, this case appears to be an exception. Domestic markets dominated the sales of firms in the early development of most of these industries.

Three of these industries found early markets in military and space applications. The U.S. Department of Defense supported the early growth of American firms in computers, semiconductors, and software, by demanding technologically sophisticated products. By contrast, in our two medical products industries the lack of government controls on healthcare costs contributed to the high profitability of the American postwar market and development of the internationally competitive Japanese medical diagnostic device industry.
facilitated rapid adoption of new products. In contrast, markets for many new products grew more slowly and were less profitable in the highly regulated markets of most Western European nations.

Although the character of domestic demand has influenced most of these industries, exploiting their domestic market required that firms innovate. And these technological innovations have affected the growth and structure of demand. Continuous declines in price/performance ratios for semiconductor and computer technologies, for example, accelerated their diffusion into a steadily expanding array of commercial applications, customers, and market segments. The progressive opening of new markets for computer hardware created opportunities for entry by new U.S. firms that challenged the dominance of established firms. The rapid growth of new segments of demand within the U.S. domestic computer market, along with the inability of hardware producers to meet demand for software for these new segments, created opportunities for entry by new independent software firms.\textsuperscript{6} The growth of new segments of the computer hardware industry in the United States also proved indispensable to the rapid development of the microprocessor segment of the U.S. semiconductor industry, which transformed the financial and competitive outlook for the U.S. industry during the 1980s and 1990s.

The importance of the “intra-national” user-producer interactions that pervade these industries has important implications. Even in global markets, large domestic markets provide an invaluable “springboard” for firms seeking to enter new industries or seize new technological opportunities. Where fixed costs, such as product R&D outlays, are high and production and marketing activities involve economies of scale, strong first-mover advantages may accrue to firms in the country in which a “critical mass” of customers is achieved first.

Our emphasis on the importance of domestic demand should not be taken as a rejection of the strength and significance of transnational technology and product flows, which in some cases reduce the significance of purely national user-producer links. The strength of

\textsuperscript{6} A similar pattern in the evolution of the computer storage-disk industry has been discussed by
British textile firms did not prevent German chemicals firms from dominating the British market for textile dyestuffs. The development by Japanese firms of new medical diagnostic instruments that relied on U.S.-developed optical fiber technologies is a case in which the flows of key enabling technologies spanned the Pacific. The adoption and improvement by German chemicals firms of U.S.-developed manufacturing processes after World War II is another example of the international flow of technology within an industry. And the refinement and application by Japanese firms of computer controllers to low-cost machine tools relied on technologies originally developed by U.S. electronics firms.

Nonetheless, the national upstream-downstream links were very strong in most of our case studies. Policies that ignore the existence or importance of these links may lead to unanticipated troubles.

V. The Locus of Industrial Leadership: Firms, Sectors, or the Nation-state?

Some theories of industrial leadership, such as the factor-endowments explanation employed by many economists, locate the key causal factors in features of the national environment. Other theories, however, such as those developed by Chandler (1990), Prahalad and Hamel (1990), Aoki (1990), and Teece, Pisano and Shuen (1997), emphasize the capabilities developed by the firms themselves. Still others (Harrison, 1992; Saxenian, 1994; Porter, 1992) focus on regional or sectoral systems as the source of leadership. What light do these industry studies shed on theories of the locus of industrial leadership? Our discussion below begins by considering industries in which the locus of leadership at both the firm and national levels has been stable for a lengthy period. We then examine cases in which the locus has changed, and consider whether these changes involved shifts in the identity of the leading firms, in the nationality of these leading firms, or changes in both.

The chemicals industry is one of extraordinarily enduring firm-level competitive advantage. Virtually all of today's leading firms were established many years ago; such
companies as BASF, Hoechst, Bayer, and DuPont, all trace their roots well into the 19th century. Similarly, many of the pharmaceuticals firms that mastered the challenge of a new biotechnology-based paradigm have been in existence for substantially more than 75 years, dominating the pharmaceuticals industry for much of this period. In these industries, it is clear that much of what makes for industrial leadership is located substantially in the firms themselves. Leading firms fit Alfred Chandler’s analysis (1990) of the sources of industrial leadership, and strong “first-mover” advantages have been important and durable. These firms built and solidified competitive advantage through their own investments and learning in an imperfectly competitive environment similar to that of the Schumpeter of Capitalism, Socialism and Democracy (1950).

But leading firms in these industries have also benefited from their national institutional and policy environments. In particular, as we stressed above, German chemical firms were strengthened by the high quality of the German university system, and the rise of the American chemicals industry was associated with the growing strength of American universities. Similar national factors supported the growth of firms in the other industries we group here, where both firm and national level leadership has been long-lived.

In other cases, e.g., computer software, medical devices, and computer hardware, we observe higher rates of turnover among “dominant firms,” but the shifting collection of dominant firms is largely headquartered in the United States. The Chandler-Schumpeter model of particular firms that achieve and sustain dominance over long periods of time does not fit these industries. Rather, such industries as the U.S. software or semiconductor industries fit the model described in the earlier Schumpeter of The Theory of Economic Development (1934). The relative stability of industrial leadership at the national level in industries marked by considerable turnover among the leading firms suggests that the factors behind leadership in these industries reside at the level of the nation-state (e.g., domestic factor supply, domestic market demand, university systems, or industrial finance) and are relatively durable.

In machine tools, firms from a single nation have dominated different segments at
various points in time, and neither the firm-level nor the national locus of industrial leadership have remained stable during the postwar period. German and U.S. dominance during the 1950s and 1960s was challenged and largely overturned in all but the most specialized segments of the industry by firms from Japan and Taiwan. These changes in leadership are related to differences in national markets and changes in these markets over time.

The picture of the locus of industrial leadership that emerges from these studies supports three broad conclusions. First, the issue is not whether it is firms themselves, or the broader national environment in which they reside, that is the locus of industrial leadership. National and firm-specific factors interact with one another, and both the environment and firms’ reaction to that environment are important. Second, although many comparative analyses assume that the institutional environment of firms is determined largely by forces beyond the reach of firms, firms often affect industry-level institutions and policies. Third, many of the sources of industrial leadership reside in structures intermediate between nations and firms. We refer to these as “sectoral support systems.”

The complex interaction between the performance of firms and the institutional environment within which they operate is readily apparent in the chemical products and pharmaceuticals industries. German firms were supported by strong German university research and training of organic chemists, but these firms also invented the industrial research and development laboratory and provided technical consulting services for their customers. The support provided by the National Institutes of Health for research and training in the biomedical sciences created opportunities for American-based pharmaceuticals firms, but these firms displayed considerable skill in exploiting such opportunities.

The same pattern of symbiosis between industry support policies and the response of business firms appears in computers and semiconductors. During the early 1950s, the U.S. Department of Defense (DoD) provided the primary market for computer hardware. DoD also organized and funded many of the early critical design and development projects
through which American computer firms developed their technical skills. Nevertheless, although U.S. firms benefited from these defense procurement and R&D programs, their eventual dominance of the worldwide commercial mainframe computer industry was hardly inevitable. Some U.S. firms, such as IBM, "bet the company" and expanded into commercial markets during the 1950s, while others either did not or did so more gradually, ceding the mainframe market to IBM. In semiconductors, a substantial domestic market for American firms also was provided largely by the DoD, which supported industry R&D to develop designs for military applications. But the major technological achievements of the 1950s were in most cases accomplished by companies using their own funds and following avenues other than those the DoD was funding.

As we noted, firms located in a particular nation often gain an early advantage in a new industry because the nation's institutions provide them with a more supportive environment than that faced by firms in other countries. As an industry develops, however, firms influence their institutional environment.

For example, although German chemicals firms had little direct role in the strength of their domestic universities in teaching and research in organic chemistry, once this industry began to develop, German firms provided considerable political support for German government funding of university training and research in chemistry. Indeed their subsequent dissatisfaction with the inflexibility and lack of responsiveness of German universities to industrial needs contributed to industrial lobbying for government endorsement of the formation of the industrially funded Kaiser Wilhelm Gesellschaft for chemical research in 1910 (See Beyerchen, 1988). U.S. pharmaceutical companies long have supported growth in the NIH budget for biomedical research and training. The mature U.S. semiconductor industry lobbied federal agencies during the 1980s for R&D subsidies to SEMATECH and trade agreements to improve their access to the Japanese market.

National firms also influence their regulatory environment. U.S. biotechnology firms have been involved in the formulation of policies on intellectual property rights and federal funding of university research. The evolution during the 1980s of American intellectual
property rights law and practice for software was shaped to a considerable degree by the interests of the American packaged software companies.

Another important lesson from many of these industry studies is the importance of national institutions that are specific to particular sectors. Although they are embedded in and supported by broader national institutions, in many cases the key sectoral ones have a structure and a life of their own.

Thus, German university strength in organic chemistry was one consequence of the broad strength of the 19th-century German university system in the natural sciences. But once the German dyestuffs industry began to grow, academic chemistry in Germany developed a unique network of industrial sources of research support. The interactions between professors and their former students in industry also contributed to this sector-specific network of linkages between German universities and German chemical companies. University-industry research and training linkages in the U.S. pharmaceutical biotechnology and medical device industries have relied for decades on funding from the National Institutes of Health, and operate primarily through academic medical centers that combine clinical and fundamental research activities. In turn, the U.S. pharmaceuticals industry supports growth in the NIH budget. This sectoral structure differs from the academic research and training infrastructure that supports the computer, semiconductor, and software industries, which has relied on funding from the U.S. Defense Department and operates in large part through physical science departments and engineering schools within U.S. universities.

Similarly, the U.S. venture capital firms, or at least the key people within the firms that operate in semiconductors, computer hardware, and software differ from those focusing on pharmaceutical biotechnology. In each case, the specialized venture capital firms are knit into complex, sector-specific networks that link firms, universities, and professional societies.

In some cases, sectoral innovation systems are concentrated in particular regions. A regional system, like a sectoral system more generally, may involve more than one industry.
The original “Silicon Valley” has grown from its origins in semiconductors to encompass computer hardware and software. Other examples of regional industrial districts among the industries discussed in this volume include the contemporary U.S. biotechnology industry’s concentration in the Seattle, San Francisco, San Diego, and Boston areas; the clustering of the leading German chemicals firms in the Rhineland in the late 19th century; and the concentrations of U.S. and German machine tool firms respectively in Milwaukee and the Connecticut River valley, and in southwest Germany.

Despite the importance of these regional effects, however, the sector rather than the region appears to be a more meaningful analytic concept for understanding the sources of industrial leadership. The sectoral system may or may not be concentrated geographically, but typically involves an array of supporting institutions and an industry structure that are distinctive. The study of sectoral innovation systems and their differences among industries, countries, and eras should assume a prominent position on the research agenda of economists and other scholars interested in the sources of industrial leadership.

VI. The Evolution of Industry Structure

Because the time period covered in all of our industry histories is relatively long and because most of these studies cover a wide range of products, theories of “industry life-cycles” that focus on the evolution of individual product classes proved to be of limited use. Nevertheless, “dominant designs” have played an important role in some of these industries’ evolution. The IBM 360 fulfilled such a role among mainframe computers for much of the 1960s and 1970s. But the dominance of the computer industry by IBM was ultimately eroded by the emergence of new segments of market demand in minicomputers in the late 1960s and (of far greater significance) in desktop systems in the early 1980s. Since the mid-1980s, the “Wintel” architecture for personal computers has been a dominant design, although its emergence is associated with high levels of entry by new...
manufacturers of desktop computers, rather than (as in the Abernathy-Utterback, 1978, and other theories) declining rates of entry. The limited relevance of “dominant design” theories reflects a broader characteristic of these industries’ development. Virtually without exception, industrial evolution has involved the progressive opening of new segments of market demand for which existing “dominant designs” were poorly suited.

Theories of industry evolution that emphasize dynamic increasing returns and durable “first-mover” advantages are germane for some but not all of our industry histories. As we discussed in the preceding section, dominant firms in the chemical products industry and in pharmaceuticals have retained leadership positions for more than three-quarters of a century. Outside of the United States, long-established, diversified electrical equipment companies remain industry leaders in computers, machine tools, and semiconductors, and both U.S. and non-U.S. firms from these industries have been important in medical equipment.

Although some form of dynamic increasing returns or other first mover advantages appear to be important in explaining such enduring leadership, the companies that have maintained leadership over a long period of time have not done so simply though their control of a dominant design or exploitation of scale economies. Instead, these long-term leaders have maintained their technological and nontechnological capabilities in the face of significant change in the underlying basic technologies. For these firms and industries, the concept of “dynamic capabilities” (Teece et al., 1997) has considerable descriptive power. But where changes in the underlying technologies were accompanied by significant changes in the structure of demand, incumbents have proven less successful.

Rather than well-behaved, relatively stable “product cycles” within industries or technologies, many of these industry histories are best portrayed as a series of “punctuated equilibria,” i.e., a series of discreet, dominant technologies, with the successor significantly different from the predecessor. In machine tools, the advent of numerical control was a major “punctuation.” In chemical products the development of petroleum as a basic

feedstock was one such punctuation. In pharmaceuticals, the discovery of antibiotics was a punctuation, and the advent of biotechnology a more dramatic one. The invention and development of the integrated circuit, and later the microprocessor, are technological punctuations in the history of the semiconductor industry. The new computer designs that these inventions permitted—the first, minicomputers, and the second, personal computers—also mark punctuations in the computer industry.

Some theories of industrial evolution argue that these sharp shifts in underlying technologies are “competence-destroying” in their effects on incumbent firms, and therefore result in the displacement of established industry leaders (Tushman and Anderson, 1986; Henderson and Clark, 1990). Does this pattern characterize our industry histories? Our industry studies provide mixed evidence on the importance of such “competence-destruction” and incumbent displacement for long-run industry evolution. The development of petroleum-based chemicals process and product technologies was undertaken by both incumbent and new entrants within the U.S. chemicals industry during the 1920s and 1930s (a number of firms, including Standard Oil of New Jersey, entered the production of chemical products at this time). Moreover, during the 1950s, European chemicals firms licensed petroleum-based process technologies from specialized engineering firms and established U.S. firms and successfully switched their process technologies to exploit the new feedstock. A number of established U.S. and European producers of pharmaceuticals also have maintained their dominant positions in the face of a dramatic technological threat from biotechnology.

On the other hand, as we have noted, major shifts in the underlying technologies have challenged industry leaders when technological change has been accompanied by change in the characteristics of market demand. (See also Christensen and Rosenboom, 1994) The destabilizing effects associated with the emergence of new segments of market demand have been most significant when the nontechnological “complementary assets” of established firms are of little use in the new markets. In chemicals, as we noted earlier, this dynamic has been of minimal importance. In medical devices and pharmaceuticals,
government regulation has enabled incumbent firms to develop broad complementary assets in the form of regulatory and marketing expertise that is relevant to a broad variety of products. The high costs and substantial specialized expertise needed to manage medical-device and pharmaceutical regulation and marketing have reduced turnover among dominant firms in the face of radical technological advances.

But in the electronics complex, incumbent firms repeatedly have found that their marketing, manufacturing, and other capabilities were insufficient to maintain dominance in new segments of rapidly growing market demand. Similarly, the capabilities developed by U.S. machine tool firms to serve their “Detroit automation” and aerospace customers were not easily applied to the new markets in which Japanese firms proved successful during the 1970s and 1980s.

Vertical specialization is another important characteristic of structural change in several of these industries. In the electronics industries, for example, growth is associated with vertical “dis-integration” and increased specialization over time by firms at different points in the industry value chain. Integrated firms such as IBM or Digital Equipment were active in all three of these industries (computer hardware, computer software, and semiconductor components) during the 1960s and 1970s, and both IBM and Digital Equipment maintained a presence in semiconductor components, software, and computer systems until at least 1997. In recent years, however, the presence of these large, vertically integrated U.S. enterprises has been overshadowed by the entry of independent U.S. suppliers of components and software, and Digital Equipment was acquired in 1997 by Compaq Computer, a new firm that entered the computer industry in 1982 as a specialized producer of PCs. The rise of biotechnology has produced similar tendencies toward higher levels of vertical specialization in the modern pharmaceuticals industry. A number of established producers of pharmaceuticals have formed “alliances” or contractual

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8 Compaq, of course, was subsequently acquired by Hewlett-Packard in 2002. There is significant evidence that component design and manufacture are being separated, as a large number of specialized “design firms” have entered the U.S. semiconductor industry. The design firms provide custom designs for components that are produced in “foundry” facilities maintained by other firms.
relationships with smaller biotechnology specialists for the discovery and development of new drugs.

These tendencies toward vertical specialization seem to be 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, are also more highly vertically integrated than their U.S. competitors. Similarly, in Europe and Japan the traditional pharmaceuticals companies themselves have tried to diversify into biotechnology, and a specialized collection of firms that specialize in biotechnology research and early-stage product development has not appeared there.

The chemicals industry has for much of the postwar period been characterized by an unusual pattern of vertical specialization, in which “specialized engineering firms” (SEFs) developed new process technologies and built facilities for the manufacture of commodity products by major firms in the United States, Western Europe, and Japan. SEFs also transferred process technologies to other firms, intensifying competitive pressure on the long-established U.S., European, and Japanese firms, and forcing a far-reaching restructuring of the industry in the 1980s.

Many elements of the progressive extension of horizontal and vertical specialization that show up in some of our industry histories seem broadly consistent with Stigler’s theory (1951) that vertical disintegration is a natural and near automatic consequence of market growth. In some cases, such as electronics, entry by vertically specialized firms (independent software vendors, merchant semiconductor producers) seems to have forced some “dis-integration” of established firms, consistent with Stigler's theory, and particularly the arguments of Langlois and Robertson (1995). But why this development should have proceeded to a much greater extent in the U.S. than in Europe and Japan requires more analysis. In our earlier discussion we proposed that the U.S. venture capital system is an important part of the explanation, but this only pushes the question back a stage. Why have comparable institutions developed so slowly elsewhere?
The picture revealed by our seven industry studies of how technologies and industries evolve over time thus is a complex and variegated one. There is no single pattern that fits all industries. Similarly, the theories that attempt to explain or predict the dynamics of comparative advantage at a national level provide only limited illumination. For example, first-mover advantages are significant in some of our industries, but not others. The Vernon-Posner product cycle theory of international trade, which posits a systematic shift in the locus of comparative advantage as an industry matures, also fits some cases but not others. This theory seems to explain the growth of manufacture of standard components of desktop computers, such as monitors and circuit boards, in Taiwan during the 1980s, the growth of “commodity” chemicals production in industrializing nations during the 1970s and 1980s, and South Korean entry into DRAM manufacture in the 1980s and 1990s. In some but not all of these cases, shifts in the locus of production led to shifts in the locus of product development and R&D--such shifts occurred in DRAMs, for example, but not in chemicals. But in pharmaceuticals, medical diagnostics, and the most advanced, “design-intensive” microelectronic components, no such shift to low-wage countries has occurred, perhaps because user-producer interactions and advances in production architecture are both important and highly dynamic.

VII. Implications for Public Policy

Both the advocates of sectoral support policies for “strategic” industries and the opponents of such policies are likely to claim support for their positions from a hasty reading of these industry studies. We believe, however, that these studies portray a more complex and subtle dynamic than either side of this debate allows.

Policies that seek to encourage the development of an industry by protection and subsidy have a mixed record. Such policies certainly have aided some industries (e.g., Japan’s electronics industry) in catching up with technology leaders. In such cases at least, the target was clear (although, as in the case of Japan’s efforts during the 1980's to catch up
with IBM, the target of the “catch-up” campaign may be misspecified). For countries that are at the technological frontier, however, targeted industrial policies are much riskier and generally less successful. Moreover, successful policies of this type generally have avoided public funding of specific commercial products or designs, instead confining themselves to promoting a broad sector or industry.

Adam Smith and his contemporary admirers are correct in arguing that an essential governmental role in stimulating industrial development involves investment in supporting infrastructure and a broader legal and institutional framework that results in productive investment and competition. Nevertheless, in many of the industries studied in this project, important elements of the government-provided infrastructure and supporting policies that gave strength to an industry were sector-specific.

A. Lessons for Sectoral Policies

Many public policies and programs typically are debated as though their benefits, costs, and design affect all sectors of the economy equally. In fact, however, these programs typically have strong sector-specific elements and effects. Much publicly supported R&D infrastructure (including funding and facilities) is sector-specific, as is support for the training of engineers and scientists. Intellectual property rights regimes have technology-specific elements and effects; patent protection is more important in fine chemicals and pharmaceuticals than in most other industries (see e.g. Levin et al, 1987). A number of regulatory policies are sector-specific by definition and design, as in the case of the FDA and the U.S. pharmaceuticals industry. Other policies, such as antitrust, are neither framed nor targeted on specific sectors as a matter of policy. Nevertheless, antitrust policy has had important sector-specific effects, as our studies of the chemicals and computer industries reveal. The differential effects of such policies on individual sectors or industries also may influence the development of these policies, since the industries that are heavily affected by them typically engage in political action to shape their formulation.
The sectoral policies that have supported industrial leadership vary significantly among sectors in scope, characteristics, and effectiveness. The study of machine tools reveals few influential sector-specific government policies. The rise of the American machine tool industry toward the middle of the 19th century undoubtedly was facilitated by the U.S. War Department’s interest in guns made with interchangeable parts. But the effects of even this substantial stimulus appear to have been minor relative to those of the rise of mass-production industry in the United States during the second half of the 19th century. The research support by the U.S. Air Force hastened the development of numerical control, but the specific goals of this R&D program drew American machine tool designers and manufacturers away from the development of tools that could support flexible manufacturing, a large commercial market. There is little evidence that government support of university research and training, import protection, or regulatory policies have influenced the evolution of industrial leadership in machine tools.

In contrast, there is little question that broadly targeted government policies have had an important impact on the evolution of chemical product technologies and the strength of national firms. But governments typically have not targeted specific technologies in chemicals, although for national security reasons the German and British governments sponsored the development of synthetic fuels during the interwar period and the American government supported the development of synthetic rubber during World War II. Instead, the important government policies have been "upstream," most notably through public support of university research. More recently, environmental regulations have had a significant influence.

Pharmaceuticals and medical diagnostic equipment both benefited during the postwar period from large-scale funding of biomedical research by government in the United States, Great Britain, and elsewhere in Western Europe. Public support for biomedical research during this period was far less significant in Japan, but limited public funding does not appear to have retarded the development of a vigorous Japanese medical devices industry. Government regulation of pharmaceuticals and medical devices has been another
important influence on the development of these industries. Interestingly, recent evidence suggests that stringent regulation of new pharmaceutical products’ safety and efficacy in the United States and selected Western European nations is associated with stronger performance. In contrast, the weaker regulatory structure in Japan has supported imitative strategies on the part of Japanese firms.

Our histories of the computer industry, the semiconductor industry, and the software industry reveal broad public sector involvement. In some cases, government involvement has helped national firms gain industrial leadership, and in other cases, this involvement has hindered national firms. As with pharmaceuticals and medical devices, government support for R&D and training has been very important. Public R&D funding of university research also aided the creation of an ample supply of well-qualified electrical engineers, material scientists, computer scientists, and sophisticated programmers, which has been an important factor in U.S. leadership in these industries.

Government procurement policies have a mixed track record in supporting the commercial performance of firms in these defense-related industries. In semiconductors and computer hardware, the large-scale procurement programs of the U.S. Defense Department provided an impetus to the growth of new and established firms during the first two decades of each industry’s existence, strengthening the commercial competitiveness of firms in both industries. But defense-related procurement in France and Great Britain proved to be a much less effective catalyst for industrial leadership in civilian markets for computers and semiconductors. And the "high precision" demands of the military market for NC machine tools caused American firms to direct their innovative efforts away from a new and important civilian market.

The explanation for these differences appears to lie in the structure of these programs. Partly because of the greater size of the U.S. defense budget, U.S. procurement programs involved competition for R&D contracts and for purchases--Western European defense

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9 Since the computer software industry was a barely distinguishable part of the computer hardware industry during this early period, such procurement also indirectly benefitted the development of the computer software industry.
programs more frequently awarded contracts on a noncompetitive basis to a “national champion.” Another critically important distinction between the structure of many U.S. and Western European defense procurement programs was the greater participation by young computer and semiconductor firms in U.S. R&D and procurement programs in these industries. The availability of defense contracts was a powerful magnet for the entry of new firms into both U.S. industries.

B. Generic Policy Principles

Thus far, we have stressed the differences among the government policies that proved to be effective in our different industries. We conclude here by attempting to identify some common characteristics of effective industrial policies, focusing on three broad areas: government R&D support, competition policy, and policies regarding intellectual property rights.

Public R&D funding has been an important source of technological advance and industrial leadership in most of these industries, but the structure of public R&D programs appears to be at least as important as the size of their budgets. In general, our industry studies support the use of extramural R&D programs that are subject to competitive allocations among performers based on some assessment of merit, rather than relying on public laboratories that are insulated from competition or peer review to perform such R&D. In most successful programs, the results of publicly funded R&D also have been widely diffused within an industry, whether this occurs through publication, R&D collaboration among firms, or some other mechanism.

We have emphasized the role of universities in research and training. Consistent with the principle we proposed above, the structure of national university systems appears to be as important as the magnitude of government support in determining the contributions made to industrial development. Thus the decentralized structure of the U.S. university system, and the associated strong inter-institutional competition for students, faculty, and
research resources, contrasts favorably with the more centralized structure of the Japanese and most Western European university systems. These factors have contributed to considerable institutional innovation within the U.S. university system. The nascent academic disciplines of chemical engineering, molecular biology, materials science, and computer science (to name but a few) were given the legitimacy of departmental status relatively rapidly, with the aid of external funding from federal and industrial sources. In this and other spheres, the pressure of inter-institutional competition for resources, talent and prestige led U.S. universities to pursue new fields of research and training more rapidly than most European and Japanese institutions.

If competition among universities and other research organizations is one hallmark of an effective sectoral innovation system, competition among firms in applying and commercializing technological advances is another. In all of these industries, the firms themselves spend far more on R&D than do public agencies. Alternative approaches to the application and commercialization of new technologies, processes that are fraught with high levels of uncertainty, are more likely to be deployed, and selection among them is more likely to be effective, when competition among these firms (and, in many cases, between domestic and foreign firms) is more intense.

Perhaps for this reason, competition policy has played an important role in shaping the national locus of industrial leadership in several of the industries treated in this volume. Although it rarely receives extensive attention in discussions of technology and competitiveness, the relatively stringent postwar competition policy of the United States aided the growth of new industries during this period. U.S. antitrust policy weakened the ability of incumbents in such industries as computers and semiconductors to control new technologies and markets. The U.S. computer software industry benefited as well from the restructuring of the U.S. telecommunications industry in the wake of the U.S. v. AT&T antitrust suit that was settled in 1982. In contrast, in Europe and Japan, where competition policy has been less stringent, the development of new technologies has been left largely in the hands of established firms, and often these have moved slowly to exploit new
opportunities.

A closely related area of government policy that has affected many of these industries relates to intellectual property rights. Although scholarly and policymaker opinion in the United States, at least, recently has shifted to favor strong intellectual property rights in technology-intensive industries, the history of these seven industries suggests that a more nuanced interpretation of the costs and benefits of stronger intellectual property rights is needed.

In the fields of chemical products and pharmaceuticals, intellectual property rights have tended to be strong since the turn of the century, and this has enhanced the ability of firms to capture the returns to their R&D. These specific industries nevertheless are unusual in their reliance on intellectual property rights to capture the commercial returns from their innovations (see Levin, Klevorick, Nelson, and Winter, 1987).

In semiconductors, a combination of historical accident and U.S. government policy resulted in a relatively weak intellectual property rights environment for most of the first three decades of the U.S. industry’s development. This environment was conducive to high levels of cross-licensing and entry by new firms, which contributed to rapid growth and innovation. Since the early 1980s, however, the role of formal intellectual property rights in semiconductors appears to have increased considerably--indeed, the “renaissance” of the U.S. industry, based as it is on microprocessors, has greatly increased the incentives for aggressive private enforcement of these rights, and both patenting and litigation have grown rapidly (See Hall and Ham, 1999). In computer hardware, U.S. antitrust policy also mandated liberal cross-licensing at an early stage in the development of the U.S. industry, reducing barriers to entry.

In computer software, intellectual property rights were of little consequence during the era of custom software. But the growth of mass markets for packaged computer software, rather than formal government policy, has greatly increased the importance of intellectual property rights in this industry. Although U.S. packaged software firms have benefited from strong domestic and strengthened international enforcement of intellectual property
rights during the 1980s and 1990s, the long-term effects of such strict enforcement on innovative performance remain uncertain.

These industry studies support a position of “neutral skepticism” toward very broad protection for intellectual property. At a minimum, these studies (as well as more recent evidence from the United States on the near-term effects of stronger intellectual property rights--see Hall and Ham, 1999; Mowery et al., 2000) suggest that the burden of proof for significant strengthening or broadening of intellectual property rights should lie with the proponents of greater stringency. This burden of proof should be highest during the early stages of an industry’s development.

In summary, two issues deserve emphasis. First, every one of these industry histories highlights the uncertainties involved in the evolution of any rapidly developing technologies. Each such episode produces a contest among firms, entrepreneurs, and developers of new technologies and applications, the outcome of which is extraordinarily difficult to forecast. Policies toward new technologies and the industries that seek to exploit them should favor greater diversity in the commercial “bets” that are placed on the development of such technologies. Another implication of these observations is that government policies that involve placing large bets on particular paths of development or particular firms are likely to fail. One exception to this rule occurs when such public policies are used to catch up with a clear leader, whose characteristics can be evaluated and targeted. But even here, the leader that provided such a clear target may have been surpassed by another technology or firm by the time the chase is in full sway. Achieving or maintaining leadership requires the encouragement of pluralism and competition.

But this does not mean that public policies should be minimal or passive. Government policies powerfully influence the vigor and fruitfulness of dynamic competition. Government research support policies can fuel it. Government regulatory policies may be needed to channel it so that what firms find profitable is also in the public interest. The earlier literature on National Innovation Systems (see Nelson, 1993) pointed out the complex and variegated institutional structures that are involved in economic growth fueled
by technological progress. Our industry studies reaffirm that conclusion, sector by sector.
REFERENCES


Lundvall, B. A. (Ed.), National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning, London, Pinter, 1992


Stigler, G.J., “The Division of Labor is Limited by the Extent of the Market,” *Journal of Political Economy*, 1951, 185-193


Defining “Industrial Leadership”

- A combination of commercial and innovative performance that gives firms commercial advantage.
  - More than simply invention or innovation; commercialization and competitive performance are central.
  - Measures of “leadership” include but are not restricted to performance in innovation, market share, % of sales attributable to new products, financial returns.
  - Focus on sectors, rather than economy-wide performance measures.
Roadmap

• Draws on Mowery and Nelson 1999 volume, Sources of Industrial Leadership: Studies of 7 Industries (Cambridge UP).
  • Tripartite focus (US, Japan, EU)
  • Relatively long time horizon (50-100 years).

• Focus on 4 sectors to highlight contrasts:
  – The ICT “complex” (semiconductors, computer hardware, computer software).
  – Chemicals.
  – Machine tools.
  – Biomedical (pharmaceuticals and medical devices).
Key issues

• The locus of industrial leadership (firms; nations; something else?).

• Evolution of industry structure.
  – Vertical specialization.
  – Do “radical” innovations displace incumbent firms?
  – Influence of firm governance and industrial finance on industry structure and industrial leadership.

• Role of market demand.

• Role of research universities.

• Public policy.
  – R&D funding.
  – Public procurement.
  – Competition policy.
  – Intellectual property rights.
Some caveats

• The 7 studies focus more intensively on US than on Europe, Asia.

• Prediction is hazardous, in view of the dramatic revision in views of US competitive performance between the late 1980s and late 1990s.
  – Many of the “causes of decline” widely cited by analysts of US weakness in late 1980s are cited by others as sources of competitive revival and strength during the 1990s.

• Intersectoral differences are significant. Generalization must be handled with caution.
The locus of industrial leadership

• Chemicals: Enduring firm-level leadership for nearly 125 years.
  – Large chemicals firms founded in late 19th century in US, Europe retain global dominance into the 1990s.
• IT complex: Industrial leadership is more nation-specific.
  – Shifting group of firms, largely located in US, retains leadership for most of the 1945-2000 period.
• Machine tools: Shift in national, firm-level leadership.
  – US firms, strong in early 20th century, decline after 1945; Japan emerges as significant producer of NC machine tools, Taiwan as producer of low-cost tools.
The locus of industrial leadership

• Biomedical sector: Shift in national, firm-level leadership.
  – Pharmaceuticals: US firms rise to global dominance after 1945, based on federal R&D funding, price-insensitive market.
  – Biotechnology: Wave of new-firm entry, limited displacement of established “big pharma” firms.
  – Medical devices: Considerable new-firm entry and entry in optical-fiber devices from Japan, but large firms (GE, Siemens) retain substantial share.
  – Regulatory policies of national governments, costly marketing assets tend to preserve incumbents’ positions.

• Sectoral contrasts reflect differences in demand, institutions, innovation process.
**Evolution of industry structure**

- Vertical specialization ("dis-integration" of vertical value chain).
  - Most pronounced in IT, sector.
  - Chemicals: entry of "specialized engineering firms" supported international diffusion of process technology and entry by new chemicals firms.
    - Large incumbent chemicals firms have "re-integrated" product, process innovation. SEFs now are much less important.
  - Limited vertical specialization in machine tools (electronic controllers).
  - Biomedical sector: Vertical specialization in pharmaceuticals has increased as a result of biotechnology "research boutique" specialists, contract manufacturers, contract clinical trials managers.
    - Much less pronounced in medical devices.
    - Incumbent firms retain control of marketing, regulatory management.
Vertical specialization and industry evolution

- Where significant, vertical specialization in all of these industries has developed most extensively in the US.
- Vertical specialization contributed to the “commoditization” of key competitive assets in chemicals, as well as globalization of production. “Foundries” in semiconductors may have similar effect.
- Vertical specialization was partly reversible in chemicals; other industries.
**Evolution of industry structure**

- “Radical innovation” and incumbent displacement.
  - Common in IT.
  - Rare in chemicals, biomedical sector.
  - NC machine tools ultimately displaced many US incumbents.
  - Key factor: does radical innovation open up new market segments for which incumbent capabilities are of limited value?
  - Do regulatory policies (e.g., biomedical sector) favor established firms?
Evolution of industry structure

• Corporate governance and finance.
  – Importance of new-firm formation and entry varies across national economies in the industries considered, especially after 1945.
  – Venture capital and equity market support entry in US IT, biotechnology, medical devices; less significant influence on entry in chemicals, machine tools.
    • Key reason for higher levels of vertical specialization.
  – But “market for corp. control” affects incumbents in some industries, as well.
    • Severe pressure on mature US chemicals firms to restructure in 1970s, 1980s, in contrast to most Japanese, many European chemicals firms.
    • Accelerated restructuring of US computer, semiconductor firms during the 1980s.
Role of demand

• Overall, change in demand (opening of new market segments) one of the most important sources of “disruptive” change that displaces incumbents.

• IT: Large, homogeneous US market contributed to industrial leadership.
  – Gov’t procurement in semiconductors.
  – User-led experimentation and “co-invention” in software and IT benefit from large domestic market.
  – US imports of low-cost hardware accelerate adoption, expanding installed base and supporting user-led innovation.

• Chemicals: User-producer interaction was important in the early years, but domestic market structure and scale less important for much of 20th century. Gov’t wartime demand an exception.
Role of demand

- **Machine tools**: US firms pursued technological approach to numerical control after 1945 that was influenced by aerospace demand and had limited applicability to their historical markets.

- **Biomedical sector**: Postwar US market was large, wealthy, and price-insensitive.
  - High profit margins, relatively rapid adoption of new pharmaceuticals, medical devices.
  - Complex regulatory structure favors national, rather than foreign firms.
  - US provides lucrative “launch market” for US firms, aiding leadership.

- **Japanese domestic demand**: conditions an important catalyst for development of optical-fiber medical devices for diagnosis, treatment.
  - An important “launch market” for Japanese firms.
Research universities

• US higher education system’s unusual structure supports high levels of university-industry collaboration and technology transfer throughout the 20\textsuperscript{th} century:
  – Large scale.
  – Dependence on regional, state-level sources of financial support.
  – Administrative autonomy and lack of central control.
  – Mix of public and private institutions.
  – National market for faculty talent and high inter-institutional mobility.
  – Strong inter-institutional competition for resources, prestige, faculty talent, students.

• Increased federal funding $\Rightarrow$ increased importance for US universities as research performers after 1940.
Research universities

- US research universities’ postwar role in technology transfer also is affected by factors outside of academe.
  - Supply of venture capital.
  - Ease of new firm formation, which varies among sectors.

- IT: Universities’ role contrasts among the 3 subsectors and shifts over time within each.
  - Computer hardware: Universities are key developers of early computers in US, UK. US universities subsequently are critical part of R&D infrastructure.
  - Semiconductors: Universities play a minor role in R&D, critical role in training of engineers. Design software a major contribution by universities.
  - Software: Universities are important source of innovations, firms, trained personnel.
Research universities

• Chemicals: Universities are an important locus of collaborative research in US during 1920s & 30s; much of chemical engineering discipline is developed at MIT, Wisconsin during this period.
  – Collaboration remains important in the postwar period, although public funding plays a minor role.
  – Training of scientists and engineers another important contribution throughout the 20th century.

• Machine tools: Relatively weak linkage with US university research, with the exception of development of NC technology after 1945.
  – Weak linkages contribute to decline of US firms.

• Biomedical sector: University research is crucial to post-1945 industrial leadership. Public funding a key factor in US universities’ role.
Public Policy

• R&D funding.
  – Public R&D funding is significant in IT, biomedical devices; less important in chemicals, machine tools.
  – Since 1945, scale of US public R&D funding has been substantial; but the structure of public R&D funding has been at least as important in affecting payoffs.
    • Competition among research performers.
    • Pluralism and competition among sources of R&D support.
    • Primary reliance on extramural performance (especially universities, which combine research & teaching), rather than public laboratories.
    • Especially in IT, long-term military R&D programs and results are relatively accessible to civilian researchers.
    • Historical reliance on diverse and relatively open channels for dissemination and application of results within industry.
    • Large-scale deployment of early innovations (e.g., ARPANET, NSF funding of mainframe computers in universities) supports further user-led innovation and R&D infrastructure.
Public Policy

• Defense-related procurement especially important in post-1945 US.
  – US defense-related procurement in semiconductors, computers favored new firms. European defense programs tended to support established-firm suppliers.
  – US wartime procurement programs involved significant technological development and forced interfirm transfer of knowhow and technology in chemicals (synthetic rubber, Manhattan Project).
  – In machine tools, procurement may have led US firms to pursue development of technologies with limited applications outside of aerospace, weakening the industry.

• Procurement plays modest role in postwar US biomedical sector, arguably more important in publicly supported healthcare systems of Europe.
Public Policy

• Competition policy
  – In IT tough antitrust policies of the 1950s and 1960s weaken entry barriers and support substantial interfirm flow of technology.
    • AT&T, IBM consent decrees.
    • IBM unbundling of software, hardware pricing in 1969.
  – Antitrust policy is important in chemicals, but does not lead to comparable interfirm knowhow transfer or entry by new firms.
  – Little significance for antitrust in machine tools, biomedical sector.
Public Policy

• IPRs
  – For much of the early period of IT industry’s development IPR policy largely a consequence of antitrust policy (e.g., licensing of semiconductor, computer patents).
    • Throughout the IT industry’s development during 1950-80, IPRs were relatively weak, encouraging new firm entry.
  – In chemicals, relatively strong IPRs supported the extensive licensing of technology that was associated with the growth of vertical specialization and the SEFs.
  – Strong IPRs support established-firm dominance in pharmaceuticals, but do not preclude entry by new firms in biotechnology.
    • Strong IPRs contribute to vertical specialization between biotechnology “research boutiques” and established pharmaceutical firms.
  – Formal IPRs of limited consequence in machine tools.
Recent US technology policy developments

• Change in US R&D policy since 1980 seems to contradict some of these policy implications:
  – IPRs have been strengthened.
  – Many US universities now patent faculty inventions (Bayh-Dole Act of 1980), which may limit the flow of the “open science” that is a critical complement to industrial innovation.
  – Emphasis on licensing also may impede collaboration outside of biomedical areas.
  – Competition policy is less stringent than during the 1950s – 1970s.

• The US industrial finance system that was cited as a source of strength during the 1990s contributed to the “dot.bomb” collapse and 00-01 recession.
  – Venture capital and new-firm formation contributed to “bubbles” and excess capacity.
Implications

• Competition among R&D funding sources, performers, commercial developers appears to be a critical component of a strong sectoral or regional innovation system.

• US universities’ role is linked to their unusual structure and external institutions.

• Emulation by other nations of US “Bayh-Dole” policies carries some risks.
  – May require complementary restructuring of higher education and R&D policies.

• Strong, broad patents may limit firm entry and the experimentation with technological alternatives that are of critical importance in the early years of a technology’s development. Caution is advisable.

• Scale of R&D programs, markets is important.