VERTICAL SPECIALIZATION AND INDUSTRY STRUCTURE IN HIGH TECHNOLOGY INDUSTRIES[☆]

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ABSTRACT

We examine the evolution of vertical specialization in three industries: chemicals, computers, and semiconductors. Vertical specialization is the restructuring of industry-wide value chains, such that different stages of the development, production, and marketing processes are controlled by different firms, rather than being vertically integrated within the boundaries of individual firms. In some cases, vertical specialization may span international boundaries and is associated with complex international production networks. After decades of vertical specialization, firms in the chemical industry appears to be re-integrating stages of the value chain. By contrast, the semiconductor and computer industries have experienced significant vertical specialization during the past ten years. We examine how and why these contrasting trends in vertical specialization have co-evolved with industry maturation and decline, and underscore the importance and role of both industry factors and business strategies necessary for

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industries to become more specialized. We also consider the effects of vertical specialization on the sources of innovation and the geographic redistribution of production and other activities. We conclude that the evolution of vertical specialization in these three industries has both reflected and influenced the strategies of leading firms, while also displaying industry-specific characteristics that are rooted in their different technological and market characteristics.

INTRODUCTION

The evolution of industry structure, especially in knowledge-intensive industries, has been the focus of a large scholarly literature during the past 50 years. Much of this literature argues that industries evolve through a process of "vertical specialization," characterized by the control by different firms of the stages of an industry "value chain," such as development, production, and marketing, rather than being vertically integrated within the boundaries of individual firms. The limited theoretical and conceptual literature on this process typically treats vertical specialization as a structural feature of industries that are relatively "mature," but rarely considers the influence of firm actions on the evolution of industry structure. Vertical specialization is also termed vertical disintegration, and often is associated with the entry of specialist firms into distinctive segments of the vertical value chain. In some cases, vertical specialization may span international boundaries and give rise to complex international production networks.

Although the argument that mature industries develop a vertically specialized structure dates back to Stigler (1951) who in turn credited Adam Smith with the basic idea, the factors underpinning this structural trend, as well as the extent to which vertical specialization accurately describes industry evolution, have received little attention. This paper examines the evolution (and reversal) of vertical specialization in three leading knowledge-intensive industries, focusing on the similarities and contrasts in the development of these industries and highlighting issues for managerial strategy and future research. As we note below, the chemical, computer, and semiconductor industries display some interesting contrasts in the pattern, pace and direction of vertical specialization in each industry's structure. The reasons for these differences merit further attention, not least because the emergence of vertically specialized industry structures can have significant consequences for industry location, competition and profitability.

Each of the three industries that we examine is characterized by levels of industry-funded research and development (R&D) that we associate with "high-technology" industries, but their age qualifies them as mature. The chemical industry dates back to the early 19th century, but the semiconductor and computer industries are more than 50 years old. All three industries display many of the hallmarks of maturity, including slower growth in industry revenues, reduced profitability and increased producer concentration. Despite these similarities, the pattern and pace of vertical specialization in each of these industries are distinct. These differences shed light on the dynamics of vertical specialization (and re-integration), and suggest that firm strategies influence the pace and in some cases can reverse the process of vertical specialization.

In chemicals, after years of vertical specialization, the industry has begun to separate into two distinct groups. Some established chemical firms are reintegrating stages of production in high value-added specialty chemicals, but a vertically specialized structure persists in other segments of the industry – notably in commodity chemicals – where specialized design and engineering firms (SEFs) remain important. By contrast, the semiconductor industry is "disintegrating" vertically, separating product design from manufacturing. Semiconductor manufacturing is increasingly concentrated in Southeast Asia, but design specialists and R&D remain concentrated in North America and Europe. Similarly to semiconductors, the computer industry has seen significant organizational and geographic separation of successive stages of production, as well as greater "vertical competition" and competitive encroachment on one another's markets by different computer platforms.

In spite of the contrasts among these three industries, common themes emerge from our analyses. Preconditions for the development of a vertically specialized industry structure are required, and include increased "codification" or dissemination of formerly tacit knowledge within an industry's value chain, the development of technical standards that promote stability and codification across interfaces, and a strong supplier tier. Vertical specialization has contributed to the "commoditization" of specific activities within value chains of all three of these industries, reducing entry barriers, attracting larger numbers of *de novo* entrants, and intensifying competition for industry incumbents. Vertical specialization also has been associated with considerable geographic redistribution of development and production activities in all of these industries. Nevertheless, a comparison of these three industries suggests that the process of vertical specialization affects and is affected by the strategies of entrant and incumbent firms, highlighting the interdependence of industry-wide trends in structure and firm strategy.

VERTICAL SPECIALIZATION AND INDUSTRY STRUCTURE

Vertical specialization can be examined from both industry and firm perspectives. Vertical specialization at the industry level may be defined as a shift from vertically integrated control of product value chains by the firm to a structure characterized by market-based coordination of the value chain among separate firms. In many cases, vertical specialization within an industry is accompanied by the entry of specialist firms.[1] Building on Adam Smith's analysis of the relationship between the "extent of the market" and the division of labor, Stigler (1951) argued that vertical specialization is closely related to the industry lifecycle:

> [I]f one considers the full life of industries, the dominance of vertical disintegration is surely to be expected. Young industries are often strangers to the established economic system. They require new kinds or qualities of materials and hence make their own; they must overcome technical problems in the use of their products and cannot wait for potential users to overcome them; they must persuade customers to abandon other commodities and find no specialized merchants to undertake this task. These young industries must design their specialized equipment and often manufacture it, and they must undertake to recruit (historically, often to import) skilled labor. When the industry has attained a certain size and prospects, many of these tasks are sufficiently important to be turned over to specialists. It becomes profitable for other firms to supply equipment and raw materials, to undertake the marketing of the product and the utilization of by-products and even to train skilled labor. And, finally, when the industry begins to decline, these subsidiary, auxiliary, and complementary industries begin also to decline, and eventually the surviving firms must begin to reappropriate functions which are not longer carried on at a sufficient rate to support independent firms.

According to Stigler, vertical specialization occurs during the early periods of growth within an industry, as specialized firms enter the production of components characterized by declining unit costs and a substantial minimum efficient scale of production. In the mature phase of industry evolution, re-integration is common, as market scale no longer supports vertically specialized firms.

A slightly different perspective on the evolution of industry structure is provided by Chandler (1977, 1990) in his work on the evolution of corporate organization in the United States and other industrial economies. For Chandler, the creation of large unified national markets in the United States and other economies, a result of advances in transportation and communications technologies (mainly the railroad and telegraph) was a necessary precondition (along with innovation in manufacturing technologies) for the emergence of the vertically integrated, multi-product corporation. The emergence of large markets accessible from one or a small number of manufacturing plants led to manufacturing operations of unprecedented scale and capital intensity in industries such as food processing, tobacco products and consumer durables. Forward vertical integration from production into distribution and marketing was essential, according to Chandler, to maintain high rates of capacity utilization in these large-scale production establishments. The expanding "extent of the market" thus triggered higher levels of vertical integration. Vertical specialization in the marketing and distribution of goods was replaced by vertical integration as the U.S. national market expanded and became more unified. But this sequence is nearly the opposite of that hypothesized by Stigler.

In his recent examination of the "post-Chandler" corporation, Langlois (2003) argues that further advances in communications and information technologies, along with the creation of stable technical interfaces and more "modular" product and process technologies (Baldwin & Clark, 2000; Garud et al., 2002; Langlois, 2002), have laid the groundwork for the "vanishing" of Chandler's "visible hand" in several industries. According to Langlois, the expanding flow and reliability of communications and information have once again elevated market mechanisms and specialists to central positions in the coordination of complex transactions among the stages of industry value chains. Under these conditions, the benefits of vertical integration are reduced, especially during the latter stages of an industry's development if certain industry preconditions are met.

In some industries, vertical specialization has been associated with the growth of international "intra-industry" trade, reflecting increased regional or national specialization in particular segments of the value chain. The vast increase in world trade among the industrial economies during the postwar period has been dominated by intra-industry trade in intermediate inputs, a phenomenon that also is apparent in the growth of foreign direct investment (FDI) during this period (Feenstra, 1998). Yi (2001) argues that growth in intra-industry trade reflects the outsourcing by multinational firms of input production to foreign affiliates, as well as the entry of specialized independent producers. Other empirical research indicates that vertical specialization accounts for about one-third of the growth in trade since 1970 (Hummels et al., 2001), although the extent of such vertical specialization varies considerably among countries and industries (Hummels et al., 1998).

Vertical specialization also has been associated with increased firm entry in a number of industries. Specialist firms may supply customers within the industry value chain or they may supply a broader array of customers in different industries. In some instances, such as the 19th-century machine tools industry (Rosenberg, 1963), the appearance of vertically specialized producers was associated with the growth of markets for a diverse array of user industries or firms. The "merchant" semiconductor industry in the U.S. during the 1950s and 1960s that served industries ranging from consumer electronics to computers, telecommunications and automobiles is another example of this type of vertical specialization. In other industries, however, vertical specialization is associated with an expansion in the scale but not the diversity of end-user demand, as in the specialized fabless product design firms and semiconductor foundries that grew rapidly in the United States and East Asia during the 1990s.

Vertical specialization typically emerges in response to some reduction in barriers to entry into specific segments of an industry value chain. But the entry of specialist producers may further erode entry barriers and reduce the value of capabilities or assets of vertically integrated firms within the industry. For example, the entry and rapid growth of specialized semiconductor manufacturing "foundries" both reflects and has contributed to the "commoditization" of the formerly proprietary process knowhow of vertically integrated semiconductor manufacturers, triggering additional entry and further reducing industry margins. A broadly similar dynamic is apparent in the history of the postwar chemical industry in the United States and Europe, as we note below. Finally, the relatively open architecture of microcomputers facilitated entry into computer hardware in the 1980s and 1990s and intensified competition among complementary component providers. In most cases, entry by specialist firms intensifies industry competition, resulting in lower prices and margins, and frequently, in more rapid introduction of new products and/or process technologies.

But vertical specialization does not appear to be an inevitable and irreversible component of industry maturation. The evolution of a number of industries, including hard disk drives (Christensen et al., 2002), computers (Fine, 1998) and semiconductor manufacturing equipment (Langlois, 2000), exhibits successive cycles of integrated and specialized business models. In addition, as Brusoni et al. (2001) and Granstrand et al. (1997) emphasize, as industries shift to a vertical specialized structure, firms that "outsource" various operations need to retain detailed knowledge of the technologies and inputs affected by such outsourcing. For this reason, these authors argue that firms, especially those involved in systems-integration activities (e.g. airframe firms, automobile assemblers, etc.) must "know more than they make" (i.e. their technological capabilities must span a broader range than those required for their production operations). Among other things, this view also indicates that the concept of "core competences" must be defined relatively broadly to include bodies of knowledge relevant to outsourced activities.

Theoretical and empirical examinations of vertical specialization at the firm level often emphasize the roles of different exchange attributes in determining the optimal boundaries of the organization, and highlight a more contingent process of industry evolution. Transaction cost economics (TCE) in particular argues that boundary choices are driven largely by the specificity of assets involved in an exchange (Williamson, 1985, 1991). In the presence of exchange-specific assets, vertical integration provides certain safeguards against the threat of opportunistic behavior from trading partners (Williamson, 1979, 1985). A different approach, often characterized as the knowledge-based view of the firm (KBV), instead argues that conducting certain activities within the firm enhances the efficiency with which these activities can be coordinated via shared languages, knowledge and routines (Conner & Prahalad, 1996; Grant, 1996; Kogut & Zander, 1992, 1996).

Both of these approaches nevertheless emphasize the factors that facilitate or impede coordination among specialist producers within a value chain as important influences on the emergence or decline of vertical integration and specialization (Chesbrough & Teece, 1996; Langlois, 2000; Sanchez & Mahoney, 1996; Teece, 1986). Integrated companies may be superior to vertical specialists in managing "systemic" innovation that affects overall design or systems-level characteristics. By contrast, autonomous innovation (e.g. technical change in a component) requires less coordinated adaptation and therefore may be handled more efficiently by vertically specialized producers (Teece, 1996). Re-integration may be necessary, however, if and when specialist firms are forced to redesign their products by integrating previously modular components in novel ways in order to achieve higher performance (Christensen et al., 2002). Although appealing, these propositions have not been widely or rigorously tested (Macher, 2003; Monteverde, 1995), reflecting the difficulties and subjectivity in characterizing innovation as either "systemic" or "autonomous." If the interface between successive stages of production is not technically stable or well-specified, the costs and difficulty of interaction and communication among these stages will increase, and integration may be a more effective mode of organization (Monteverde, 1995).

Nonetheless, vertical integration can increase costs, reflecting higher levels of intrafirm bureaucracy and other costs (Fama, 1980; Jensen & Meckling, 1976). Input prices for vertically integrated producers also may be higher because of a lack of competition among such suppliers (D'Aveni & Ravenscraft, 1994). The potential problems of inflexible commitments associated with highly specialized activities (Thorelli, 1986) limits in the speed or timing of adaptation to changing circumstances (Langlois, 1992; Teece, 1996), or "span of control" problems associated with the management by a centralized organization of many stages of production, marketing, and distribution (Stuckey & White, 1993), have led these and other scholars to argue that firms should outsource "non-core" activities. Such outsourcing obviously creates opportunities for the development of vertical specialization in a given industry (Prahalad & Hamel, 1990). But theory has thus far failed to develop robust criteria for predicting the locus and sustainability of "core competences."[2]

A similar theoretical indeterminacy is apparent in firm-level analyses of the extent to which vertical specialization is self-reinforcing, or the effects of vertical specialization and any associated relocation of production activities on the location of other activities, such as R&D. The basic argument rests on assumptions about the nature of "spillovers" of knowledge or other capabilities among segments of the value chain. If these spillovers are important, then firms or regions specializing in one activity may develop capabilities in others. If such spillovers are of little consequence, the vertical separation of activities within the value chain should be relatively enduring, and specialization in one activity, such as manufacturing, should have limited consequences for the ability of specialist firm to expand its activities in product development. This argument applies as well to the analyses by Brusoni et al. (2001) and Granstrand et al. (1997) – if knowledge-based spillovers among activities are important, it may be very difficult for firms to maintain a position in which they "know more than they make."

The importance or extent of such spillovers also may change as a result of innovations in product design and production technologies, thereby making it possible for production specialists to develop the capabilities to enter other segments of the value chain. Discussion of this issue has been inconclusive for reasons similar to those limiting progress toward a theoretical understanding of "core competences." Measures and predictive models of the importance, direction and sustainability of knowledge and other "spillovers" among value-chain segments are lacking, as are predictive models of the dynamics of regional agglomeration. As we note below, some deeper understanding of this issue is necessary to evaluate the consequences of any geographic redistribution of activities associated with vertical specialization.

These firm-level analyses of vertical integration and outsourcing have important implications for the industry-wide phenomenon of vertical specialization. First, as knowledge linking successive stages of the value chain becomes codified and therefore subject to wider dissemination, the feasibility and cost-effectiveness of vertical specialization should increase. Second, the development of *de facto* or formal technical standards promotes stability and codification in important technical interfaces that may in turn serve as the basis for entry by specialized producers. Both of these factors suggest that the development of a modular technological interface (Baldwin & Clark, 1997; Sanchez & Mahoney, 1996; Ulrich, 1995) may provide sufficient information for markets in complex inputs to function efficiently, creating opportunities for the entry of specialized suppliers.

The factors emphasized by Chandler, especially ease of communications and transportation, also are relevant, but their significance and specific implications for vertical specialization appear to have shifted over time. The advances of the 19th century in telegraphy and reliable, all-weather transportation created preconditions favorable to vertical integration. But the rapid growth since 1945 in "intra-industry" trade, often associated with vertical specialization, has relied on precisely the types of global transportation and communications links that Chandler emphasized in his discussion of the development of industrial economies during the late 19th and early 20th centuries. And widespread adoption of information technology (IT), including electronic commerce and other Internet applications, has facilitated further vertical specialization by supporting more complex arms-length transactions and extending modular technological interfaces in many industries (Scupola, 2002; Slywotzky et al., 2000).

Vertical specialization also facilitates the exploitation of scale and scope economies in manufacturing. Firms that outsource manufacturing to specialists may be able to reduce production costs respond more quickly to changes in demand. These firms also may be able to access larger and more diverse supply bases or play off suppliers against one another. Specialized firms that do not conduct large-scale manufacturing operations may more effectively focus on areas of competitive advantage, such as product definition and development. Firms may also be able to access more diverse competencies or build competencies in particular areas in comparison to integrated firms through increased specialization (Langlois & Robertson, 1992).

INDUSTRY ANALYSES

Drawing on the discussion above and empirical analyses of each industry, we take an inductive approach below in analyzing the evolution of vertical specialization in the chemical, semiconductor, and computer industries. For each industry, we examine how and why contrasting trends in vertical specialization co-evolve with industry maturation and decline. We provide an historical overview of the organization of each industry, which helps us underscore the importance and role of both industry factors and business strategies necessary for industries to become more specialized or integrated. We also consider the effects of vertical specialization on the sources of innovation and the geographic redistribution of production and other activities in each industry study. Finally, we consider the evidence from these three industries on the question of the "inevitability" of vertical specialization in industry evolution. In particular, we discuss the specific preconditions for vertical specialization and the extent to which firm-level decisions to outsource specific activities create irreversible trends toward further vertical specialization.

We note here and in the discussion section that a consistent outcome of vertical specialization in each of the industries examined has been the "commoditization" of specific activities within the value chain, typically characterized by the *de novo* entry of specialized firms. At the same time, however, both the chemical and semiconductor industries have evolved into a two-tiered industry structure, whereby one segment, populated by integrated firms, competes (and often collaborates) with the vertically specialized firms in the other segment. One of the most interesting findings of these firm-level strategic decisions is the changing geographic pattern of production and R&D activity in each of these industries. The evolution of vertical specialization in the three industries examined has both reflected and influenced the strategies of leading firms, while also displaying industry-specific characteristics that are rooted in their different technological and market characteristics.

The Chemical Industry

One of the defining differences between U.S. chemical firms and those in Germany and Great Britain from the 1920s through the 1950s was their use of different feedstocks – petroleum in the U.S.; coal in Great Britain and Germany – based on the natural resource endowments of each region. These differences in feedstocks had profound implications for the evolution of product and process capabilities within the firms of each region, and for the development of a vertically specialized structure in the global chemical industry.

The U.S. market for chemical products during the 1920s and 1930s was the largest single national market in the global economy, and in the face of political tensions and economic and financial disruptions to international trade flows, the scale of domestic market demand assumed great importance for firm strategies and patterns of innovation. In addition, the U.S. market was dominated by the rapid growth in the automobile industry's demand for chemicals (e.g. paints and finishes), and the rapidly expanding demand of U.S. automobile owners for gasoline (Mowery & Rosenberg, 1998). Faced with this rapidly expanding market for a relatively homogeneous mix of products, U.S. chemical firms, long known for their design of production plants of large scale (Rosenberg, 1998; Trescott, 1982), pursued the development of continuous-process technologies for manufacturing gasoline and other petroleum-based products. Their efforts benefited from and contributed to the development of chemical engineering, a new academic discipline for the design, construction, and management of these manufacturing processes and facilities. Advances in oil exploration and extraction technologies expanded domestic supplies of petroleum, and U.S. chemical firms focused their scale-intensive efforts in process innovation on the use of this new feedstock. In contrast to the "batch" manufacturing processes that relied on coal tar-based feedstocks, the new petroleum-based manufacturing technologies were continuous-process technologies, which led U.S. firms to build plants of unprecedented scale. The pioneering efforts of U.S. chemical firms to exploit petroleum feedstocks received an additional impetus from wartime demand for aviation fuel during the 1940s.

The development of a "science of process engineering" for the chemical and petrochemical industries, along with the demands of wartime mobilization in the United States for a huge expansion in production capacity for chemicals and fuel, contributed to the growth of a new group of firms, the specialized engineering firms (SEFs), who designed and built large-scale chemical production facilities that relied on petroleum feedstocks. A number of the first SEFs were founded during the 1930s as plant-construction contractors with particular expertise in the scale-intensive petrochemical plants brought into operation during this period by Standard Oil of New Jersey and other firms. In the course of designing and building chemical plants, an area of limited expertise for chemical and petroleum firms, SEFs developed expertise in process innovation. The process expertise of SEFs was further enhanced by the huge wartime plant-construction programs coordinated by the U.S. government, many of which mandated extensive cross-licensing among chemical and petrochemical firms, and between chemical firms and SEFs. The resulting structure of vertical specialization in process and product innovation had important implications for the interfirm transfer and diffusion of process technology within the global chemical industry, and eventually, for entry by firms from other nations.

Specialized engineering firms helped create a global market for process technologies during the 1950s and 1960s, especially in processes used to produce basic and intermediate chemicals. Entry by both British and German chemical firms into the production of petroleum feedstock-based chemicals in the late 1950s and 1960s relied on this global market for process technology. The continuing diffusion of chemical process technologies to firms in other industrial economies and, by the 1970s, to firms in developing economies, created significant competitive challenges to U.S. and European chemical firms in the 1970s and 1980s.

Vertical Specialization and "Re-Integration" into Specialty Chemicals

During the 1950s, the technology licensing activities of specialized design and engineering firms facilitated entry into the chemical industry (especially petrochemicals) by a number of new chemical producers. By the 1960s, SEFs dominated the design and construction of new plants and were important sources of process technology (Mansfield et al., 1977). Their involvement in the construction of a large number of chemical and petrochemical plants meant that SEFs accumulated process knowhow through learning, while enjoying other scale-related advantages from selling their expertise to a rapidly growing client population. Arora and Fosfuri (2000) report that SEFs accounted for 36% of all new chemical process technologies incorporated into new plants constructed during the 1980s, well above the share of chemical technologies developed in-house by established chemical firms (21%). Another 43% of new process technologies, however, were developed and licensed out by established chemical firms. SEF-led licensing encouraged entry into the production of bulk chemical products, which subsequently reduced the strategic importance of process technology knowhow for established producers.

In addition to supplying process knowhow, many SEFs acted as licensors to chemical firms. Expanded licensing by SEFs drew established, vertically integrated chemical and petrochemical firms into licensing as well, and SEFs often acted as the licensing agents for these firms.[3] The development of markets for chemical process technologies expanded the contribution of licensing to overall revenues for many established chemical firms (Arora & Fosfuri, 2000).

Although the importance of SEFs in chemical plant construction and technology development increased during 1945–1990, their role differed significantly among geographic regions. Evidence from Arora and Fosfuri (2000) indicates that from 1980 to 1990, firms in North America and Europe relied on in-house expertise for the construction of nearly 40% of the new chemical plants built during this period, whereas chemical producers in less developed regions, including Eastern Europe, Africa, Middle East and South America, relied on SEFs for the construction of 95% of their plants. Large chemical corporations from advanced countries licensed less than 50% of their technology (by value) from licensees, relying instead on in-house sources for the majority of their technology. In contrast, developing-economy chemical producers relied almost entirely on SEFs (45%) and chemical producers from developed countries (53%) for their technology development and acquisition needs. SEFs were most important in supplying process technology in sectors of the chemical industry with large production facilities, relatively homogenous products and large numbers of new plants. The SEFs played a less prominent role in sectors of the industry characterized by significant product differentiation, custom tailoring of product markets, and small production scale (Arora & Fosfuri, 2000); see Fig. 1).[4]

Increased entry into chemical production, much of which was facilitated by SEFs, intensified competition for established chemical firms. The competitive consequences of entry for these firms were exacerbated by the broader slowdown in economic growth and higher feedstock prices that resulted from the 1973 oil shock. In response to the declining profitability of commodity chemicals, leading North American and European chemical firms entered into a prolonged process of restructuring in the 1980s and 1990s. Several traditional chemical companies, including Du Pont, Hoechst and ICI, exited from commodity chemical businesses and expanded their presence in markets where product differentiation, based on quality and/or performance, allowed for higher margins.

The chemical industry of today is characterized by greater product specialization at the firm level, with some firms focusing on high-value specialty chemicals

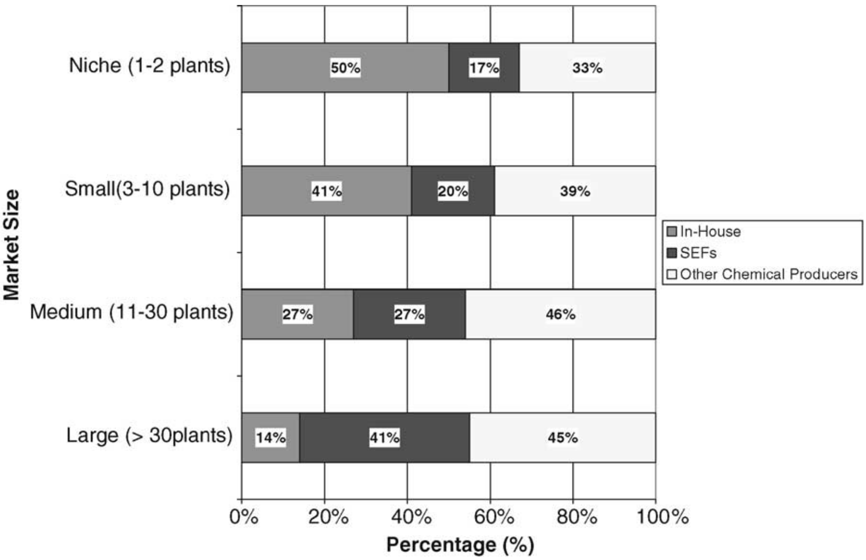

Fig. 1. Chemical Technology Market Share by Product Market Size. *Source:* Arora and Fosfuri (2000).

and other firms retaining a focus on large-volume commodity chemicals. The firms that have shifted their product portfolios to specialty chemicals, however, have re-integrated their process and product technology development activities, reversing the decades-old trend toward higher levels of vertical specialization. These shifts in chemical firm strategies have reduced the profitability of SEFs in recent years.

Geographic Patterns and Regional Differences

The international technology transfer promoted by SEFs significantly altered the geographic distribution of capacity investment in the chemical industry during the last quarter of the 20th century. Eichengreen (1998) reports that the share of world exports originating in the developed countries – including the U.S., Britain, Germany and other Western European countries – shrank from more than 80% in 1899 to less than 45% by 1993, whereas developing economies expanded their share of exports from a mere 5.2% in 1899 to more than 33% in 1993. Arora et al. (2001) also show that growth in the number of developed country SEFs during 1980–1990 increased the number of developing-economy chemical plants, most of which licensed process technologies rather than internally developing them. SEFs were particularly prominent technology licensors in the developing countries of India, China, and Brazil.

Summary

Vertical specialization grew significantly in the postwar global chemical industry during 1945–1985, but this trend was reversed to a considerable degree during 1985–2000. Vertical specialization was both a cause and an effect of the emergence and growth of specialized engineering firms (SEFs). The entry of SEFs led vertically integrated firms to utilize SEFs' services and to increase their licensing activities. Expanded international flows of licensed technology and increased entry into chemical production increased pressure on the competitiveness of the firms that had dominated the chemical industry for much of period between 1900 and 1945. As the once-dominant integrated chemical producers began to lose market share, they exited low-margin products, restructuring their operations and re-integrating their product and process development activities. As a result, the importance of vertical specialization in general and SEFs in particular has declined in the chemical industry since 1985. Chemicals is thus an industry that has reversed a trend toward increased vertical specialization in the face of rapid growth in the "extent of the market," contradicting both Stigler and Smith.

The Semiconductor Industry

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 & MacDonald, 1978). During the late 1950s, "merchant" manufacturers entered the U.S. 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 in the industry by the early 1960s.

The strong interdependence between product design and process innovation (Pisano, 1997) that existed during this period meant that leading firms developed their product and process technologies internally, relying heavily on firm-specific, tacit knowhow. During the past 15 years, the interdependence between product design and process development has weakened considerably in many semiconductor product fields. This weaker interdependence has enabled specialist firms to enter into the design (and marketing) of semiconductor devices, and other specialists to enter the manufacture of semiconductor devices meeting the design specifications of these “fabless” firms and others. Entry by specialized firms has further weakened the formerly strong links between process and product development in some product lines, thereby accelerating the trend.

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. 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. Fabless firms’ share of global semiconductor industry revenues has grown from a negligible amount in 1989 to almost 12% of the industry by 2002. During the past five years, fabless revenues have grown at a 15% compound annual growth rate, compared with a 1% growth rate for overall semiconductor industry sales (Arensman, 2003).

Foundries, by contrast, specialize in semiconductor manufacturing. This group includes “pure-play” foundry firms, as well as the foundry subsidiaries of some established integrated semiconductor manufacturers seeking to utilize their excess fabrication capacity. Just as was true of chemicals, increased vertical specialization in the global semiconductor industry has resulted in the entry of numerous new firms and has been associated with significant geographic redistribution in production capacity.

Vertical Specialization in Product and Process Development

The growth in vertical specialization in semiconductors since 1985 reflects the influence of both market-related and technological factors. The expansion of markets for semiconductor devices enabled vertically specialized semiconductor design and production firms to exploit economies of scale and specialization, consistent with the predictions of Stigler and Smith. Scale economies lowered production costs, expanding the range of potential end-user applications for semiconductors and creating additional opportunities for entry by vertically specialized firms. The increasing capital requirements of semiconductor manufacturing provided another impetus to vertical specialization, since these higher fixed costs make it necessary to produce large volumes of a limited array of semiconductor components in order to achieve lower unit costs. The design cycle for new semiconductor products also has become shorter and product lifecycles more uncertain, making it more difficult to determine whether demand for a single product will fully utilize the capacity of a fabrication facility that is devoted exclusively to a particular product and increasing the risks of investing in such "dedicated" capacity. Since foundries tend to produce a wider product mix, they are less exposed to these financial risks.

The emergence of vertical specialization in semiconductors has been facilitated by at least three technological factors. Through a process of competitive selection played out over several years, manufacturing technologies have "converged" on standardized Complementary Metal Oxide Semiconductor (CMOS) processes for the manufacture of "mainstream" digital products. The emergence of this "process standard" has facilitated the division of labor between product designers, who are able to operate within relatively stable design rules, and process engineers working to incrementally improve new process technologies (Macher et al., 1999). Significant improvements in design software for the layout and simulation of novel semiconductor products have increased the computer-simulation capabilities available to product designers for evaluating the performance of novel circuits prior to production. Powerful electronic design automation (EDA) tools and cell libraries also support the design of more complex chips. A final factor supporting greater vertical specialization within the industry is the entry of specialized providers of semiconductor designs and EDA software, as well as systems houses that compete in the provision of intellectual property (IP) design blocks and system-on-chip (SOC) technology, licensing their designs (known as "IP blocks," "design cores," or "virtual components") for specific parts of a semiconductor device. Revenues associated with licensing, royalties and service/maintenance in markets for IP blocks and design cores have grown from roughly $17 million in 1995 to $933 million in 2002 (Clarke, 2003).

Other technological innovations have also contributed to vertical specialization in the semiconductor industry. The "open-standards" PC architecture that was the fastest-growing market for semiconductor components during the 1980s and 1990s created standardized interfaces among components (see below), which in turn facilitated the specialized production of individual components and vertical specialization in component design. This pattern of vertical specialization seems entirely consistent with the "extent of the market" predictions of Stigler and Smith. The advent of partially programmable semiconductor devices now allows semiconductor designers to incorporate increasing levels of functionality onto devices (system-on-a-chip technology) without sacrificing the applications flexibility required of a true "systems" product. Advances in computer-aided design (CAD) software and tools, as well as high-bandwidth digital communications networks, also facilitate the exchange of huge amounts of data among design specialists and between fabless design firms and manufacturing foundries.

At the same time, however, a number of large semiconductor firms remain integrated into both semiconductor device design and manufacture, and are now referred to as "Integrated Device Manufacturers" (IDMs). The advantages of integrated management of design and manufacture appear to be greatest in product lines at the leading edge of semiconductor technology, especially in DRAMs (Macher, 2003). In these areas, the demanding requirements for close coordination of design and process innovation mean that intrafirm management of these activities provides advantages in flexibility, responsiveness, and the "debugging" of new manufacturing methods. Demand growth and larger markets thus appear to be necessary conditions for the success of vertical specialization in semiconductors, but they are by no means sufficient.

Vertical specialization in the semiconductor industry has been associated with expanded licensing and interfirm transfers of technology, but the timing and pattern of these technology transfer channels differ somewhat from the chemical industry. During the 1970s and 1980s, U.S. IDMs were important sources of product and process technologies for less advanced semiconductor firms in Japan and South Korea, while U.S., Japanese and European IDMs supplied process and product technologies to Taiwanese and Singaporean foundry firms during the 1980s and 1990s. Many IDMs established relationships with foundries during the semiconductor market boom of the late 1990s, providing process technologies to foundries in exchange for guaranteed wafer supply. The development of a robust semiconductor intellectual property (IP) market also has spurred growth in the number and importance of specialized design firms. In some contrast to the chemical industry, however, product and process licensing in the semiconductor industry has facilitated entry by both vertically specialized and integrated firms.

Geographic Patterns and Regional Differences

Although regional specialization by product and stage of the manufacturing process has characterized the semiconductor industry for most of its history, the growth of foundry production has extended these trends. Since the early 1980s, roughly 85% of packaging and testing capacity in the semiconductor industry has been concentrated in Southeast Asia (Leachman & Leachman, 2001). Since the capital investment requirements for packaging and test activities are roughly one-tenth those of wafer fabrication, however, the networks developed around packaging and testing involve much more modest flows of investment than the more recent expansion of fabrication capacity in this region.

Wafer fabrication capacity (measured in terms of memory bits and logic gates[5]) in the global semiconductor industry grew at an average rate of 36% per year during 1980–2001 (Leachman & Leachman, 2001). Growth in overall capacity was combined with the retirement of substantial amounts of "mature" capacity, reflecting the effects of rapid technological change. Since much of the investment in new capacity occurred in Southeast Asia and much of the retirement of capacity occurred in Japan and North America, the regional distribution of semiconductor manufacturing capacity has shifted considerably over the past 20 years. The North American and Japanese shares of global semiconductor production capacity fell significantly during 1980–2001, while the share attributable to "Asia/Pacific" has substantially increased (Leachman & Leachman, 2001), reflecting significant net expansion in capacity in Taiwan, South Korea and Singapore.

A reclassification of manufacturing capacity by region of ownership rather than location reveals a slightly different geographic pattern. Although Southeast Asian firms still account for the largest share of fabrication-capacity ownership, they are followed closely by North American producers (Leachman & Leachman, 2001). This pattern reflects the relocation of wholly-owned production capacity by North American, Japanese, and European firms to Southeast Asia since the mid-1990s. Southeast Asian firms, on the other hand, have tended to invest primarily within their home regions during this period.

The growing concentration of manufacturing capacity in Southeast Asia in general and Taiwan in particular is attributable in large part to the success of the foundry business model. Leachman and Leachman (2001) indicate that foundries' worldwide fabrication capacity has risen from 8% in 1990 to nearly 25% by 2001, with "pure-play" foundries supplying roughly 75% of the worldwide foundry market and IDMs accounting for the remainder. Foundry revenues represent a growing portion of overall industry sales and approached $10 billion in 2000 (McClean, 2001). Pure-play foundries' manufacturing capabilities still lag those of the most advanced integrated manufacturers in Korea, Japan and the United States, but this gap has narrowed and continues to do so (Macher et al., 1998).

Although semiconductor manufacturing has become a more global enterprise, semiconductor design activities remain heavily concentrated within North America. A number of factors help explain North American dominance of semiconductor product design. Established regional high-technology clusters in areas such as Silicon Valley, Boston's Route 128, and Austin, Texas attract large numbers of product designers. These centers are often located near universities and other research centers that produce new design techniques and engineering talent. The role of U.S. universities in developing new design software and chip architectures has long outstripped their role as a source of new manufacturing methods, in part because the cost of constantly re-equipping the necessary facilities exceeds the resources of most academic institutions.

Fabless design firms remain concentrated in North America, although nearly 1,000 fabless firms are operating in two dozen countries outside of this region (see Table 1).[6] Most of the non-U.S. fabless firms are relatively small in global terms, but Table 1 suggests that several non-U.S. concentrations of design expertise, largely concentrated in fabless firms, have emerged in the 21st century, mainly in Israel, Taiwan and the United Kingdom. Many of these non-U.S. fabless firms represent

Table 1. Fabless Firms by Country of Location (2002).

Top Countries	Fabless Firms	To Non-U.S. Cities	Fabless Firms
U.S.	475	Tel Aviv, Israel	14
Canada	30	Ottawa, Canada	13
Israel	29	Hsinchu, Taiwan	13
Taiwan	22	Seoul, South Korea	9
U.K.	22	Taipei, Taiwan	8
South Korea	13	Toronto, Canada	8
Germany	8	Cambridge, England	4
France	6		
Japan	5		
Sweden	5		
Switzerland	4		
India	3		
Spain	3		
Others	15		
Total	640		

Source: Arensman (2003).

North American off-shore design centers, but roughly half are from companies based outside the United States and Canada. Many of these non-North American regional centers offer significant pools of engineering design talent that is far less expansive than North American semiconductor designers. The growth of non-North American fabless semiconductor firms therefore could portend some shifts in design employment away from the United States.

The most advanced foundries are located primarily in the Southeast Asian countries of Singapore and Taiwan. If these countries remain the leading site for pure-play foundries, continued growth of the fabless/foundry model could result in substantial migration of semiconductor manufacturing employment from the United States to Southeast Asia. Nevertheless, a few Taiwanese firms have opened foundries in the United States. Moreover, Taiwan's dominant position in the foundry industry faces significant competition from lower-cost production sites in other areas of Southeast Asia and elsewhere. Indeed, Malaysia and the People's Republic of China are widely cited as important future sites for foundries.

The separation of design and manufacturing activities in the semiconductor industry thus appears to have produced geographic separation of design and production activities. Although there is some evidence of a similar geographic separation occurring in chemicals, the patterns in semiconductors are more dramatic and raise an important issue not treated in most analyses of vertical specialization – how do the "spillovers" and other links among the stages of an industry's value chain that are organizationally and potentially geographically separated influence future growth in vertical specialization within an industry? Obviously, the sustainability of both the "fabless" and "foundry" business models is based on the limited interdependence between these stages in the semiconductor industry's value chain in some product areas. But the dynamic effects of the shift of a growing share of the global semiconductor industry's production capacity to Southeast Asia are much more difficult to predict.

The long-term effects of expansion in the fabless/foundry model on the geographic location of manufacturing capacity and employment thus are uncertain, but on balance, growth in foundries is likely to result in the movement of production capacity and employment from the United States, Japan, and Europe to Taiwan, Singapore, Malaysia and mainland China. Even more uncertain are the effects of shifts in the regional distribution of production activity on the global distribution of semiconductor design and technology development activities. At present, the agglomeration economies that have supported the regional concentration of device design and R&D in a few areas around the globe remain strong, a situation that is similar to that of the chemical industry.

Nevertheless, the agglomeration effects that have sustained North American dominance of R&D employment in the semiconductor industry may weaken as the geographic dispersion of semiconductor design and manufacturing activities grows. There is little evidence from the history of the chemical industry that the entry of new producers in offshore locations shifted the geographic distribution of more knowledge-intensive activities, but the characteristics of the product-process technology linkage in semiconductors may be different. Very little research has attempted to compare such cross-industry differences in knowledge spillovers among stages of the value chain, despite the importance of these spillovers for long-term trends in vertical specialization and change in the location of high value-added activities within these or other knowledge-intensive industries.

Summary

The structure of the global semiconductor industry has shifted from one dominated by vertical integration to a more complex structure that blends vertical specialization and vertical integration. Specialized design and manufacturing firms have entered the industry in large numbers, and the growth of "foundry" firms has been associated with a substantial shift in production capacity investment to Southeast Asia. In semiconductors, like chemicals, vertical specialization has facilitated the entry of new firms, many of which are located outside of the regions that were homes to established firms. But like chemicals, the greatest effects of vertical specialization in shifting industry location thus far appear to be in the location of production, rather than product design and R&D, activities. In many respects, the history of vertical specialization in the semiconductor industry is a textbook illustration of the effects of growth in the "extent of the market" on the entry of specialist firms. Nonetheless, thus far there are limits to the operation of the vertically specialized structure within semiconductors, as "bleeding-edge" products still require the integration of product design and process technology development.

An interesting contrast between vertical specialization in semiconductors and chemicals concerns the role of technology licensing in the development of this industry structure. As we noted earlier, both of these industries are relatively "mature," in that both industries have been in existence for decades, their markets are global, and entry has slowed somewhat. In chemicals, vertical specialization both caused and was accelerated by the technology licensing efforts of the SEFs and the integrated major firms. In semiconductors, however, arms-length technology licensing has been less common, and considerable interfirm technology transfer has taken place. But the primary sources of the process technology transfers in semiconductors have been established integrated producers, rather than the specialist firms. In contrast, the recent growth in markets for "design cores" and product-related IP has been spurred by growth in the number of "fabless" design specialists, although the interfirm technology transfers that characterize these transactions deal in component technologies, rather than "turnkey" design packages.

The Computer Industry

The evolution of industry structure in computers closely resembles that of the semiconductor industry but differs somewhat from chemicals. We focus our discussion of vertical specialization in computers on the "vertical" separation of hardware and software that began during the late 1960s in the United States and consider the evolution of vertical specialization within the desktop computer industry. This summary highlights an important contrast between this industry and the chemical and semiconductor industries: vertical specialization within the computer industry reflected the emergence of stable interfaces among the various components of the product, rather than the development of a robust separation of product and process technologies. As has been the case in chemicals and semiconductors, however, vertical specialization in computers has shifted the sources of profits and the primary locations for production.

The concept of computer software as a distinguishable component of a computer system was effectively born with the advent of the von Neumann architecture for stored-program computers in the late 1940s. But the development of a U.S.

software industry really began after computers appeared in significant numbers. The large commercial market for computers that was created by the IBM 650 provided strong incentives for the computer industry to develop standard software for this architecture. Along with the development by IBM and other major hardware producers of standard languages such as COBOL and FORTRAN, widespread adoption of a single platform contributed to growth in “internal” software production by large users. But the primary suppliers of the software and services for mainframe computers well into the 1960s were the manufacturers of these machines. In the case of IBM, which leased many of its machines, the costs of software and services were “bundled” with the lease payments.

By the late 1950s, however, a number of independent firms had entered the custom software industry. Some service bureaus that had provided users with operating services and programming solutions began to unbundle their services from their software, providing yet another cohort of entrants into the independent development and sale of traded software. Sophisticated users of computer systems, especially users of mainframe computers, also developed expertise in the creation of solutions to their applications and operating system needs. A number of leading U.S. suppliers of traded software were founded by computer specialists formerly employed by major mainframe users.

Steinmueller (1996) argues that several factors contributed to the development of a large independent software industry in the United States during the 1960s. IBM’s introduction of the System/360 in 1965 provided a single mainframe architecture that utilized a standard operating system spanning all machines in this product family. This development increased the size of the installed base of mainframe computers that could use packaged software designed to operate specific applications, and made entry by independent developers more attractive. In addition, IBM “unbundled” its pricing and supply of software and services in 1968, a decision that was encouraged by the threat of federal antitrust prosecution.[7] The “unbundling” of its software by the dominant manufacturer of hardware (a firm that remains among the leading software suppliers worldwide) provided opportunities for the growth of independent software vendors. Finally, the introduction of the minicomputer in the mid-1960s by firms that typically did not provide “bundled” software and services opened up another market segment for independent software vendors. As a result, a vigorous industry of “independent” software vendors began to develop in the United States during the 1970s. Nonetheless, IBM, the leading global computer systems firm, remains a very important source of commercial software to this day. Its software revenues were larger than those of Microsoft, the leading independent software vendor, until 1997. Computer software, like chemicals and semiconductors, thus is produced by both vertically integrated and specialized commercial vendors.

Rapid diffusion of low-cost desktop computer hardware, combined with the emergence of a few “dominant designs” for this architecture, eroded vertical integration between hardware and software producers and opened up significant commercial opportunities for independent software vendors (ISVs) by the early 1980s. The ISVs that entered during this period were largely new to the industry. Few of the major suppliers of desktop software came from the ranks of the leading independent producers of mainframe and minicomputer software, and mainframe and minicomputer ISVs are still minor factors in desktop software. A growing installed base of ever-cheaper computers has been an important source of dynamism and entry into the traded software industry, because the rapid expansion of market niches in applications has outrun the ability of established computer manufacturers and major producers of packaged software to supply them.

The development of the personal computer in the early 1980s also had significant implications for vertical specialization in computer hardware. The relatively rapid standardization of the “dominant design” of desktop computers in the United States around the “Wintel” (Windows/Intel) architecture not only created a huge market for vertically specialized producers of “packaged” software, but also opened up large markets for microcomputer components. As in the other industries discussed in this chapter, the strategies of leading firms influenced the development of vertical specialization in the PC industry. IBM’s decision to rely on external vendors for the operating system and microprocessor in its development of an “entry-level” desktop computer contributed to the creation of an architecture dominated by product standards controlled by suppliers of these critical components, rather than by the leading systems producer (Bresnahan & Malerba, 1999). Although the “Wintel” standard relied on a proprietary architecture, the system-level architecture of the PC that became the dominant design was open, and characterized by stable and clearly defined interface standards. This “modular” systems-level architecture, along with the rapid growth of markets of unprecedented size, created opportunities for entry by producers of specialized components and peripherals (Bresnahan, 1998).

Vertical specialization now characterizes all computer hardware product platforms – markets for components span the full spectrum from desktop to supercomputer systems, although the demands for systems integration clearly are greater at the performance frontier (Bresnahan & Malerba, 1999). In addition, the locus of rent generation has shifted from hardware to software and services. Computer hardware for most widely utilized systems is largely “commoditized,” with relatively little differentiation among producers and narrow margins (Sturgeon, 2002). Perhaps most importantly, smaller computers can now be networked together through “client-server” or related configurations and open interface standards. In its most common form, firms and technologies from the PC segment supply "clients," which are then networked to other products and technologies, generally termed "servers," from the organizational computing segment.

Open interface standards have allowed entrants to offer new technologies, applications or systems by developing and producing hardware and software (hardware manufacturers), by integrating different parts of the system for specific applications (systems integrators) or by offering specialized software for specific applications. Not surprisingly, the growth of computer networking through client-server architectures has intensified competition between networks of PCs and minicomputers and mainframes.

Vertical Specialization in Computer Software and Hardware

Vertical specialization in the computer industry has resulted from the same expansion in the "extent of the market" that influenced the growth of vertically specialized firms in both chemicals and semiconductors. The appearance of a truly mass market for desktop computer systems in the 1980s transformed the opportunities for producers of "complements," be they software or hardware components, to enter the industry. But the technological dynamics of vertical specialization in computers differ from those in chemicals and semiconductors. In contrast to these industries, vertical specialization in computers did not reflect the development of a stable separation of process and product technologies. Instead, the development of "modular" product architectures proved to be the key technological factor facilitating vertical specialization in computers.

The development of vertical specialization in personal computers was only the most dramatic appearance of a trend that was immanent in the earlier history of the computer hardware industry. IBM's introduction of the System 360 in 1965 created an architectural standard that was nearly as dominant within the mainframe industry of the 1960s and 1970s as the PC proved to be during the 1980s. And the 360s dominance created opportunities for entry by vendors of 360-compatible peripherals and components, as well as producers of software that competed directly with IBM products. But the 360 obviously differed from the PC in that IBM maintained complete control of the architecture and component interfaces. The introduction of the PC thus created a situation of rapidly expanding demand, proliferating applications, and clearly defined architectural standards and interfaces under the control of no single firm, all of which favored the entry by vertically specialized firms. But here too, firm strategy was essential to the development of vertical specialization. Had IBM adopted a different strategy for developing the PC, had IBM negotiated more restrictive licensing arrangements with the suppliers of the critical components for the PC, or had IBM's subsequent efforts to maintain control of the BIOS standard proven successful, the subsequent development of both the software and hardware industries' structure might have been quite different.

In many respects, the development of vertical specialization in the computer hardware and software resembles the sequence described by Rosenberg (1963) for machine tools in the 19th century U.S. economy. Originally manufactured for their own use by large textile producers and armaments firms, applications and markets for metalworking machine tools expanded rapidly during the mid-19th century, creating opportunities for entry by specialized producers of these goods. The increasing sophistication and declining costs relative to alternatives of computer software expanded applications for this "general-purpose technology" (Bresnahan & Trajtenberg, 1995), creating larger markets for specialized producers of software who in turn expanded applications to new niches untapped by the leading computer systems firms. The advent of the personal computer accelerated this process, but it had begun before the development of mass-market microcomputers.

Although this "virtuous cycle" appears inevitable in retrospect, reflecting the dynamics proposed by Stigler, the very different history of the Japanese packaged software industry (Cottrell, 1996) suggests that a vertically specialized U.S. software industry was by no means foreordained. The ability of established Japanese computer systems firms to extend their dominance of computer systems from mainframe to microcomputers during the 1980s contributed to the absence of any architectural standard in Japan's domestic market with a dominant position comparable to that of the Wintel standard in the United States. Combined with other characteristics of Japan's system of corporate governance and finance (e.g. limited sources of finance for start-up firms), this contrasting pattern of market evolution stunted the growth of a domestic packaged software industry and severely limited the opportunities for entry by specialized software vendors.

Is vertical specialization an "inevitable" feature of the computer industry of the future, or will it be reversed in specific segments, similarly to the situation in chemicals? The recent growth of client-server platforms has increased the diversity of company strategies and industry structure in the computer industry (Bresnahan, 1999). As in PCs, no single firm can exploit all market opportunities in components or subsystems, and the vertically specialized structure of the industry thus is likely to endure. Many vendors now are attempting to control parts of the client-server standard, but are simultaneously required to maintain open (non-proprietary) standards.[8] Control of one or a few key interfaces for connecting the modular products that make up the client-server architecture, however, could become important for buyer acceptance (Bresnahan & Greenstein, 1999), providing a competitive advantage for some vertically integrated firms (Bresnahan, 1999). But as in chemicals and semiconductors, vertically integrated business models are likely to remain competitive only at the technological frontier.

Geographic Patterns and Regional Differences

The development of a vertically specialized structure in the computer industry for innovation and production has been associated with increased entry, just as was the case in chemicals and semiconductors. And like these other industries, international relocation of various production activities in computers has occurred with the development of a vertically specialized industry structure.

Reflecting the PC's "modular architecture," the production of many PC components, as well as some types of systems (e.g. laptops), has largely moved offshore from the United States to East Asia, particularly Taiwan, Singapore, and Malaysia (Bresnahan, 1999). Nevertheless, the (limited) available data suggest that U.S. firms retain dominant positions in the production of high-margin products in the modern computer industry, including CPUs and software. Figure 2 indicates that U.S. software firms dominate Japanese and European markets for operating systems, although their market shares decline somewhat as one moves from operating systems to tools and applications, both of which require greater "localization" and close links with users. As Mowery (1999) and Bresnahan (1999) point out, the dominance of U.S. firms in these relatively high-margin products reflects a combination of factors, not least among which is the large investments of public funds by the U.S. government over several decades in the creation of a

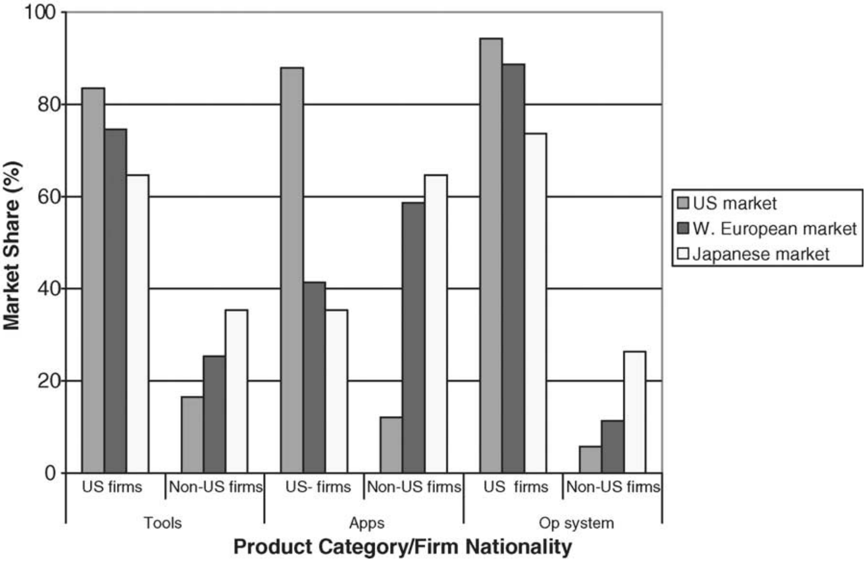

Fig. 2. Worldwide Packaged Software Market Share by Product Class and Consuming Region (1993). *Source:* Mowery (1999).

large national "R&D infrastructure," much of which is based in U.S. universities, as well as the large size and monoglot character of the U.S. domestic market for software.

Summary

After decades of vertical integration the structure of the computer industry has shifted to one characterized by vertical specialization. Specialized producers now play a key role in the development and marketing of computer software and in the manufacture of components and peripherals for each computer platform. Entry by vertical specialized manufacturers of hardware has been associated with rapid growth of production outside of the United States, in lower-cost countries. The growth of vertical specialization in these areas was affected by strategic decisions (some of which in retrospect appear to have been serious errors) of the industry's dominant firm, IBM. Nonetheless, although IBM's strategic decisions contributed to vertical specialization in this industry, the size and rapid growth of markets for this "general-purpose technology" eventually would have increased vertical specialization, regardless of the actions of the industry's leading firm.

As we noted earlier, vertical specialization in computers did not require the development of a stable "interface" between product and process technologies, simply because the process technologies for computer systems fabrication (as opposed to the fabrication of certain key components, such as CPUs or storage devices) have never driven product innovation to the same extent as was true of chemicals and semiconductors. Perhaps because of this weaker interdependence of process and product technologies in final assembly, as well as other factors (e.g. the weaker IPR regime), interfirm technology licensing has not been closely associated with the growth of vertical specialization in the computer industry, in contrast to semiconductors and chemicals. Although interfirm flows of technology have on occasion been very important (e.g. IBM's transfers of technology to its Japanese subsidiary), they have more often than not involved vertically integrated firms, rather than being facilitated in a significant way by the growth of specialist firms.

DISCUSSION

Comparing Vertical Specialization in these Three Industries

Chemicals, semiconductors, and computers exhibit interesting similarities and contrasts in both their patterns of vertical specialization and the factors influencing the evolution of vertical specialization. In the chemical industry, the growth of

SEFs supplying proprietary processes and designs accelerated the diffusion of technology and process knowhow from the United States to developing economies, resulting in substantial entry by new producers of commodity chemicals. Expanded licensing by SEFs also spurred growth in licensing by vertically integrated chemical firms, further expanding international flows of chemical-manufacturing process technologies and knowhow. In response to intensified competition, many leading chemical firms exited low-margin commodity markets during the 1980s and 1990s, restructured their operations, and re-integrated product and process development activities. This reversal of vertical specialization in significant segments of the global chemical industry contrasts with the situation in semiconductors and computers, where vertical specialization, entry, and international redistribution of production activities all have continued apace.

As we noted in the Introduction to this chapter, vertical specialization has contributed to and has been facilitated by expanded international flows of trade, investment, and technology throughout the post-1945 period. In all three of these industries, vertical specialization has been associated with expanded production outside of the nations that are the home of the industry's original, established producers. Vertical specialization in these industries also has been associated with the growth of foreign production capacity that is not controlled by established producers. Indeed, vertical specialization thus far has affected the locus of production activities more significantly than product development or R&D in each industry. The apparent "stickiness" of these more knowledge-intensive activities in all three of these industries, as we noted earlier, reflects the limited knowledge and knowhow spillovers among successive stages of these industries' value chains. Movement of production offshore thus far has not produced product design and R&D centers of comparable sophistication to those remaining in the United States, Japan, and Europe in all of these industries.

In part, this outcome reflects the fact that the conditions underpinning the location of R&D activities respond to more than just the strategic and investment decisions of firms. Governments play an especially important role in supporting R&D in both semiconductors and computers, and the historic strengths of industrial-nation university systems (many of which themselves are beneficiaries of substantial public investments) continue to influence the location of R&D activities in the chemical industry. Even in a globally integrated economy, and even in industries whose structure includes many specialized firms, "national innovation systems" retain considerable importance in the investment decisions of firms (Nelson & Rosenberg, 1993).

In all three industries, vertical specialization has "commoditized" specific activities within the value chain and entry has increased. By diffusing technology and process knowhow, SEFs in the chemical industry reduced the technology gap among producers, facilitating entry into chemical product markets. Ironically, their licensing and diffusion efforts hastened the SEFs' own demise, as chemical producers began to differentiate themselves by re-integrating stages of production, reducing their dependence on SEFs. In semiconductors, growth in the "fabless-foundry" business model has been associated with an increase in the number of new fabless firms exploiting their access to the increasingly standardized manufacturing skills of foundries. In the computer industry, greater standardization and modularity in systems design created opportunities for entry by specialized producers of components and peripherals in desktop computers.

What remains unclear in these industries, and more broadly in scholarly analyses of vertical specialization, is the extent to which "commoditization" of one segment of an industry value chain is contagious. The offshore movement of chemicals production and the entry of new firms do not appear to have affected the international location of established firms' R&D operations, nor have most of the developing-economy entrants created strong in-house technology development capabilities in chemicals. The situation in semiconductors and computers appears at present to be similar, although this remains an area of great uncertainty. The lack of good predictive models or criteria for assessing the effects of "commoditization" on the broader strategic prospects of established firms reflects the lack of criteria to analyze "capabilities," or to assess firms' "core competencies." They retain enormous intuitive appeal, but these concepts lack sufficient rigor to guide managers or scholars.

Preconditions for Vertical Specialization

Although expansion in their product markets contributed to vertical specialization in all three of these industries, the other factors affecting vertical specialization in each industry differ. In semiconductors and chemicals, vertical specialization rested in part on advances in industrial and academic research that created a relatively stable separation between product and process technologies in major product lines. In the computer industry, however, the evolution of product architectures, along with nationally idiosyncratic characteristics of the "innovation systems" of major industrial economies, were important preconditions for vertical specialization.

The growth of chemical engineering made it possible to systematically isolate, categorize, and analyze basic (or unit) processes for chemicals manufacture, allowing for the separation of product and process innovation and the emergence of specialized process design and engineering firms (SEFs). The SEFs aided in the diffusion and licensing of process technology on a global scale, which helped to standardize basic processes on a global scale, facilitating entry by new chemicals firms. In semiconductors, vertical specialization was facilitated by standardization around the CMOS production technology, as well as significant improvements in design software for the layout and simulation of new products. Improvements in information technology (Macher et al., 2002) also have facilitated vertical specialization. The success of specialized manufacturing foundries has contributed to vertical specialization, as their manufacturing capabilities now are much closer to the industry-wide technological frontier and span a broad array of products.

In the computer industry, the creation of "standard platforms" in mainframe products by IBM, as well as this firm's shift in its marketing strategy for hardware and software, were important early factors in the emergence of specialized software vendors. The "general purpose" nature of computing technology, as well as the rapid growth of markets for computers, had attracted vertically specialized software and hardware firms to the industry by the mid-1970s. But vertical specialization in both software and hardware received an enormous impetus from the development of the PC. The adoption of the Wintel standard within the U.S. for the PC facilitated vertical specialization in software and hardware. Although software remains dominated by U.S. firms, the manufacture of many hardware components and peripherals now has migrated to East Asia.

Implications for Firm Strategy

As we noted above, vertical specialization has been both a cause and an effect of the strategies of leading firms in each of these three industries. In both computers and chemicals, the actions of leading firms contributed to the growth of vertical specialization and to efforts to reverse the trend once it was well established. As we noted earlier, IBM's product development and marketing strategies facilitated the development of vertically specialized software vendors and the creation of the "open architecture" associated with the PC. IBM attempted unsuccessfully to maintain control of the PC architecture, opening this rapidly growing market to entry by numerous specialized hardware manufacturers. In response to the "commoditization" of this major component of its hardware product line, IBM has worked during the 1990s and early 21st century to expand the "knowledge-intensity" of its product line and exploit the vertically specialized structure of the computer industry by expanding its activities in computer services, custom software development and systems integration, relying on contract manufacturers to provide a growing share of the firm's hardware products in the "commodity" segments of PCs and desktop systems.

In the chemical industry, established U.S. and European firms contributed to the growth of vertical specialization and entry by licensing their process technologies to competitors and entrants. Responding to declining profits and intensified competition during the 1990s, many of the established U.S. and European chemical firms that were major technology licensors have sought to reverse vertical specialization by shifting their product portfolios and re-integrating their process technology development. Such re-integration relied on the retention by these established chemical firms of innovative capabilities in process technologies, consistent with the arguments of Brusoni et al. (2001) and Granstrand et al. (1997). Knowledge-management strategies in vertically integrated industries thus are demanding and complex.

In semiconductors, some product markets (in particular, microprocessors and DRAMs) still require close coordination between product design and process development, and vertical integration remains essential to competitive strength. These products resemble specialty chemical products in their demands for vertical integration. Many integrated device manufacturers have adapted to this competitive entity by outsourcing a portion of their manufacturing needs to foundries for (typically) older products and process technologies, freeing up capital and technical talent to focus on the development and manufacture of more advanced products. A number of fabless firms and foundries compete head-on in well-established product markets where CMOS is the manufacturing industry standard, and some IDMs remain vertically integrated in areas where internal communication is critical over the product design and manufacturing interface.

The strategies of established firms affected the development of vertical specialization in each of these three industries through their management of interfirm technology flows. As we noted in our discussion of the chemical industry, the growth of SEF-mediated international technology licensing led a number of integrated firms to expand their licensing activities as well, accelerating the international diffusion of process technologies for commodity chemicals. The situation in semiconductors has some similarities with that in chemicals, in that the growth of vertically specialized manufacturing firms has been aided by product and technology licensing agreements and alliances involving “foundries” and integrated producers. In both of these industries, the growth of international markets for technology licensing and other vehicles for the exploitation of their knowledge-based assets led established, vertically integrated firms to pursue strategies that accelerated entry and vertical specialization. In computers, by contrast, vertical specialization expanded licensing and markets for related intellectual property, rather than being an effect of the growth of such markets.

As this discussion of firm strategy suggests, vertical specialization presents established firms with a series of complex tradeoffs. Among the first such tradeoffs is the management of firm-specific intellectual property. In chemicals and semiconductors, established firms responded to incipient entry by new producers, many of whom were specialists, by encouraging such entry through alliances and licensing. In retrospect, at least some of these licensing and technology exchange agreements may appear shortsighted, but the situation faced by established firms resembles the classic prisoner's dilemma – either license one's own technology and face intensified competition (perhaps regulated by terms of a licensing contract) that yields a modest return through licensing revenues, or allow competitors to license their technologies and face intensified competition with no licensing revenues. At the same time, however, an important complement to such licensing strategies is the retention in-house of the capability to advance the technological frontier in these areas. As outsourcing progresses, however, maintaining these in-house "knowledge assets" may prove costly and difficult.

A second set of strategic decisions concerns the response of established firms to a well-established pattern of vertical specialization within an industry. In both semiconductors and computers, a number of established firms have utilized specialist firms for the production of low-margin "commodity" products, helping to reduce their costs and maintain a "full product line" of branded products. The actions of these firms are almost precisely the reverse of the late 19th-century strategic decisions of pioneering U.S. firms, who integrated forward from production into marketing, branding, and distribution. In the 21st century, established, vertically integrated semiconductor and computer firms seek to retain control of their marketing and distribution activities, while selectively exiting from upstream production activities.

Of course, the choice of "commodity" and "strategic" products for outsourcing remains fraught with uncertainty. IBM responded to the growth of software specialists by outsourcing the development of critical components for its PC and compounded its strategic error by failing to govern the terms under which MS-DOS could be sold to other firms. In so doing, IBM effectively lost control of key strategic assets in the booming PC market. The chemical industry now consists of two large groups of firms: those that produce high value-added, specialty chemicals completely in-house and those that manufacture larger-volume commodity chemicals. Established chemical firms have attempted, with varying degrees of success, to exit from commodity products and re-integrate process and product development. Their decisions reflect their strength in technology development, as well as the very different character of downstream markets for most chemical products, which are primarily sold to industrial users as intermediate goods.

For entrants (actual or prospective) in vertically specialized industries, a key issue concerns the sustainability of competitive advantage. Entrants specializing in the production of "commodity" goods must seek forms of competitive advantage other than those associated with product-specific technologies. In semiconductors, successful foundry firms have mastered the very complex tasks of continually upgrading their process technologies (Appleyard et al., 2000), while exploiting information technology to enhance the quality of services that they provide to their customers. Leading-edge foundries now provide customers real-time updates on the progress of manufacturing jobs and commit to demanding delivery schedules. The prospects for entrants in commodity chemicals appear to be less promising, and many of the state-owned entrants of the 1970s and 1980s have performed poorly. A number of privately held firms that acquired the commodity-chemical product lines of established U.S. producers have been profitable, but their long-term prospects remain uncertain.

In computers, of course, entrants are a much more varied lot, reflecting the fact that vertical specialization in this industry has created a large "commodity" segment as well as a very profitable segment in the development and production of the software complements to leading architectures. Entrants into the production of hardware components and systems include contract manufacturers who fabricate systems to the design specifications of established firms and specialists in such components as disk drives and displays. Contract manufacturing in particular is a classic "commodity" segment, in which cost management is central to competitive performance and firm-specific technological capabilities are likely to be modest, precisely because of the relatively unsophisticated fabrication technology, which contrasts with semiconductor foundries. In contrast to contract manufacturers, however, computer-components firms may be better positioned to develop and sustain product and process-related technological advantages, because of the greater complexity of their products and the ability to improve product design.

Software specialists, on the other hand, have benefited from the high switching costs and strong "bandwagon effects" associated with successful products in the desktop market to develop hugely profitable niches in operating systems and applications. In addition, the very different structure of costs in the software industry, characterized by high fixed costs and extremely low production and other variable costs, means that the industry more closely resembles publishing or popular music than computer hardware. "Killer applications" are enormously profitable, and such widely adopted products are difficult to dislodge from their dominant positions. Profitability for many entrants in PC software rests as well on the enduring network effects associated with and dominance of the "Wintel" architecture, something that arguably is less assured as of 2003 than in the 1990s. As and if the "Wintel" standard loses its dominance (either to network-centered architectures or a more remote prospect, to a Linux-based operating system and associated "open-source" applications library), the profitability of niches based on switching costs and architectural standards could decline sharply.

The contrasts among these three industries suggest that any search for "laws" of industry evolution must be tempered by recognition of the role of firm-level strategic decisions in this evolutionary process, as well as recognition of the long-lasting effects of systemic shocks. The exception to the "laws of industry evolution" that is highlighted by much of the global chemical industry results from firm-level decisions to restructure product portfolios (Martin & Eisenhardt, 2004) and effectively to re-integrate product and process innovation. The entry of the SEFs into the chemical industry, as well as their early success as specialized suppliers of process technology, resulted in part from U.S. government "industrial mobilization" and antitrust policies during the 1940s.

CONCLUSION

The timing and pattern of vertical specialization within industry evolution is the focus of a large scholarly literature that provides surprisingly few generalizable findings. As we have noted in this chapter, the evolution of vertical specialization in the chemical, semiconductor, and computer industries has both reflected and influenced the strategies of leading firms, while also displaying industry-specific characteristics that are rooted in the different technological and market characteristics of these three industries. Although Stigler's (1951) emphasis on the "extent of the market" as an important influence on the growth of vertical specialization is supported for each of these industries by our analysis, this condition appears to be necessary but not sufficient for vertical specialization to emerge. Nor does the scale of markets provide guidance as to the form or consequences for firm strategy of vertical specialization. Finally, of course, the Stigler argument provides little insight into the circumstances under which "re-integration" emerges and begins to compete with vertical specialization.

The growth of vertical specialization in all of these industries also presents a challenge to Chandler's (1977, 1990) analysis of the emergence of the modern U.S. corporation, which stresses the replacement of vertically specialized by vertically integrated enterprises. Chandler emphasizes the economies of speed, throughput, and coordination that were provided by vertical integration (both "upstream" and "downstream") in the enterprises created in the late 19th and early 20th centuries in the United States and other industrial economies. But Chandler's framework provides little insight into the limits to these economies and largely fails to explain the emergence during the post-1945 period of significant competition from vertically specialized entrants for many of these large, integrated corporations. Langlois' (2003) assertion that Chandler's "visible hand" is vanishing also may claim too much, since it is apparent from the chemical industry that vertical specialization can be reversed by the strategic decisions of firms in specific product lines. Both Chandler and Langlois bring important new insights to the analysis of industrial evolution, but these conceptual arguments would benefit from a more systematic consideration of exceptions to their conclusions. This is an important task for future research.

Vertical specialization is associated with specific industry preconditions. Among the most notable are greater codification or dissemination of formerly tacit knowledge linking successive stages of a value chain and the development of technical standards that promote stability and codification across interfaces. These developments, which are most apparent in the evolution of the chemical and semiconductor industries, reduce entry barriers in specific segments of the industry value chain, support greater specialization along the value chain, and eventually, reduce overall industry margins. In computers, on the other hand, the rapid adoption of a new technology and expansion of demand for a “general purpose technology,” along with the development of modular product architectures (aided by strategic missteps on the part of leading integrated firms) led to increased vertical specialization.

These three relatively mature industries thus display some contrasts in the causes of vertical specialization as well as the strength and even the direction of current trends in their vertical organization. Nonetheless, all three industries have undergone considerable restructuring in the face of vertical specialization. For instance, the long-term process of vertical disintegration and subsequent re-integration in the chemical industry has created a “two-tiered” industry structure, with one segment populated by large firms seeking to re-integrate their product and process technologies and a second segment populated by low-cost producers of commodity chemicals. A similar “shakeout” could occur in semiconductors, with a few integrated manufacturers competing and collaborating with foundries and fabless firms. The situation in the computer industry is if anything even more difficult to forecast, although there is little prospect for a re-integration of hardware and software. In all three of these industries, vertical specialization has been associated with geographic redistribution of development and production activities.

It is hardly surprising that vertical specialization and firm strategies are jointly determined, rather than one unambiguously “causing” the other. In chemicals, the role of SEFs and the decisions by chemical producers to license process technology helped level the technological playing field and facilitate entry by chemical firms in developing countries. In semiconductors, greater standardization in both product and process has led to a separation of the value chain, and subsequent changes to strategy by both entrant and incumbent firms. In computers, the growth of market demand in new segments and the strategic decisions of leading firms accelerated vertical specialization. In all of these industries, firm-level strategic decisions shaped the long-term pace and pattern of vertical specialization.

NOTES

1. Others have called the vertical disintegration phenomenon outsourcing, fragmentation, multi-stage production, slicing-up-the-value-chain, disintegration of production and intra-product specialization. See Hummels et al. (2001) for more discussion.

2. Progress has been made in identifying competencies important in specific contexts, including component and architectural capabilities necessary for survival by firms facing "market-fusing" technological change (Roy & McEvily, 2004) and dynamic capabilities and modular organizational structures that facilitate corporate entrepreneurship in the face of declining product markets (Martin & Eisenhardt, 2004), among others.

3. SEFs would offer a complete technology bundle to other chemical producers, consisting of a core technology licensed from a chemical producer, along with process knowhow, installation, and engineering services.

4. Arora and Fosfuri (2000) note that in commodity industries, such as Pulp and Paper, Gas Handling, Fertilizers, Industrial Gases and Organic Refining, more than 90% of the plants involve the sale of technology between firms that are not linked through ownership ties, whereas in product markets with significant differentiation, including Pharmaceuticals, Organic Chemicals and Plastics, this percentage falls to near fifty.

5. There are many possible measures of fab capacity, including the number of wafers processed over a given time period, the total wafer surface area that can be processed, the amount of installed processing equipment, etc. Leachman and Leachman (2001) measure fabrication capacity as the estimated number of electrical functions that are produced by chip manufacturers, where a function is a memory bit or logic gate.

6. Table 3.2.2 indicates 640 fabless firms, which is measured by Fabless Semiconductor Association (FSA) membership and all non-members verified by the FSA. At least 300 other small fabless firms are thought to exist, but have not been verified by the industry association.

7. As the U.S. International Trade Commission (1995, p. 2-2) pointed out in its recent study, U.S. government procurement of computer services from independent suppliers aided the growth of a sizeable population of such firms by the late 1960s. These firms were among the first entrants into the provision of custom software for mainframe computers after IBM's unbundling of services and software.

8. Firms with strong positions on the server end of the business, including Sun, Oracle and IBM, have attempted strategies to extend control over clients (e.g. through network computers and Java). At the same time, firms with strong positions on the client side (e.g. Microsoft) are attempted to extend control on the server side.

REFERENCES

Appleyard, M. M., Hatch, N. W., & Mowery, D. C. (2000). Managing the development and transfer of process technologies in the semiconductor manufacturing industry. In: G Dosi, R. R. Nelson

& S. G. Winter (Eds), *The Nature and Dynamics of Organizational Capabilities* (pp. 183–207). London: Oxford University Press.

Arensman, R. (2003). Fabless goes global. *Electronic Business*, Vol. 03/21/2003.

Arora, A., & Fosfuri, A. (2000). The market for technology in the chemical industry: Causes and consequences. *Revue d'Economie Industrielle*, *92*(Special Issue), 317–332.

Arora, A., Fosfuri, A., & Gambardella, A. (2001). Specialized technology suppliers, international spillovers and investment: Evidence from the chemical industry. *Journal of Development Economics*, *65*, 31–54.

Baldwin, C. Y., & Clark, K. B. (1997). Managing in an age of modularity. *Harvard Business Review*, *75*(5), 84–93.

Baldwin, C. Y., & Clark, K. B. (2000). *Design rules: The power of modularity*. Cambridge, MA: MIT Press.

Braun, E., & MacDonald, S. (1978). *Revolution in miniature: The history and impact of semiconductor electronics*. Cambridge: Cambridge University Press.

Bresnahan, T. F. (1998). New modes of competition and the future structure of the computer industry. In: *Competition, Convergence, and the Microsoft Monopoly*. New York: Kluwer Press.

Bresnahan, T. F. (1999). Computing. In: D. C. Mowery (Ed.), *U.S. Industry in 2000: Studies in Competitive Performance* (pp. 215–244). Washington, DC: National Academy Press.

Bresnahan, T. F., & Greenstein, S. (1999). Technological competition and the structure of the computer industry. *Journal of Industrial Economics*, *47*(1), 1–40.

Bresnahan, T. F., & Malerba, F. (1999). Industrial dynamics and the evolution of firms' and nations' competitive capabilities in the world computer industry. In: D. C. Mowery & R. R. Nelson (Eds), *The Sources of Industrial Leadership*. New York: Cambridge University Press.

Bresnahan, T. F., & Trajtenberg, M. (1995). General purpose technologies: Engines of growth? *Journal of Econometrics*, *65*, 83–108.

Brusoni, S., Prencipe, A., & Pavitt, K. (2001). Knowledge specialization, organizational coupling, and the boundaries of firms: Why do firms know more than they make? *Administrative Science Quarterly*, *46*, 597–621.

Chandler, A. D. (1977). *The visible hand: The managerial revolution in american business*. Cambridge, MA: Harvard University Press.

Chandler, A. D. (1990). *Scale and scope: The dynamics of industrial capitalism*. Cambridge: Belknap Press.

Chesbrough, H. W., & Teece, D. J. (1996). When is virtual virtuous? Organizing for innovation. *Harvard Business Review*, 65–73.

Christensen, C. M., Verlinden, M., & Westerman, G. (2002). Disruption, disintegration, and the dissipation of differentiability. *Industry and Corporate Change*, *11*(5), 955–993.

Clarke, P. (2003). MIPS slides as semiconductor IP market grows. *Electronic Times*, Vol. 06/18/2003.

Conner, K. R., & Prahalad, C. K. (1996). A resource-based theory of the firm: Knowledge vs. opportunism. *Organization Science*, *7*(5), 477–501.

Cottrell, T. (1996). Standards and the arrested development of japan's microcomputer software industry. In: D. C. Mowery (Ed.), *The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure*. New York: Oxford University Press.

D'Aveni, R. A., & Ravenscraft, D. J. (1994). Economies of integration vs. bureaucracy costs: Does vertical integration improve performance? *Academy of Management Journal*, *37*(5), 1167–1206.

Eichengreen, B. (1998). Monetary, fiscal, and trade policies in the development of the chemical industry. In: A. Arora, R. Landau & N. Rosenberg (Eds), *Chemicals and Long-Term Economic Growth: Insights from the Chemical Industry*. New York: Wiley.

Fama, E. F. (1980). Agency problems and the theory of the firm. *Journal of Political Economy*, *88*, 288–307.

Feenstra, R. C. (1998). Integration of trade and disintegration of production in the global economy. *Journal of Economic Perspectives*, *12*(4), 31–50.

Fine, C. H. (1998). *Clockspeed*. New York, NY: Perseus Press.

Garud, R., Kumaraswamy, A., & Langlois, R. (2002). *Managing in the modular age: Architectures, networks and organizations*. Blackwell.

Granstrand, O., Patel, P., & Pavitt, K. (1997). Multi-technology corporations: Why they have "distributed" rather than "distinctive core" competencies. *California Management Review*, *39*(4), 8–25.

Grant, R. M. (1996). Toward a knowledge-based theory of the firm. *Strategic Management Journal*, *17*, 109–122.

Hummels, D., Ishii, J., & Yi, K. M. (2001). The nature and growth of vertical specialization in world trade. *Journal of International Economics*, *54*, 75–96.

Hummels, D., Rapoport, D., & Yi, K. M. (1998). Vertical specialization and the changing nature of world trade. *FRBNY Economic Policy Review*, *4*(2), 79–99.

Jensen, M., & Meckling, W. (1976). Theory of the firm: Managerial behavior, agency costs and ownership structure. *Journal of Financial Economics*, *3*, 260–305.

Kogut, B., & Zander, U. (1992). Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science*, *3*(3), 383–397.

Kogut, B., & Zander, U. (1996). What firms do? Coordination, identity and learning. *Organization Science*, *7*(5), 502–518.

Langlois, R. (2003). The vanishing hand: The changing dynamics of industrial capitalism. *Industrial and Corporate Change*, *12*(2), 351–385.

Langlois, R. N. (1992). Transaction-cost economics in real time. *Industrial and Corporate Change*, *1*(1), 99–127.

Langlois, R. N. (2000). Capabilities and vertical disintegration in process technology: The case of semiconductor fabrication equipment. In: N. J. Foss & P. L. Robertson (Eds), *Resources, Technology, and Strategy: Explorations in the Resource-Based Perspective*. London: Routledge Press.

Langlois, R. N. (2002). Modularity in technology and organization. *Journal of Economic Behavior & Organization*, *49*, 19–37.

Langlois, R. N., & Robertson, P. L. (1992). Networks and innovation in a modular system: Lessons from the microcomputer and stereo component industries. *Research Policy*, *21*, 297–313.

Leachman, R. C., & Leachman, C. H. (2001). Globalization of semiconductor manufacturing. U. C. Berkeley Competitive Semiconductor Manufacturing Research Program Working Paper.

Macher, J. T. (2003). Firm organization and performance in knowledge assets: An empirical examination in semiconductor manufacturing. Georgetown University Working Paper (pp. 1–38).

Macher, J. T., Mowery, D. C., & Hodges, D. A. (1998). Reversal of fortune? The recovery of the U.S. semiconductor industry. *California Management Review*, *41*(1), 107–136.

Macher, J. T., Mowery, D. C., & Hodges, D. A. (1999). Semiconductors. In: D. C. Mowery (Ed.), *U.S. Industry in 2000: Studies in Competitive Performance* (pp. 245–286). Washington, DC: National Academy Press.

Macher, J. T., Mowery, D. C., & Simcoe, T. S. (2002). e-Business and the disintegration of the semiconductor industry value chain. *Industry and Innovation*, *9*(3), 155–181.

Mansfield, E., Rapoport, J., Romeo, A., Villani, E., Wagner, S., & Husic, R. (1977). *The production and application of new industrial technology*. New York: W. W. Norton.

Martin, J. A., & Eisenhardt, K. M. (2004). Coping with decline: Dynamic capabilities and organizational form as mechanisms for corporate entrepreneurship. In: J. A. C. Baum & A. M. McGahan (Eds), *Business Strategy over the Industry Lifecycle – Advances in Strategic Management* (Vol. 21). Oxford, UK: Elsevier/JAI Press.

McClean, B. (2001). IC foundries: A driving force in the IC industry. *Semiconductor FabTech*, *12*, 17–19.

Monteverde, K. (1995). Technical dialog as an incentive for vertical integration in the semiconductor industry. *Management Science*, *41*(10), 1624–1638.

Mowery, D. C. (1999). The computer software industry. In: D. C. Mowery & R. R. Nelson (Eds), *Sources of Industrial Leadership: Studies of Seven Industries* (pp. 133–168). Cambridge, UK: Cambridge University Press.

Mowery, D. C., & Rosenberg, N. (1998). *Paths of innovation: Technological change in the 20th-century America*. Cambridge: Cambridge University Press.

Nelson, R. R., & Rosenberg, N. (1993). Technological innovation and national systems. In: R. R. Nelson (Ed.), *National Innovation Systems* (pp. 3–21). New York: Oxford University Press.

Pisano, G. P. (1997). *The development factory: Unlocking the potential of process innovation*. Boston: Harvard Business School Press.

Prahalad, C. K., & Hamel, G. (1990). The core competence of the corporation. *Harvard Business Review* (May–June), 79–91.

Rosenberg, N. (1963). Technological change in the machine tool industry, 1840–1910. *Journal of Economic History*, *4*, 414–443.

Rosenberg, N. (1998). Technological change in chemicals: The role of university-industry relations. In: A. Arora, R. Landau & N. Rosenberg (Eds), *Chemicals and Long-Term Economic Growth*. New York: Wiley.

Roy, R., & McEvily, S. K. (2004). Incumbent survival during market fusion: The effects of breadth of component and architectural capabilities on survival of U.S. machine tool manufacturers during 1975–1999. In: J. A. C. Baum & A. M. McGahan (Eds), *Business Strategy over the Industry Lifecycle – Advances in Strategic Management* (Vol. 21, forthcoming).

Sanchez, R., & Mahoney, J. T. (1996). Modularity, flexibility, and knowledge management in product and organization design. *Strategic Management Journal*, *17*, 63–76.

Scupola, A. (2002). The impact of electronic commerce on industry structure: The case of scientific, technical and medical publishing. *Journal of Information Science*, *28*(4), 275–284.

Slywotzky, A. J., Christensen, C. M., Tedlow, R. S., & Carr, N. G. (2000). The future of commerce. *Harvard Business Review*, (January–February), 3–11.

Steinmueller, W. E. (1996). The U.S. software industry: An analysis and interpretive history. In: D. C. Mowery (Ed.), *The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure* (pp. 15–52). New York & Oxford: Oxford University Press.

Stigler, G. (1951). The division of labor is limited by the extent of the market. *The Journal of Political Economy*, *59*(3), 185–193.

Stuckey, J., & White, D. (1993). When and when not to vertically integrate. *Sloan Management Review*, *34*, 71–83.

Sturgeon, T. J. (2002). Modular production networks: A new american model of industrial organization. MIT IPC Working Paper, 1–62. Boston, MA.

Teece, D. J. (1986). Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research Policy*, *15*(6), 285–305.

Teece, D. J. (1996). Firm organization, industrial structure, and technological innovation. *Journal of Economic Behavior and Organization*, *31*, 193–224.

Thorelli, H. B. (1986). Networks: Between markets and hierarchies. *Strategic Management Journal*, *7*, 37–51.

Trescott, M. M. (1982). Unit operations in the chemical industry. In: W Furter (Ed.), *A Century of Chemical Engineering*. New York: Plenum Press.

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy*, *24*, 419–440.

Williamson, O. E. (1979). Transaction-cost economics: The governance of contractual relations. *Journal of Law and Economics*, *22*(October), 233–261.

Williamson, O. E. (1985). *The economic institutions of capitalism*. New York: Free Press.

Williamson, O. E. (1991). Strategizing, economizing, and economic organization. *Strategic Management Journal*, *12*(Special Issue), 75–94.

Yi, K. M. (2001). Can vertical specialization explain the growth in world trade. *Journal of Political Economy*, *111*(1), 52–102.