# Reversal of Fortune?

## THE RECOVERY OF THE U.S. SEMICONDUCTOR INDUSTRY

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The international economic competitiveness of a number of U.S. manufacturing industries has improved significantly since the early 1990s. One of the most dramatic reversals of fortune—which is particularly remarkable because of its reliance on strengths formerly regarded by many analysts as weaknesses—is that of the U.S. semiconductor industry. Although evidence of this industry's improved performance is abundant, explanations for it are surprisingly scarce. This article draws on previously unpublished data on manufacturing performance, along with other indicators, to examine the reasons for the recovery of the U.S. semiconductor industry since the early 1990s.

This analysis is important because of the economic significance of the U.S. semiconductor industry and because of this industry's role as a "poster child" for U.S. competitive decline during the 1980s and resurgence during the 1990s. The economic importance of this industry needs little elaboration—semiconductor devices are the basic building blocks of many electronics industries. Declines in the price/performance ratio of semiconductor components have propelled their adoption in an ever-expanding array of applications, and semiconductor

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technology has increased the variety of products offered in industries such as consumer electronics, personal communications, and home appliances.

During the 1980s, the competitive difficulties of the U.S. semiconductor industry were used in several analyses of U.S. competitiveness to illustrate the competitive problems of the broader U.S. economy.[1] Both "impatient capital," a tendency by U.S. high-technology entrepreneurs to develop innovative products that they were unable to manufacture in commercial volumes with high quality, and predatory foreign-firm trade practices figured prominently in gloomy assessments of the future of this and other U.S. manufacturing industries. Moreover, the semiconductor industry was the focus of attention from senior federal policymakers, and many of the broad competitiveness-related policy measures of the 1980s and early 1990s were motivated by concern over this industry's performance and supported by evidence from its history. Finally, this industry was among the first to implement a number of the technology management practices that now characterize other U.S. manufacturing industries, such as increased domestic and international collaboration and greater "vertical specialization" by firms. Our assessment of these new approaches therefore is germane to evaluations of these other sectors.

This discussion of the changing competitive performance of the U.S. semiconductor industry examines the 1980-1997 period in some detail in order to establish the dimensions of the "fall and rise" of this industry during this period. The recovery of U.S. semiconductor firms since 1989 rests on improvements in product quality and manufacturing process yields, as well as their withdrawal from the fiercely competitive Dynamic Random Access Memory (DRAM) segment of the semiconductor industry. U.S. firms have reoriented their strategies since the mid-1980s to concentrate on logic and microcomponent products,[2] where foreign competition was less intense and they could pursue new product opportunities by exploiting their proximity to developers of computer software and other complementary products. Other successful U.S. firms have entered the industry as specialists in innovative device designs.[3] Meanwhile, the Japanese firms that dominated DRAMs now face a domestic recession and entry by low-cost producers from South Korea and Taiwan. Although the Asian economic crisis that began in 1997 is likely to depress global demand for semiconductors in the near term and has eroded the financial performance of U.S. producers, the relative performance of U.S. semiconductor firms remains strong, as their continuing leadership in global market share indicates.

Much of the "renaissance" of U.S. competitive advantage in semiconductors reflects exploitation by U.S. firms of long-standing strengths in product innovation. Many of the new opportunities that appeared in the late 1980s for such product innovation reflected developments in other industries such as telecommunications and computers, in which U.S. firms demonstrated renewed innovative and competitive vigor. Moreover, many of the factors cited in the 1980s by expert and scholarly analyses as sources of competitive weakness in this industry have instead contributed to its competitive revival. The repositioning of

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U.S. semiconductor firms was, if anything, aided by the "fragmentation" of the U.S. industry's structure that the MIT Commission and others[4] criticized. The inaccuracies in these analyses raise serious problems for both managers and policymakers seeking speedy diagnoses and solutions to competitive problems in high-technology industries.

A number of federal government initiatives, ranging from trade policy to financial support for university research and R&D consortia such as SEMATECH,[5] played a role in the industry's revival. However, the specific links between these undertakings and improved manufacturing performance are difficult to measure. Industry managers are virtually unanimous in emphasizing that the crisis of the 1980s forced them to devote much more attention to improving their development and management of manufacturing process technology. It is not clear how much of the overall improvements reflected this renewed focus by managers, nor is it clear why poor performance was tolerated for so long.

In a complex industry such as semiconductors, no single explanation for improved U.S. performance is likely to suffice. All of the factors discussed above have contributed to this industry's revival, and it is futile to attempt to assign weights to individual causes. At the same time, the foundation for this competitive revival is fragile. U.S. producers' success in repositioning their product lines and developing innovative products does not guarantee enduring dominance. The MIT Commission's grim diagnosis of the "structural crisis" of the U.S. semiconductor industry contains important insights, and at least some of the negative consequences of the U.S. industry's unusual structure have not been addressed. Many of the large corporations that supported much of the basic research that propelled the semiconductor industry's early growth have reduced the scope of their in-house basic research, and public funding for long-term R&D is more uncertain in the wake of the Cold War. Without a clearer understanding of the factors that gave rise to it, maintaining interfirm collaboration may prove difficult.

## Industry Performance, 1980-1997

Our discussion of industry performance begins with a summary of the development of the global semiconductor industry during the 1980-1997 period, highlighting trends in the market shares of U.S. and non-U.S. semiconductor manufacturers. Our market share data are measured in terms of revenues and therefore confound trends in output quantity and the price per unit of that output. This effect is not entirely undesirable—one of the primary factors behind the resurgence of U.S. manufacturers' market share in semiconductors is precisely the higher average selling prices of their output during the 1990s.

### *Market Share Measures*

The first transistors, and subsequently the first integrated circuits (ICs), were developed and manufactured in the United States for military and space

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programs. By the mid-1960s, the computer and communications industries surpassed the U.S. military as the primary markets for semiconductors, and the market for semiconductor components has been dominated by commercial applications ever since.[6] From the invention of the IC in 1959 through 1985, the combined market share of U.S. producers exceeded that of firms from all other nations.[7]

A combination of circumstances—including abundant venture capital, widespread licensing of key patents, and the willingness of U.S. military and space agencies to purchase semiconductor devices from new firms—produced an industry structure that by the 1960s contrasted with those of the Japanese and Western European semiconductor industries. The leading commercial producers of semiconductors in the U.S. included a number of relatively young "merchant" firms that specialized in semiconductor manufacture.[8] In contrast, the Japanese and Western European semiconductor industries were and continue to be dominated by subsidiaries of large, diversified electrical equipment firms.

Foreign semiconductor producers challenged the dominant position of U.S. firms in the late 1970s. Japanese firms had been active in the semiconductor industry since the 1950s, but lagged behind U.S. firms in product and process technology. But in the mid-1970s, the Ministry of International Trade and Industry (MITI), NTT (at the time, Japan's state-owned telecommunications firm), and Japanese producers of semiconductor devices and manufacturing equipment launched several research programs to improve the semiconductor manufacturing capabilities of domestic firms. These initiatives included the well-known VLSI Program overseen by MITI and a parallel program for its semiconductor suppliers sponsored by NTT. Paradoxically, the VLSI program sought to improve Japanese semiconductor capabilities in order to strengthen the international competitiveness of Japan's computer industry.

These technology development programs focused on memory devices, which were important in computer systems and whose relative design simplicity facilitated the testing of new process technologies. The market outlook for these devices appeared to be favorable, a projection that was amply borne out by subsequent trends. In addition, "Moore's Law"[9] provided a clear "roadmap" of the path of future developments in DRAM technology, enabling Japanese firms to focus their efforts to "catch up" in semiconductor technology. By 1979, Japanese producers accounted for almost 42 percent of global DRAM sales.[10]

By the mid-1980s, Japanese producers were the dominant global suppliers of semiconductor memory devices. U.S.-Japanese competition in DRAM production took on the characteristics of a "capacity race"—firms in each nation invested aggressively in production capacity for next-generation products. Aided by their access to internal sources of finance, Japanese semiconductor manufacturers were able to dominate this investment competition. The U.S. share of capital spending in the world semiconductor industry declined from nearly 60 percent in 1980 to roughly 30 percent in 1990.[11] The enormous capital requirements of the investment capacity race, combined with fierce price competition

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in DRAMs and a U.S. industry recession, forced many U.S. merchant firms (with the notable exceptions of Texas Instruments and Micron Technology) out of the DRAM market by 1985. By 1990, Japanese firms accounted for 98 percent of sales of 4-megabit DRAMs, then the most advanced memory product (See Table 1).

Reflecting their declining fortunes in memory devices, U.S. merchant semiconductor producers lost considerable market share in semiconductors during this period (See Figure 1). From a leading share of almost 62 percent in 1980, U.S. chipmakers' global market share declined to a low point of 37 percent by 1989. Japanese semiconductor firms by 1989 were responsible for more than half of global semiconductor revenues.

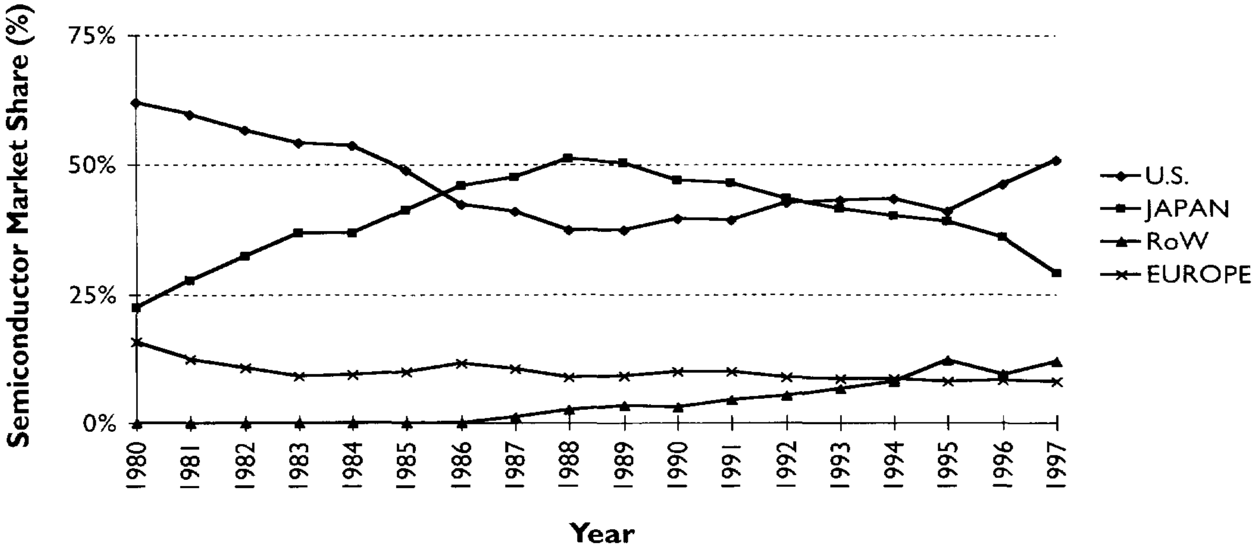
Remarkably, this dire competitive situation began to change in the late

**TABLE 1.** Maximum Market Share (%) By Device Type

| Device Type | Volume Production | Maximum Market Share | |
|---|---|---|---|
| | | U.S. | Japan |
| 1K | 1971 | 95 | 5 |
| 4K | 1974 | 83 | 17 |
| 16K | 1977 | 59 | 41 |
| 64K | 1979 | 29 | 71 |
| 256K | 1982 | 8 | 92 |
| 1M | 1985 | 4 | 96 |
| 4M | 1990 | 2 | 98 |

Source: Dataquest, cited in David T. Methé, *Technological Competition in Global Industries: Marketing and Planning Strategies for American Industry* (Westport, CT: Quorum Books, 199[illegible]), p. 69; and R. Langlois and W.E. Steinmueller, "The Evolution of Competitive Advantage in the Global Semiconductor Industry: 1947-1996," in D.C. Mowery and R.R. Nelson, eds., *The Sources of Industrial Leadership* (New York, NY: Cambridge University Press, 1998), p. 31.

**FIGURE 1.** Worldwide Semiconductor Market Share, 1980-1997



Source: SIA 1997 Annual Databook; Integrated Circuit Engineering Corporation (ICE), "Status: A Report on the Integrated Circuit Industry," 1980-1998.

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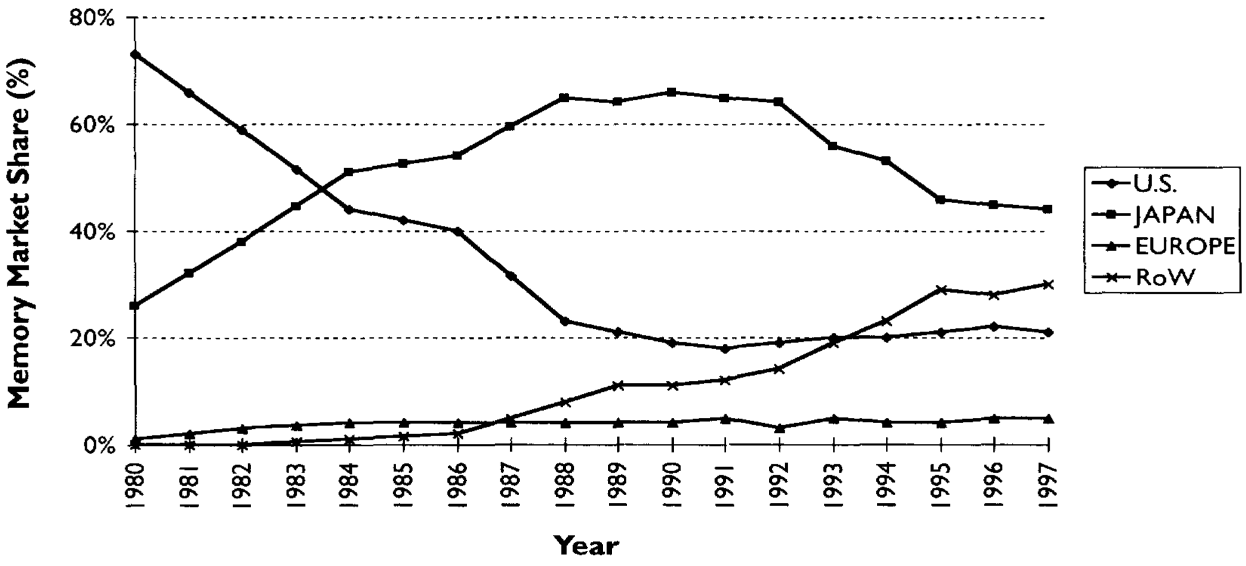
**FIGURE 2.** Worldwide Memory Market Share, 1980-1997



Source: ICE, "Status A Report on the Integrated Circuit Industry," 1980-1998.

1980s. U.S. producers reversed their global market share decline in 1990 for the first time since 1975.[12] But this reversal in market share occurred in areas other than memory products, where U.S. firms' global market share has grown only slightly since 1990 (See Figure 2). Instead, U.S. firms shifted away from low-margin products such as DRAMs in favor of products that enabled them to exploit their strengths in product innovation. Having largely exited DRAMs by 1985, U.S. semiconductor manufacturers in the 1990s concentrated on logic devices and "mixed-signal" and other digital signal processor (DSP) components for the burgeoning market in computer networking equipment. Strong demand for these "design-intensive" components propelled U.S. chipmakers back to market share leadership in the global semiconductor industry by 1993 (See Figure 1). By 1997, U.S. producers controlled over 50 percent of the total semiconductor market, well above the 29 percent held by Japanese firms. Contradicting the predictions of analysts who argued that DRAM production was an indispensable "technology driver" for semiconductor manufacturing, U.S. firms' enduring market share losses in DRAMs did not prevent this revival in their competitive fortunes.

The post-1990 decline in Japanese firms' global market share also reflected entry by South Korean and Taiwanese firms into the DRAM market. Rather than shifting to logic products, Japanese firms sought to be technology leaders in introducing next-generation DRAM devices. But DRAMs now are essentially "commodity" products, and Japan, Taiwan, and South Korea are

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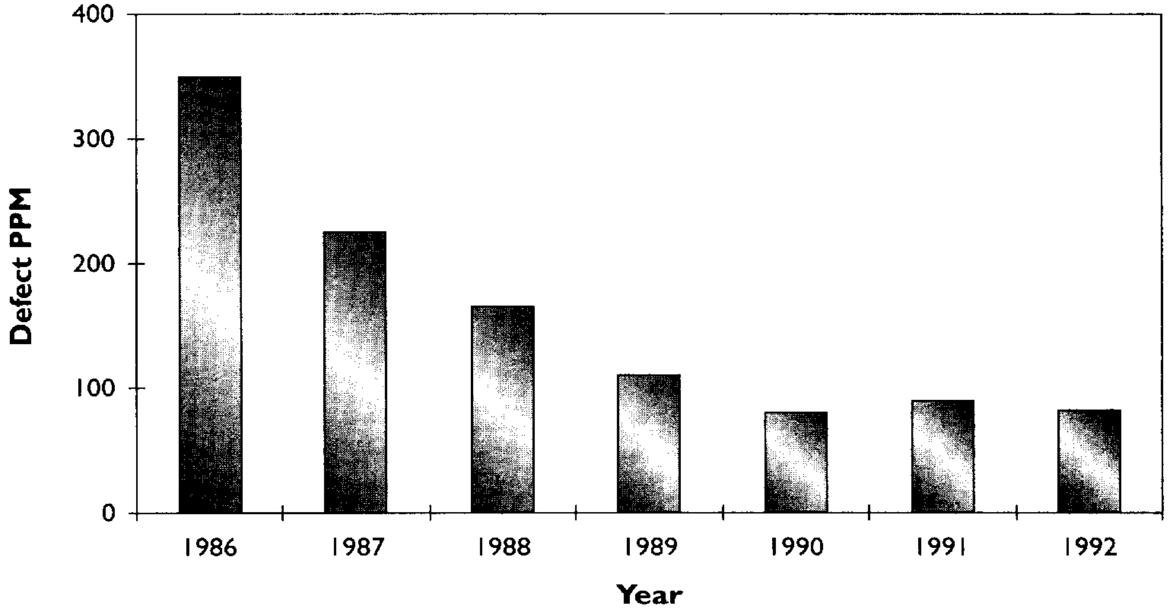
**FIGURE 3.** Defective Parts per Million (PPM) in U.S. Firms' Integrated Circuits



Source: SIA Quarterly Quality Survey (1992), cited in W. Finan, "Matching Japan in Quality: How the Leading U.S. Semiconductor Firms Caught Up With the Best in Japan," MIT-Japan Working Paper, 1993.

engaged in a global battle for market share based upon low production costs and high yields. As Figure 2 indicates, Japan no longer dominates the memory market as it did in the 1980s, having lost market share to Korean and Taiwanese semiconductor firms (the primary components of the "RoW" category in Figure 2). Indeed, Japanese firms no longer are the consistent leaders in the introduction of next-generation DRAMs—Samsung has matched industry-leader NEC in the introduction and commercial production of 64MB and 256MB DRAMs, and it appears to have surpassed NEC in development and prototype fabrication of 1GB DRAMs.[13]

### Product Quality Measures

Japanese semiconductor firms' dominance of DRAM markets during the 1980s rested on low prices and high quality. Drawing in many cases on practices they had long followed in their other product divisions, Japanese semiconductor manufacturers applied Statistical Process Control (SPC), Total Quality Management (TQM) and Total Preventive Maintenance (TPM) to their operations.[14] This resulted in significant quality differences between Japanese and U.S. semiconductor products. Users of U.S. and Japanese devices discovered that Japanese memory products had defect rates that were one-half to one-third those of comparable U.S. memory products;[15] in 1980, leading Japanese memory producers averaged 160 defective parts per million (PPM) while U.S. producers averaged

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780 PPM for the same devices.[16] Their skills in managing the development and introduction of new process technologies also enabled Japanese semiconductor manufacturers to "ramp" output of new products more rapidly than their U.S. counterparts. Faster achievement of high production volumes gave Japanese firms advantages in defining product standards for leading-edge memory devices, strengthening their market position.[17]

By the mid-1980s most of the leading U.S. semiconductor firms recognized the strategic importance of quality and had initiated quality improvement programs. Some U.S. semiconductor firms devoted considerable effort to learning from Japanese firms, and those with operations in Japan, particularly TI and Motorola, were among the first to apply Japanese quality management techniques. Confronted with evidence of improvement in the performance of these domestic competitors, other U.S. firms began to emulate their practices. A survey in 1990 by the National Institutes of Standards and Technology (NIST) of 11 U.S. semiconductor firms' quality assurance investments revealed a doubling of the share of spending related to quality in the previous five years.[18] According to industry managers, the formation of SEMATECH also supported more effective collaboration between U.S. manufacturers and equipment suppliers on quality and reliability problems.

These and other efforts were associated with a reduction in average defect rates in U.S. semiconductor firms' products to less than 400 PPM by 1986, according to the Semiconductor Industry Association (SIA), the U.S. semiconductor manufacturers' trade group.[19] Defect rates continued to decline through the rest of the decade and by the early 1990s, leading U.S. firms had matched Japanese memory producers' defect levels at less than 100 PPM (See Figure 3).

### *Manufacturing Performance Measures*

In addition to improving product quality, U.S. semiconductor firms strengthened their performance in manufacturing process management. Data from the UC Berkeley Competitive Semiconductor Manufacturing (CSM) Program[20] suggest that U.S. firms have improved manufacturing "yield" and direct labor productivity in some product lines since the early 1990s,[21] although they still lag behind the best Japanese and other Asian firms in most of these performance measures. Nevertheless, narrowing this gap in manufacturing performance appears to have been sufficient—in combination with U.S. firms' product innovations and strategic repositioning—to improve their competitive performance.

A key measure of semiconductor manufacturing performance is die yield, the number of usable die per silicon wafer that emerge from the manufacturing process. Die yield is a measure of manufacturing "process quality" that differs in at least one important respect from the product defect data discussed earlier. Product defects can be reduced by investments in "end-of-line" inspection, which enables producers to discard defective components (or in some cases, to repair defects) after manufacture and before distribution to the market. Our

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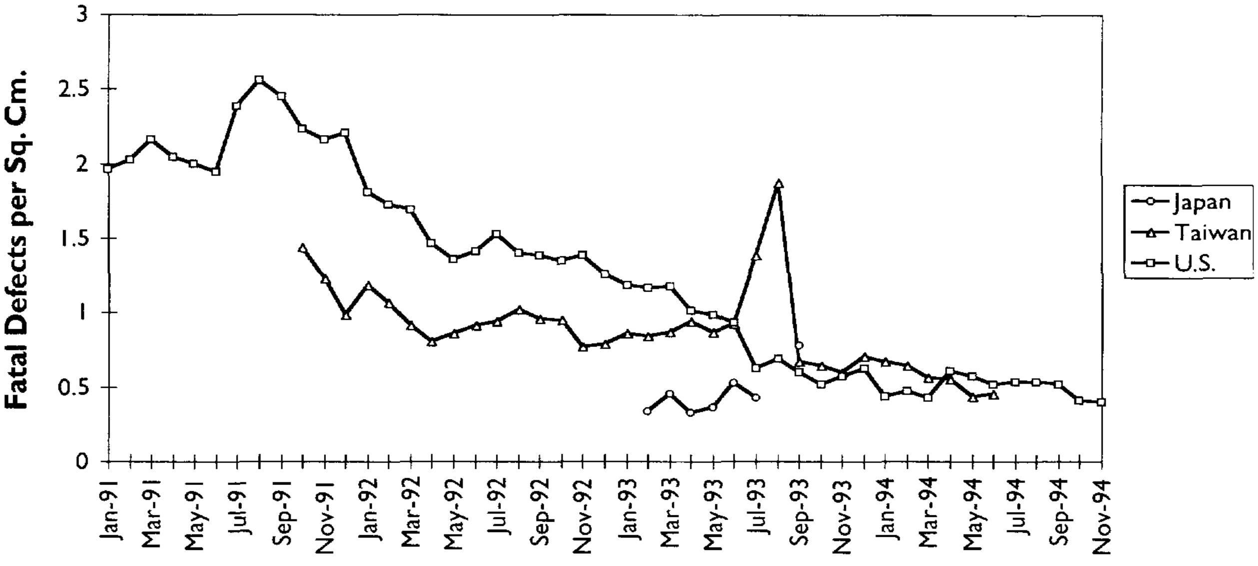
**FIGURE 4.** Defect Density in 0.7–0.9 CMOS Logic Processes*



*The figure reports defect density for CMOS logic processes, the largest single category of MOS manufacturing processes. During the period of the sample, CMOS represented more than 90% of MOS technology used in IC manufacturing [Integrated Circuit Engineering Corporation (ICE), "Status: A Report on the Integrated Circuit Industry," 1989-1994]. CMOS is the acronym for Complementary Metal Oxide Semiconductor and is a transistor-based circuit or device. MOS refers to the type of transistor that comprises the circuit. Complementary refers to two specific types of transistors that "complement" each other in the circuit in that one can be turned on while the other is turned off.

Source: R. Leachman and C. Leachman, "National Performance in Semiconductor Manufacturing," University of California, Berkeley Competitive Semiconductor Research Program working paper #CSM-40, 1997.

measure of die yield, however, is not directly affected by such inspection procedures. Instead, this yield measure is sensitive to the execution of the numerous steps involved in the production of a semiconductor component, and its improvement reflects improved manufacturing methods—in many respects a more difficult achievement.

We present data only for logic products, because we lack a sufficient number of observations for U.S.-located, domestically owned memory production capacity to support a comparison of performance in U.S.- and Japanese-owned memory production facilities for this period. The CSM data for logic devices reveal significant improvements in U.S. firms' performance during this period. U.S. firms reduced their defect densities from as many as 2.5 fatal defects per square centimeter in 1991 to levels comparable with the 1993 performance of Japanese fabs by 1994 (See Figure 4).[22]

Along with Finan, Leachman and Leachman attribute improvements in U.S. manufacturing performance to increased use of quality-management techniques.[23] Widespread adoption of SPC methodologies by U.S. firms appears to have lowered defect densities and improved die yields. In addition, U.S. firms improved the speed of collection, the reliability, and the accessibility of data on

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**TABLE 2.** Average Probe Yield: U.S. and Japanese Semiconductor Manufacturers

| | Average Probe Yield (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Country** | **1981** | **1986** | **1987** | **1988** | **1989** | **1990** | **1991** |
| U.S. | 55 | 60 | 60 | 67 | 74 | 80 | 84 |
| Japan | 45 | 75 | 79 | 81 | 85 | 89 | 93 |

Source: U.S. General Accounting Office, "Federal Research: SEMATECH's Technological Progress and Proposed R&D Program," July 1992.

manufacturing performance, all of which enabled rapid identification and diagnosis of problems in manufacturing yields. These steps included the use of "end-of-line" yield analysis that relies on rapid transmission of data from probe tests of wafers to engineers; the increased use of data collection systems that provide statistical correlation of in-line data on process steps and lot characteristics with end-of-line yield tests; the increased automation of manufacturing process information;[24] and the improved collection of equipment performance and control parameters.

Other measures of die yield indicate significant improvement in U.S. semiconductor firms' manufacturing performance by the end of the 1980s. According to the U.S. General Accounting Office, U.S. firms had fallen behind Japanese firms in "probe yield"[25] by 1981, but U.S. firms' performance in this quality measure improved significantly during the 1986-1991 period.[26] By 1991, U.S. manufacturers had narrowed but had not eliminated the gap between their performance and that of Japanese manufacturers (See Table 2).

Although U.S. semiconductor firms have narrowed the gap with Japanese firms in die yield for some devices, they continue to lag in other areas, such as direct labor productivity. The CSM data support comparisons of productivity performance among fabs in Europe, Japan, Taiwan, and the United States. Productivity is measured as the number of wafer layers processed per operator per day, and captures differences in physical productivity—the value of output per worker is not captured by this measure.[27] As such, differences in the price per die on wafers produced in different fabs may partially or entirely offset the financial consequences of differences in this measure of performance.

At CMOS logic fabs, U.S. firms' direct labor productivity improved during the 1991-1994 period, but U.S. firms still lag behind Taiwanese and Japanese firms (See Figure 5). The importance of scale economies in semiconductor manufacturing means that the smaller average size of U.S. fabs, relative to those in Japan and Taiwan, depresses U.S. firms' performance in this comparison.[28] Nevertheless, as was noted above, the consequences of these differences in physical productivity are mediated by the prices and margins per die in each region's product mix. U.S. firms have specialized in relatively high-margin products and therefore are somewhat insulated from the financial consequences of their

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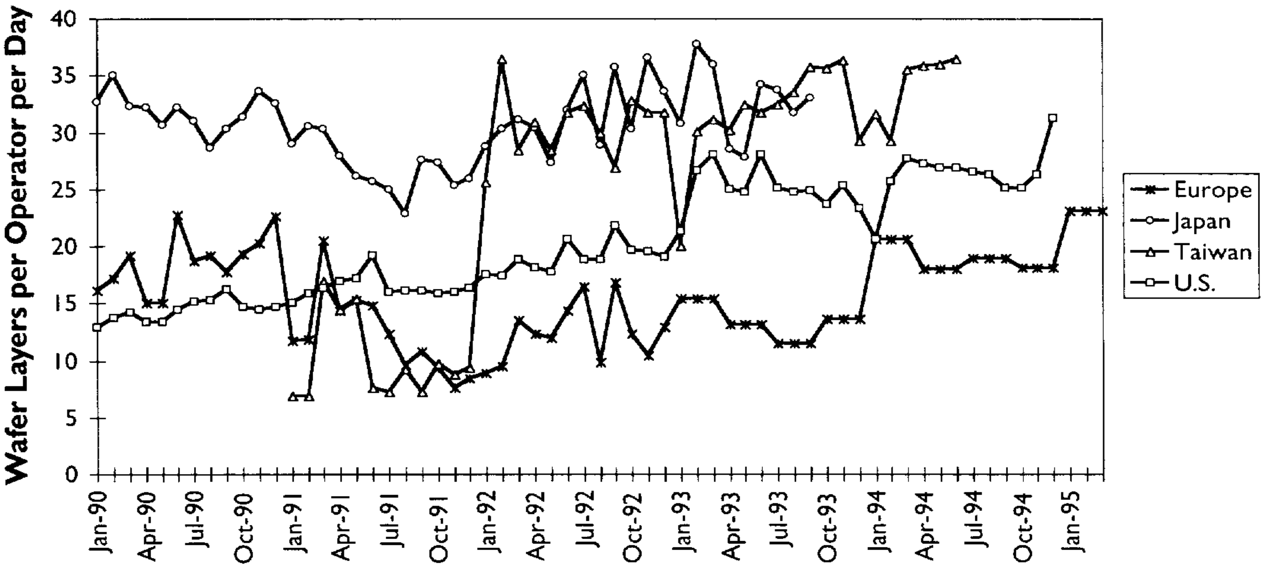
**FIGURE 5.** Direct Labor Productivity at CMOS Logic Fabs



Source: R. Leachman and C. Leachman, "National Performance in Semiconductor Manufacturing," University of California, Berkeley Competitive Semiconductor Research Program working paper #CSM-40, 1997.

relatively low physical productivity. However, as and if non-U.S. firms strengthen their capabilities in product innovation and shift their output mix to become direct competitors with U.S. firms in these newer, more design-intensive products (see below), the relatively low direct labor productivity of U.S. fabs could produce competitive difficulties.

During the late 1980s and 1990s, U.S. firms also improved their management of the development and introduction of new process technologies into high-volume manufacturing.[29] Increases in the design complexity of semiconductor devices during the 1980-1997 period made it much more difficult to predict the performance of new process steps and equipment through simulation or laboratory-scale experimentation and complicated the "debugging" of new process technologies in the manufacturing environment. At the same time, intensified competition in many product lines meant that rapid expansion of the output of new products was essential to maximize sales in the increasingly brief period prior to entry by competitors. A prolonged period of "learning"—during which yields are low and/or product quality is unreliable—reduces profits. The difficulties associated with new process development and introduction thus have grown simultaneously with the competitive and financial penalties of a poorly managed introduction. Evidence from the CSM study and other sources suggests that U.S. firms were slow to respond to these new realities until forced to do so by Japanese competition.

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There is no single best practice for managing the development and introduction of new process technologies. Many U.S. firms have expanded their use of "development facilities," which are similar in many respects to pilot process plants in the chemicals industry. These facilities support the development and debugging of new process technologies and equipment in an environment that is insulated from the demands of high-volume manufacturing, yet is designed to reproduce as many characteristics of that environment as possible.[30]

But much more than a development facility is needed for performance improvements in process development and introduction. Introducing a radically new manufacturing process (for which 75-90 percent of the hundreds of individual steps is new) and attempting to simultaneously begin large-scale production of a new product design with this process is formidable. Many U.S. firms instead introduce incremental advances in manufacturing processes and debug these modified processes on new versions of existing product designs (e.g., a smaller version or "shrink" of an established logic or memory chip). This more incremental approach to new process development and introduction requires close coordination among product design, process development, and equipment procurement over multiple generations of existing and new products.

## *Summary: Factors Behind U.S. Decline and Revival*

The performance of the U.S. semiconductor industry during the 1980-1997 period reflected shifts in both product and process technology management. U.S. firms proved to be relatively agile—especially by comparison with Japanese firms—in repositioning their product portfolios to emphasize new products that were relatively design-intensive. At the same time, however, U.S. firms improved their manufacturing performance, which enabled them to exploit their long-standing strengths in product innovation more effectively. From a position of substantial inferiority in the development and management of semiconductor process technologies in the early 1980s, U.S. chipmakers narrowed the gap between U.S. and Japanese manufacturing capability and productivity in some product lines by the early 1990s.

Both repositioning and improved manufacturing performance almost certainly were necessary; neither was sufficient. Improvements in both of these dimensions of performance reflected improved technology management practices, where these practices are defined to include management of process technologies on the shop floor, as well as improvements in the development and adoption of new process and product technologies. In addition to these changes in their internal management of innovation and production, U.S. firms expanded collaboration among one another, with equipment firms, and with non-U.S. firms. Finally, the entry of specialized design firms into the U.S. semiconductor industry signaled the development of new approaches to the organization of the innovation process.

Although U.S. semiconductor firms' performance during the 1993-1997 period has been impressive, it has been aided in part by Japanese and South

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Korean semiconductor firms' failure to shift their product portfolios away from DRAMs to design-intensive components. The 1998 industry downturn, which reflects the continuing economic problems in Asia and excess capacity in DRAMs, may bring new competitors to semiconductor markets that have traditionally been dominated by U.S. producers. Indeed, some Taiwanese DRAM producers have recently entered product markets led by U.S. semiconductor firms, such as flash memory.[31] Drawing on their experience in operating "foundry" production facilities, other Taiwanese firms now are able to switch from memory to advanced logic components, depending on market conditions. The flexibility gives them an advantage over South Korean and Japanese semiconductor firms, and may foreshadow the development of a formidable future challenger to U.S. firms.

## Changing Technology Strategies

The structure and management of technology and new-product development in the U.S. semiconductor industry has changed since 1980 in ways that anticipate similar trends in other U.S. industries. Perhaps the most important of these structural changes is increased reliance on collaborative strategies. Collaboration has been both "vertical" (linking suppliers of equipment with semiconductor manufacturers) and "horizontal" (linking semiconductor manufacturers with one another); it has been both domestic and international; and it has been supported by public and by private funds. In addition, collaboration in the semiconductor and other industries (e.g., computer hardware and software, or even long-distance trucking and logistics management) has been associated with specialization by firms in different phases of the vertical "value chain" that links product development and manufacturing. In semiconductors, as in these other industries, collaboration and vertical specialization reflect the higher costs and risks of new product development and the spiraling costs of new production capacity,[32] as well as the ability of modern information technology to support complex, arm's-length collaborations in product development and manufacturing.

### *Producer-Designer Collaboration*

One strategy to reduce financial risks that has been adopted by recent entrants into the U.S. semiconductor industry is specialization in design. These so-called "fabless" semiconductor firms design semiconductor components, but rely on specialized "foundries" for the production of their designs. The fabless firm is largely a North American phenomenon—more than 300 of the worldwide population of roughly 500 fabless firms were located in North America in 1998.[33] By contrast, most state-of-the-art foundries are located in Asia.[34]

Fabless firms serve a variety of fast-growing industries, especially personal computers and telecommunications, and seek to dominate their markets by offering more innovative designs and shorter delivery times than merchant

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firms.[35] Constant-dollar industry revenues have grown at an average annual rate of 32 percent since 1991, almost twice the average for the global semiconductor industry as a whole. The fabless industry's trade association estimates 1997 fabless industry revenues at $7.8 billion,[36] and Dataquest forecasts fabless industry revenues will grow to $11.7 billion in 2000 and 40% of the world's chip production by 2010.[37]

### *International Collaboration*

U.S., Japanese, and European semiconductor manufacturers have increased offshore R&D spending since 1980, but all still perform the majority of firm-financed R&D in their home regions.[38] During the past 20 years, a number of non-U.S. firms have established R&D facilities in the United States and other developed nations outside their home region.[39] These foreign R&D investments are motivated by the same factors that drive U.S. offshore R&D investment, although many foreign firms are especially interested in tracking new semiconductor product and process developments in the U.S. market and in U.S. universities.

Although U.S. semiconductor firms have not significantly expanded their foreign R&D operations, alliances among U.S. and non-U.S. semiconductor firms have grown rapidly since 1980. Indeed, the costs and risks of new-product development and production capacity meant that U.S. semiconductor firms were among the first U.S. high-technology firms to pursue extensive alliances with foreign firms.[40] Many alliances focus on specific product or process development projects, and frequently involves some exchange by U.S. firms of product technology for foreign (often Japanese) expertise in process technology. Such partnerships also facilitate access to international markets that are otherwise impeded by tariffs or political mechanisms. Many of these international collaborative agreements focus on a single product area (e.g., nonvolatile memory or microprocessors) and many involve no U.S. partners.

A number of expert groups have expressed concern over the "export" of technology and know-how by U.S. semiconductor firms to foreign competitors through these arrangements,[41] but most evidence suggests that U.S. firms have reaped considerable technical and commercial benefits from alliances through a two-way flow of technology and managerial know-how, including the advanced quality manufacturing techniques discussed above. But the growing "internationalization" of the R&D process that is implied by these alliances and by other forms of international collaboration in the U.S. semiconductor industry, such as expanded support for U.S. university research by foreign firms, raise complex questions for public policy in this and other high-technology industries. Simply put, formulating and implementing a "national" technology policy requires new approaches in industries whose technology development, manufacturing, and marketing operations are global in structure and scope.[42]

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## *Domestic Collaboration*

Expanding domestic collaboration, some of which is supported with public funds, has paralleled international collaboration in the semiconductor industry. Japanese firms' growing domination of the global market for semiconductor memory chips in the late 1980s contributed to an unusual initiative to strengthen U.S. semiconductor firms' commercial-device manufacturing capabilities.[43] SEMATECH was formed in 1987 by 14 U.S. semiconductor manufacturing firms that together accounted for more than 80 percent of U.S. semiconductor manufacturing capacity,[44] and was financed jointly by member firms and the federal government.[45]

SEMATECH's original objectives—improving member firms' semiconductor manufacturing process technology—underpinned its decision to build a large-scale fabrication facility in Austin. However, SEMATECH's research agenda shifted in 1990-1991 to improving the technological capabilities of U.S. suppliers of semiconductor manufacturing equipment.[46] SEMATECH focuses on "medium-term," rather than long-term, research, and a 3- to 5-year time horizon typifies most of its R&D investments.

The period following the formation of SEMATECH is characterized by improvements in U.S. semiconductor manufacturing performance and in the market shares of U.S. semiconductor equipment suppliers. It is difficult at best, however, to find direct cause-and-effect links between SEMATECH's activities and these developments. In the case of semiconductor manufacturing equipment, for example, a significant portion of the improved market share of U.S. suppliers reflects the decline in Japanese semiconductor firms' capital investments, which has depressed the growth of equipment demand in a market long dominated by Japanese equipment firms.[47] Nevertheless, SEMATECH member firms have continued to support and participate in SEMATECH since the cessation of federal support, which is a strong signal that industry managers believe that the consortium provides important benefits. Although it is the best-known example, SEMATECH is by no means the only U.S. collaborative program in semiconductor R&D; a number of other programs now are funded jointly by industry and federal and state government funds.[48]

Publicly and privately funded R&D collaboration has expanded significantly within the U.S. semiconductor industry since 1980. The U.S. semiconductor industry was among the first to establish such consortia, and as the discussion of SEMATECH suggests, the evaluation of their effects on industry performance is difficult. The operation of SEMATECH also points out the complexities of public funding for technology development by firms whose operations are global in scope. SEMATECH's defense-related funding and sponsorship, along with broader political concerns, led to the exclusion of non-U.S. firms from membership.[49] Yet many non-U.S. firms have been able to benefit from SEMATECH-supported R&D, either through their purchase from U.S. equipment vendors of new products that have been improved in SEMATECH programs, or through their collaborative relationships with U.S. semiconductor

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manufacturing firms. As Ham et al. point out, SEMATECH's most recent initiative for the development of "next-generation" (300mm wafer-compatible) manufacturing equipment and methods now enlists a number of non-Japanese foreign firms.[50]

In the semiconductor and other U.S. high-technology industries, both failures and successes are likely in R&D collaboration, and the essential point is to try to capture sufficient knowledge from each to improve performance. Collaboration is not a panacea, but it may offer some solutions to the competitive weaknesses associated with the fragmented industry structure cited by the MIT Commission. At the same time, however, collaboration thus far has not addressed another weakness in this industry mentioned by the MIT Commission and other analyses—insufficient industrial investment in long-term research.

### *Who Will Fund and Perform Basic Research?*

However useful, collaborative R&D in the U.S. semiconductor industry has supported little long-term industrial research. The large U.S. corporate laboratories of the 1950s and 1960s, most notably those of AT&T, GE, and IBM performed much of the fundamental research that underlies modern semiconductor technology. Those laboratories now focus on near-term corporate goals and applied research, and no U.S. organization has emerged to fund the basic research needed for the future. Federally funded R&D in the U.S. semiconductor industry, most of which was funded by the Defense Department and related agencies, has declined from nearly 25% of total R&D spending in the industry (imperfectly defined in this case as SIC 367, "electronic components") in 1980 to slightly less than 7% in 1992.[51] Defense-related federal R&D funding is likely to continue to decline in the aftermath of the Cold War.

Although the leading U.S. merchant semiconductor firms (such as Intel, TI, Micron, and AMD) spend 10-15 percent of revenues on R&D, the bulk of these expenditures focus on new product development. Intel has announced its intention to expand its long-term research program, but few other semiconductor manufacturing firms conduct much R&D beyond development of next-generation products. None of the new leaders in digital communications perform any fundamental research or maintain much internal semiconductor R&D, instead focusing their efforts on the development and marketing of next-generation semiconductor products.

The U.S. semiconductor industry is not alone in its low levels of investment in long-term R&D. Data from the National Science Foundation suggest that U.S. firms overall have reduced their constant-dollar funding of basic research, while increasing investment in development, during the 1991-1995 period. But the challenges for U.S. semiconductor firms in this area are particularly significant, since major non-U.S. semiconductor manufacturers—such as NEC, Hitachi, Toshiba, Philips, and Siemens, most of which are larger and far more diversified than U.S. merchant semiconductor firms—still conduct considerable long-range R&D.[52] Despite these apparent advantages over their smaller

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U.S. merchant and fabless competitors, these large, diversified foreign firms thus far have been relatively slow or ineffective in exploiting new opportunities for innovative products. Nevertheless, they could re-emerge as formidable competitors in product lines in which the pace of innovation has slowed or assumed a more incremental and capital-intensive character, as was the case in DRAMs during the 1980s.

## The Role of Nontechnological Factors in the U.S. Industry's Revival

The performance of the U.S. semiconductor industry during the 1980-1997 period was influenced by an array of other public policies, such as federal trade and antitrust policies that affected all U.S. industries. Indeed, the U.S. semiconductor industry's competitive crisis of the 1980s was widely cited as an illustration of the failure of both government policies and other economic factors, such as the environment for capital formation, to support competitive high-technology industries in the United States. A number of broad policies that affected all U.S. industries were adopted during the 1980s in part because of their perceived importance to the semiconductor industry and because of the belief by policymakers and others that the semiconductor industry's difficulties were representative of those faced by other U.S. industries. The development by the U.S. semiconductor industry of an influential political voice in the Semiconductor Industry Association (SIA) also played an important role in changes in U.S. government policy. As such, some assessment of the influence of these "nontechnological factors"—which we define to include new public policies—on this industry's competitive revival is important for what it reveals about the sources of this revival in semiconductors and its implications for evaluation of these factors' influence in other industries. This section discusses the contributions to the U.S. semiconductor industry's improved performance since 1980 of the domestic environment for capital formation, as well as the changes in federal antitrust, trade, and intellectual-rights protection policies implemented during this period.

### *Capital Formation*

A recurrent theme in debates and analyses of the competitive difficulties of the U.S. semiconductor and other industries during the 1980s and 1990s has been the asserted high cost of capital for industrial investment. A corollary critique emphasizes the lack of "patient" capital, and the resulting myopic investment behavior of U.S. high-technology firms. A number of changes in federal tax policy, including the R&D tax credit and reductions in capital-gains taxation, have been justified in terms of their contributions to capital formation in U.S. industry. What role has capital formation played in the fall and rise of the U.S. semiconductor industry?

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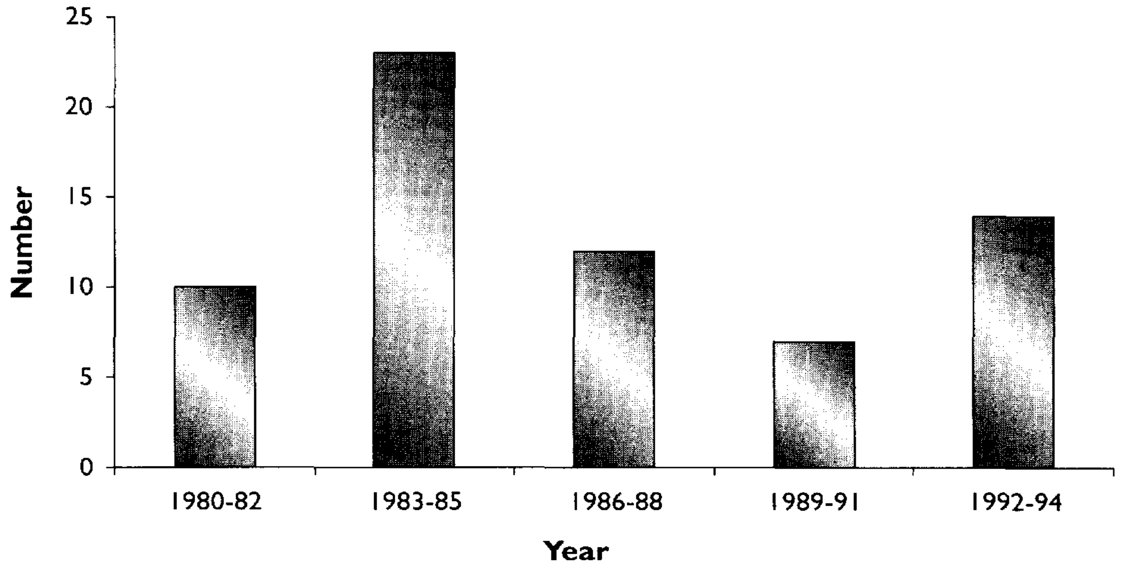
**FIGURE 6.** Formation of New U.S. Semiconductor Firms



Source: FSA, *Fabless Forum*, 2/1 (1995).

Any discussion of the cost and availability of capital in competitive performance within this industry confronts a paradox. On the one hand, this issue is important in some segments of the industry, where the costs of a single commercial-scale production facility significantly exceed $1 billion. Indeed, as noted earlier, U.S. firms faced significant handicaps in the DRAM "capacity races" that developed in the early 1980s.

On the other hand, capital expenditures by U.S. merchant semiconductor producers amounted to more than $14 billion in 1996 and $13 billion in 1997.[53] Investments of this size suggest that constraints on the supply of capital to U.S. firms are scarcely binding. Moreover, the U.S. semiconductor industry has an abundant supply of venture capital, which has supported the foundation of literally hundreds of semiconductor firms since this industry's inception four decades ago. The data in Figure 6 suggest that this high "birthrate," which has contributed significantly to the industry's technological dynamism, show few signs of declining. The recent competitive performance of the large firms active in both the Japanese and South Korean semiconductor industries, especially those specializing in DRAMs, suggests that an excess of inexpensive capital for investment in physical plant and equipment may lead to poorer performance. In both of these nations' semiconductor industries, low-cost capital has been associated with over-investment in production capacity for commodity products that yield low profits.

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Although there are few reliable estimates of the risk-adjusted cost of capital in the U.S., Japanese, South Korean, and other semiconductor industries, U.S. firms may well face a higher cost of capital. Nevertheless, any such cost differential has not deterred the formation of new U.S. firms, nor has it deterred large-scale capital investments by U.S. firms that have developed successful competitive strategies that rely on their strengths in product design and innovation. For established U.S. semiconductor firms, competitive success appears to lead to abundant capital for investment in plant and equipment, rather than vice versa. A higher cost of capital may contribute to the low level of investment in long-term, basic research by many U.S. semiconductor firms. Nevertheless, given the competitive realities of this industry, especially the short product cycles and high costs of R&D for maintaining near-term competitiveness, the risk-adjusted cost of capital would have to be very low indeed to produce higher levels of such investment.

## *Trade Policy*

Yet another policy experiment whose political currency and feasibility were advanced significantly by the competitive crisis of the U.S. semiconductor industry during the 1980s was "managed trade"—bilateral policies and negotiations pursued by the U.S. government that sought to go beyond specifying the "rules of the game" to focus more explicitly on trade outcomes. Among the most widely publicized and discussed initiatives was the U.S.-Japan Semiconductor Trade Agreement of 1986, which responded to accusations by U.S. firms that Japanese DRAM producers were "dumping" their products in the U.S. market.[54] By preventing the imposition of heavy antidumping duties on U.S. imports of DRAMs, the Agreement sought to avoid a policy that would drive up the domestic prices of components that were essential to U.S. manufacturers of electronic systems, creating strong incentives for them to shift production to foreign locations. A system of "fair market value" prices for DRAMs was created under the terms of the Agreement that was intended to prevent dumping in the U.S. and third-country markets. The Agreement also included an "understanding" that foreign-sourced components would achieve a 20 percent share of the Japanese domestic market within five years. An extension of the Agreement in 1991 retained the market share language but dropped the price-monitoring system.

Although the Agreement was negotiated in response to the competitive crisis facing U.S. producers of DRAMs, its effects on these firms' activities in DRAM production were limited. Most of the major U.S. DRAM producers had exited from this product line by 1985, well before the Agreement was finalized.[55] The Agreement's price floors and the associated implementation by MITI of controls on production and capacity investment by Japanese DRAM producers, however, had several interesting effects, few of which directly benefited U.S. semiconductor manufacturers or were foreseen in 1986.[56] Higher prices for DRAMs provided an opportunity for South Korean firms to expand their production of these devices, sowing the seeds for more intense competition in this

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product line in the future. Flamm argues similar restrictions on production of erasable programmable memory chips (EPROMs) reduced Japanese exports of these devices and enabled U.S. producers of EPROMs to remain in this product line.[57]

Although the Semiconductor Trade Agreement may have provided some benefits to U.S. EPROM producers, the effects of its pricing provisions seem to have had little effect on the overall U.S. industry. These provisions did not attract U.S. manufacturers back into DRAM production and imposed heavy short-term costs on major U.S. consumers of DRAMs. The market-share provisions of the 1986 and 1991 Agreements, however, were eventually followed by a significant increase in U.S. semiconductor manufacturers' market share in Japan, and the Agreement is viewed as a key factor in expanded Japanese imports of foreign components.[58] The Agreement's market-share provisions thus contributed to the revival of U.S. semiconductor firms after 1990, but the timing of this revival is such that the lack of an import target would not have prevented the U.S. industry's recovery, which was well underway by 1990.

### *Antitrust Policy*

The competitive crises of the semiconductor and other U.S. industries contributed to a far-reaching shift in U.S. antitrust statutes and enforcement policy in the 1980s. Despite (or possibly, because of) the historical influence of antitrust policy on the semiconductor industry's development,[59] U.S. antitrust policy was widely criticized in the late 1970s for discouraging R&D collaboration in this and other industries. The U.S. Justice Department issued guidelines in 1980 that were intended to clarify the antitrust statutes and the Department's enforcement philosophy toward R&D collaboration in order to remove impediments to such collaborative undertakings. Nevertheless, continuing industry and Congressional dissatisfaction resulted in the 1984 passage of the National Cooperative Research Act (NCRA), and Justice Department enforcement of antitrust statutes was relaxed somewhat to account for the importance of non-U.S. markets, non-U.S. producers, and the benefits of innovation in determining the costs and benefits of market power in the U.S. semiconductor and other industries. The NCRA is credited with facilitating the formation of SEMATECH, among other industry-wide collaborations; the Act was amended in 1993 to extend its coverage to joint production ventures.

An evaluation of the "real" effects of the NCRA and the broader shift in antitrust enforcement policy on the U.S. semiconductor industry's decline and revival is difficult without some clearer specification of the counterfactual: Would SEMATECH have been formed without the NCRA? Has R&D collaboration contributed to increased market power and/or poorer industry performance? Given the size of the firms that joined together to create SEMATECH and the sustained acquaintance of several of them with the federal antitrust authorities, the legislative endorsement of R&D collaboration under the terms of the NCRA almost certainly did aid in the creation of this consortium. The

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semiconductor industry's performance suggests that R&D collaboration need not result in cartelization and a weakening of competitive forces, although the large share of the U.S. semiconductor equipment market represented by SEMATECH member firms means that this consortium's vertical relationships deserve continued monitoring. Indeed, collaboration may provide one mechanism for combining the benefits of the U.S. industry's atomized structure and technological dynamism with those flowing from closer user-supplier relationships. Nevertheless, very few production joint ventures have been formed since the passage of the 1993 amendments to the NCRA, suggesting that this policy shift thus far has had little effect.

### *Intellectual Property Rights*

A final area of major policy change since 1980 that has affected the U.S. semiconductor and other industries is intellectual property rights. Shifts in U.S. policy toward intellectual property rights began with the 1982 legislation that established the Court of Appeals for the Federal Circuit (CAFC), which strengthened the protection granted to patentholders.[60] The U.S. government also pursued stronger international protection for intellectual property rights in the Uruguay Round trade negotiations and in bilateral venues.

In addition to these shifts in federal policy affecting all U.S. industries, the Semiconductor Chip Protection Act (SCPA) of 1984 established protection for the design or "mask work" used in semiconductor manufacturing.[61] Although it is an interesting experiment in sui generis protection of new forms of intellectual property, the SCPA's economic significance appears to be limited—only one case has ever been litigated under its provisions.[62] The SCPA's unanticipated insignificance appears to be one result of the increasing complexity of manufacturing process technologies in the semiconductor industry. Copies of a device design and maskwork are necessary, but by no means sufficient, to enable large-scale production of infringing products.[63] As a result, semiconductor firms during the 1980s and 1990s continue to rely on trade secrets and patents, the value of which has been highlighted by the policy shifts noted above.[64]

The SCPA nevertheless may play an important, albeit unintended, economic role in the fabless segment of the U.S. semiconductor industry. In order to maintain short design cycles, fabless firms must extensively reuse design data, "porting" designs from one product to another or contracting with another firm for all or some part of the design. Reusable design components are generally referred to as "intellectual property (IP) blocks," and protection for these "IP blocks" under the SCPA facilitates the licensing process. The growth of licensing of IP blocks has supported further specialization by some design firms in specific components of overall device designs. These "virtual companies" operate by licensing their proprietary designs and architectures to other semiconductor firms that produce an integrated design, contract with a foundry, and (in many cases) market the final product.

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The broader shift of federal policy toward stronger enforcement of patent-holder rights has been associated with a dramatic increase in patenting and licensing among integrated semiconductor manufacturers in the U.S. industry.[65] Licensing has become an important component of profits for some leading manufacturers. The royalty income of Texas Instruments (TI) grew from roughly $200 million in 1987 to more than $600 million in 1995, but has decreased since the expiration of several key patents.[66] Other firms, such as Intel, IBM, and AT&T, now rely on licensing to generate revenues and protect product and process technologies.

The historic strengths of U.S. firms in product design and rapid innovation should be reinforced by stronger enforcement of patents and trade secrets. The distribution of these benefits within the industry, however, is less clear. Stronger intellectual property protection appears to have benefited established firms. Intel's strong position in its microprocessor product line relies in large part on the firm's intellectual property rights. Another historic strength of the U.S. industry, however, is the ease with which new firms can enter. The effects of stronger intellectual property rights on rates of new-firm formation and entry are less clear. On the one hand, new firms with strong patent positions often find it much easier to attract financing. On the other hand, the costs (in terms of litigation and patent prosecution expenses) of establishing such a patent position are very high. The empirical evidence on the social benefits from stronger intellectual property protection is thin and equivocal. In the semiconductor industry, as in others, the U.S. is conducting an experiment in the effects of stronger intellectual property protection, and the implications of these new policies for long-term industry performance are surprisingly uncertain.

### *Summary*

Based on the experiences of the U.S. semiconductor industry, a tentative assessment of the influence of these factors on the competitive revival of U.S. industry since the 1980s would conclude that their influence has been modest but broadly positive. Certainly, this assessment provides little support for the argument that U.S. industry was or is starved for "patient capital," while it suggests that managed trade policies can open markets rather than restrict U.S. imports. Finally, the effects of the far-reaching changes in U.S. antitrust and intellectual property rights policies instituted during the past 18 years are only gradually being felt and remain uncertain.

## Conclusion

Forecasts of the impending demise of the U.S. semiconductor industry in the late 1980s were considerably overstated. After declining through much of the 1980s, U.S. semiconductor firms undertook corrective actions on several fronts. They exited from product lines in which their historic skills at product innovation provided limited competitive advantage and their foreign

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competitors' superior access to capital made long-term competition difficult. U.S. firms also improved their product quality and enhanced their manufacturing performance, narrowing the gaps between them and foreign competitors, rather than moving ahead. The results of these steps have been dramatic. The U.S. semiconductor industry has regained its formerly dominant global market share, and the financial performance of U.S. semiconductor manufacturers now outstrips that of their South Korean and Japanese competitors. Moreover, the revival of the U.S. semiconductor manufacturing industry has reinvigorated the U.S. semiconductor equipment industry. Simultaneously, the South Korean and Japanese firms that specialize in the production of DRAMs are experiencing serious financial losses.

In many respects, the revival of the U.S. semiconductor industry relied on the elements of its structure that were criticized in the 1989 report of the MIT Commission on Industrial Productivity. The structure of the U.S. semiconductor manufacturing industry remains very different from that of the Western European or Japanese industries, although the emergent Taiwanese semiconductor industry is based on the U.S. model and still bears a passing resemblance to it. Populated by numerous, relatively small (by comparison with foreign competitors), highly innovative firms and exposed to competition by new entrants pursuing new product opportunities and new approaches to the semiconductor business, the U.S. industry remains adept at product innovation and rapid strategic repositioning. In addition, U.S. firms have relied on collaboration among semiconductor manufacturers—and between manufacturing firms and suppliers of equipment—to improve their manufacturing performance. The links between the collaborative initiatives of the 1980s and 1990s and the industry's improved performance remain elusive, however, and further research on these issues is essential if the current strengths of U.S. manufacturers and equipment producers are to be maintained.

Although the MIT Commission's overall prognosis of the industry's future was inaccurate, its analysis of the U.S. industry's weaknesses in manufacturing and long-term R&D investment highlighted other issues that could lead to future competitive difficulties. The very best U.S. semiconductor manufacturers appear to be capable of matching the yield and productivity of the best non-U.S. producers, but there is little evidence of consistently superior U.S. manufacturing performance. As a result, U.S. firms are likely to do best in periods of rapid product innovation, especially because of their ability to exploit their presence in one of the world's most dynamic markets for applications of new products that use semiconductor components. But U.S. firms may have trouble competing on the basis of their manufacturing skills alone and therefore are likely to face challenges in future periods where they and foreign competitors are pursuing similarly incremental innovations within a well-defined technological "trajectory." The U.S. industry structure is enormously effective in exploiting scientific advances for rapid commercialization, but may under-invest in the basic research supporting these advances.

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During the 1980s, the semiconductor industry was almost without equal (steel and automobiles are among the few that approach its salience) in the amount of attention devoted to its welfare and competitive prospects by federal policymakers. As pointed out above, many of the policy initiatives that sought to respond to this industry's difficulties have had significant economy-wide effects. Nevertheless, the federal policies that sought to target semiconductors in particular avoided a number of alternatives that would have been far more detrimental for the industry's competitive prospects. For example, consider the costs and consequences of a public-private venture like U.S. Memories (which specializes in DRAMs), during the 1990s. Policymakers and industry managers might well have faced some very unpleasant choices between erecting trade barriers against competing imports or allowing this venture to slide into insolvency. The proposal of the National Advisory Commission on Semiconductors for a government-backed Consumer Electronics Capital Corporation—which would have been charged with financing the revival of a U.S. industry to consume the products of the domestic semiconductor industry—experienced an even more rapid and fortuitous demise. In hindsight, the avoidance by federal policymakers in the Executive and Congressional branches of government of programs that would involve the support with public funds of specific designs of commercial products was wise and was consistent with well-established principles of technology policy.

The complex history of the U.S. semiconductor industry's fall and rise since 1980 illustrates another very important point that both industry managers and public policymakers need to consider carefully. In hindsight, it seems clear that many of the diagnoses of this industry's competitive weaknesses and strengths during the 1980s were misguided. As Rosenberg,[67] among others, has pointed out, the process of technological innovation is fraught with fundamental uncertainties, and these uncertainties characterize many other aspects of the environment and outlook within high-technology industries. Regardless of the quality or quantity of data, the rapid pace of technological and market-driven change in these industries means that the "signal-to-noise" ratio in these indicators is likely to be quite low, creating abundant opportunities for costly or counterproductive responses. Over-commitment to any specific commercial vision of the future of an industry is no less hazardous to policymakers than to industry managers in such surroundings.

Finally, given its status as a key source of evidence for all sides in the "industrial competitiveness" debates of the 1980s and 1990s, what does the improved performance of the U.S. semiconductor industry suggest for the analysis of competitive trends in other U.S. industries? The U.S. semiconductor industry shares a common set of strengths and weaknesses with a number of other U.S. high-technology industries. In industries ranging from biotechnology to pharmaceuticals and computer software, U.S. competitive strength (or revival) has relied on:

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- substantial federal investments in R&D, especially in fundamental research in academia and industry, rather than in federal laboratories;
- the enormous, unified U.S. domestic market, which provides a large, demanding group of users for new products and processes and supports a robust flow of new technologies among different industrial sectors;
- a system of corporate finance and governance that supports the formation and entry of numerous new firms to experiment (and frequently, to fail) in the exploitation of new commercial products;
- federal trade, antitrust, and intellectual property rights policies that tend to favor competition among firms and open markets; and
- particularly since the early 1990s, fiscal and monetary policies that promote economic stability, low interest rates, and low inflation.

These factors were ignored or downplayed in much of the most critical assessment of U.S. competitiveness of the 1980s, which was influenced heavily by the performance of Japanese industry during that decade. Some, but by no means all, of the policy shifts inspired by the semiconductor industry's competitive difficulties are consistent with these elements. Furthermore, the industry's crisis failed to produce any political consensus on one of the most important of these factors: the role and appropriate structure for the federal R&D infrastructure in a post-Cold War world.

The resurgence of the U.S. semiconductor industry is an impressive feat, for which government policymakers and industry managers, engineers, and researchers should share credit. But the unexpected nature of this revival, its complex causes, the contributions to it of cyclical factors, and the fragility of its foundation all suggest that competitive strength in this industry cannot be taken for granted. Indeed, some foreign producers, notably Taiwanese semiconductor firms, now are entering markets traditionally dominated by U.S. producers, a development that will intensify pressure on U.S. firms and increase the importance of manufacturing performance for competitive leadership. In other words, U.S. semiconductor firms must maintain their strategic agility and strength in product innovation while avoiding significant erosion in their manufacturing capabilities in order to maintain their strength. This task will require imagination and collaboration among government, industry, and academia.

## Notes

1. A representative comment was that of the MIT Commission on Industrial Productivity: "The traditional structure and institutions of the U.S. [semiconductor] industry appear to be inappropriate for meeting the challenge of the much stronger and better-organized Japanese competition... The technological edge that once enabled innovative American companies to excel despite their lack of financial and market clout has disappeared, and the Japanese have gained the lead." MIT Commission on Industrial Productivity. Working Papers of the Commission on Industrial Productivity, two volumes (Cambridge, MA: MIT Press, 1989), p. 261.

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2. Microcomponents include microprocessors, microcontrollers, DSP devices, and microperipheral devices.
3. These firms are called "fabless" semiconductor firms, as they design new microelectronic products but subcontract out the manufacture of these products to other firms ("foundries") specialized in wafer fabrication.
4. See, for example, R. Florida and M. Kenney, "Silicon Valley and Route 128 Won't Save Us," *California Management Review*, 33/1 (Fall 1990): 68-88.
5. The SEmiconductor MAnufacturing TECHnology (SEMATECH) consortium was created in 1987 to develop semiconductor manufacturing technology, using a combination of industry and federal government funding (see below).
6. J. Tilton, *International Diffusion of Technology: The Case of Semiconductors* (Washington, D.C.: Brookings Institute, 1971), p. 61; E. Braun and S. MacDonald, *Revolution in Miniature: The History and Impact of Semiconductor Electronics* (Cambridge: Cambridge University Press, 1978), p. 113.
7. Integrated Circuit Engineering Corporation (ICE), "Status: A Report on the Integrated Circuit Industry," Integrated Circuit Engineering, 1976-1998.
8. Merchant semiconductor firms sell most of their production on the open market, in contrast to captive semiconductor firms who produce semiconductor devices principally for internal "parent" systems divisions.
9. Moore's Law was articulated in 1965 by Dr. Gordon Moore, one of the founders of Intel, who pointed out that the number of transistors integrated on semiconductor devices tend to double every 18 months.
10. Integrated Circuit Engineering Corporation (ICE), "Status: A Report on the Integrated Circuit Industry," Integrated Circuit Engineering, 1980.
11. Integrated Circuit Engineering Corporation (ICE), "Status: A Report on the Integrated Circuit Industry," Integrated Circuit Engineering, 1981-1991.
12. Integrated Circuit Engineering Corporation (ICE), "Status: A Report on the Integrated Circuit Industry," Integrated Circuit Engineering, 1976-1991.
13. Integrated Circuit Engineering Corporation (ICE), "Status: A Report on the Integrated Circuit Industry," Integrated Circuit Engineering, 1998.
14. See W. Finan, "Matching Japan in Quality: How the Leading U.S. Semiconductor Firms Caught Up With the Best in Japan," MIT-Japan Working Paper, 1993.
15. C.A. Barron, "Microelectronics Survey: All That Is Electronic Does Not Glitter," *Economist*, March 1, 1980, pp. 3-4.
16. Finan, op. cit.
17. Ibid.
18. Ibid. Finan measures this increased spending on product quality as a doubling in the share of total firm expenses (operating, R&D, and capital outlays) devoted to quality improvement programs.
19. Ibid.
20. This multi-year research effort is a joint project of the College of Engineering, the Haas School of Business, and the Berkeley Roundtable on the International Economy at U.C. Berkeley. The Alfred P. Sloan Foundation and semiconductor producers from Asia, Europe and the United States have supported the project. Program directors are Dave Hodges and Robert Leachman of U.C. Berkeley's College of Engineering.
21. In a CSM working paper, Robert Leachman and Chien Leachman report fab performance in logic and memory devices for sub-micron CMOS processes using eight different performance metrics. National statistics are tabulated based upon fab location, rather than the nationality of the owner firm, but the data reported here contain no "transplants." The next several paragraphs draw on Leachman and Leachman, and the interested reader is referred to their paper for a more thorough discussion. R. Leachman and C. Leachman, "National Performance in

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Semiconductor Manufacturing," University of California, Berkeley Competitive Semiconductor Research Program working paper #CSM-40, 1997.

22. Japanese defect density data for logic products are available only for 1993, but during this period, their defect densities are far lower than those are for U.S. or other firms.
23. Leachman and Leachman, op. cit.
24. Such as "downloading" of recipes for specific device types to operators, helping to reduce errors.
25. Probe yield is the percentage of good die on a silicon wafer after the last electrical test for functionality before semiconductor devices are cut from the wafer, packaged, and assembled. It is similar to defect density, although it does not control for variation in die size.
26. The GAO study cited unpublished data from VLSI Research in this assessment. U.S. General Accounting Office, "Federal Research: SEMATECH's Technological Progress and Proposed R&D Program," July 1992.
27. Significant differences within the sample in fab organization and relationships with other corporate functions, such as R&D, process development, and the like mean that the amount of "indirect" labor, i.e., engineering and management staff, is likely to vary among fabs in this sample. "Direct" labor productivity should reduce the influence of these differences in the comparison of fab-level productivity.
28. Leachman and Leachman, op. cit.
29. For further discussion of these issues, see N.W. Hatch and D.C. Mowery, "Process Innovation and Learning by Doing in Semiconductor Manufacturing," *Management Science* (forthcoming 1998); M.M. Appleyard, N. Hatch, and D.C. Mowery, "Managing New Process Introduction in the Semiconductor Industry," in G. Dosi, R. Nelson, and S. Winter, eds., *Corporate Capabilities and Competitiveness* (London: Pinter, forthcoming).
30. Intel's integrated process development facility in northwest Oregon dramatically improved manufacturing yields from roughly 50% in the 1980s to nearly 90% by the mid-1990s, and it accelerated the "ramping" of production of new device designs. R.C. Cole, *Managing Quality Fads: How American Business Learned to Play the Quality Game* (New York, NY: Oxford University Press, 1998).
31. D. Takahashi, "Chip Makers Enter Slump; Sales Fall 13%," *Wall Street Journal*, July 6, 1998.
32. Modern chip facilities now cost more than $1 billion per plant, and many semiconductor firms have found it impossible to invest in new products or manufacturing capacity without some arrangement for risk-sharing.
33. The estimate of North American fabless firms was provided by the Fabless Semiconductor Association's *Fabless Forum*, 5/2 (July 1998). The estimate of the worldwide population of fabless firms was provided by the FSA through personal communication on August 1, 1998.
34. Major "pure-play foundries" include TSMC and UMC (both Taiwan), Chartered Semiconductor (Singapore) and Tower Semiconductor (Israel). New pure-play foundries include Anam (a Korean startup) and WSMC (a Taiwanese startup). The prevalence of Southeast Asian pure-play foundries is subsiding as merchant semiconductor producers from all nations are converting older facilities or dedicating entirely new facilities to provide foundry services to this industry. IBM Microelectronics (US), LG Semicon (Korea), Samsung (Korea), Winbond (Taiwan) and VLSI (US) are notable examples.
35. Access by fabless firms to foundry capacity was aided by rise to dominance of Metal-Oxide Semiconductor (MOS) manufacturing processes, which effectively standardized manufacturing technologies for commercial semiconductor devices.

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The diffusion of MOS production technology facilitated the division of labor between device designers in fabless firms, who were able to operate within relatively stable design rules, and foundries, who were able to incrementally improve their process technologies to accommodate a succession of new device designs.

36. Fabless Semiconductor Association, "State of the Fabless Business Model," mimeo, September 1997.
37. *Semiconductor Business News*, "Foundries May Build 40% of World's Chips by 2010," 1998.
38. Examples of departures from this pattern by U.S. firms are long-established, relatively small R&D organizations maintained for ten to thirty years by TI in Bedford, England, by IBM in Zurich and Tokyo, by Motorola in Hong Kong, and by Intel in Israel.
39. Philips, Siemens, NEC Hitachi, and Fujitsu are examples.
40. See W. Steinmueller, "Industry Structure and Government Policies in the U.S. and Japanese Integrated-Circuit Industries," in J.B. Shoven, ed., *Government Policy Towards Industry in the United States and Japan* (Cambridge: Cambridge University Press, 1988).
41. See National Research Council, Committee on Japan, *U.S.-Japan Strategic Alliances in the Semiconductor Industry: Technology Transfer, Competition, and Public Policy* (Washington, D.C.: National Academy Press, 1992).
42. See R.M. Ham and D.C. Mowery, "Improving the Effectiveness of Public-Private R&D Collaboration: Case Studies at a U.S. Weapons Laboratory," *Research Policy*, 26/6 (February 1998): 661-675.
43. This discussion of SEMATECH draws on P. Grindley, D.C. Mowery, and B. Silverman, "SEMATECH and Collaborative Research: Lessons in the Design of High-Technology Consortia," *Journal of Policy Analysis and Management*. (1994).
44. SEMATECH's founders included the following firms: Advanced Micro Devices; AT&T; Digital Equipment Corporation, Harris Corporation, Hewlett-Packard Company, Intel Corporation, IBM, LSI Logic, Micron Technology, Motorola, National Semiconductor, NCR, Rockwell International, and Texas Instruments. Three of the founding members of SEMATECH (Harris Semiconductor, LSI Logic, and Micron) left the consortium in 1991.
45. SEMATECH's federal funding ceased in 1996.
46. (Katz and Ordover, 1990; U.S. Congressional Budget Office, 1990) M.L. Katz and J.A. Ordover, "R&D Cooperation and Competition," *Brookings Papers on Economic Activity*, 1990; U.S. Congressional Budget Office, "SEMATECH's Efforts to Strengthen the U.S. Semiconductor Industry," Washington, D.C., 1990.
47. U.S. equipment producers have not increased their share of the Japanese market significantly during the 1990s but have benefited from the rapid growth in South Korean and Taiwanese markets, which were far easier to penetrate.
48. The Semiconductor Research Corporation (SRC) is funded by industry, the Defense Department, and more recently, by SEMATECH, to support university research that seeks to bolster an important portion of the U.S. research infrastructure, to attract faculty and students to work on problems of relevance to industry, and to attract high-quality students to seek employment opportunities in the U.S. semiconductor industry. State-level programs, such as the California MICRO program, pursued similar objectives through a combination of public and industry support. Finally, the Microelectronics Advanced Research Corporation (MARCO) is a new industry-financed collaborative research initiative that will support long-range university research on silicon IC technology.
49. In addition to paying dues totaling $100 million per year (which were matched by $100 million from federal sources), the member firms contributed roughly two-thirds of SEMATECH's 300-member research staff through temporary (usually 2-

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year) rotation of "assignees" at the consortium. Concurrently with the foundation of SEMATECH, U.S. semiconductor materials and equipment (SME) suppliers formed SEMI/SEMATECH to facilitate linkages between U.S. SME suppliers and SEMATECH. SEMI/SEMATECH has more than 100 members who account for more than 85 percent of U.S. SME sales.

50. R.M. Ham, G. Linden, and M.M. Appleyard, ""The Evolving Role of Semiconductor Consortia in the United States and Japan," *California Management Review,* 41/1 (Fall 1998).
51. National Science Foundation, *National Patterns of R&D Resources* (Washington, D.C.: National Science Foundation, 1996).
52. These firms are integrated from materials and components to system-level products, and their varied internal customers for semiconductors allow them to extend the productive life of their semiconductor production facilities. Their other businesses produce generous cash flows that help to offset the heavy R&D and investment costs of the capital-intensive semiconductor business.
53. Integrated Circuit Engineering Corporation (ICE), "Status: A Report on the Integrated Circuit Industry," Integrated Circuit Engineering, 1998.
54. Flamm provides the most objective account of the Agreement, and these paragraphs draw on his analysis. K. Flamm, *Mismanaged Trade? Strategic Policy and the Semiconductor Industry* (Washington, D.C.: Brookings Institution, 1996).
55. The Agreement's "price floor" nevertheless may have aided the remaining U.S. domestic producer of DRAMs, Micron Corporation.
56. The period following the Agreement was also associated with severe shortages of 256K DRAMs, then a vital component of personal computer and other electronic systems. U.S. computer producers, among others, blamed the Agreement and the informal, MITI-guided domestic production cartel that oversaw the Agreement's implementation within Japan for the shortages. Concern over DRAM shortages and the alleged Japanese cartelization of the DRAM market (a condition to which U.S. policy, in the form of the bilateral Trade Agreement, arguably had contributed) led to the proposal by a group of U.S. computer manufacturers to jointly fund the creation of a DRAM manufacturing consortium, U.S. Memories. As supplies of DRAMs became more abundant, this proposal was abandoned in early 1990.
57. Flamm, op. cit.
58. In late 1992, the foreign share of Japan's domestic consumption of semiconductor components increased beyond 20 percent, and recent data suggest that this share now is at roughly 25 percent. U.S. semiconductor components account for roughly 20 percent of domestic Japanese consumption, a significant increase from their 12.3 percent share in 1990. According to Flamm, this increase cannot be attributed solely to growth in Japanese consumption of microcomponent devices in which U.S. firms have a strong competitive advantage, but includes significant growth in other product areas. Flamm, op. cit.
59. U.S. antitrust policy played an important role in the earliest years of the semiconductor industry, as Bell Laboratories' liberal licensing of the original transistor and related patents was motivated in part by concern over the outcome of the federal government's antitrust suit against the firm that was settled in 1956. The 1956 settlement also led AT&T to manufacture semiconductor devices solely for internal consumption, rather than entering the commercial market. These early actions by the technological pioneer in semiconductors powerfully influenced the subsequent development of the U.S. semiconductor industry.
60. According to Katz and Ordover, at least 14 Congressional bills passed during the 1980s focused on strengthening domestic and international protection for intellectual property rights. The Court of Appeals for the Federal Circuit created in 1982

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has upheld patent rights in roughly 80% of the cases argued before it, a considerable increase from the pre-1982 rate of 30% for the Federal bench. Katz and Ordover, op. cit.

61. Mask works represent the three-dimensional pattern of the layers (the "topography") of a semiconductor component. H. Brown, "Fear and Loathing of the Paper Trail: Originality in Products of Reverse Engineering Under the Semiconductor Chip Protection Act as Analogized to the Fair Use of Nonfiction Literary Works," *Syracuse Law Review* (1990); R. Stern, *Semiconductor Chip Protection* (New York, NY: Law & Business, 1986).
62. This case, *Brooktree Corporation v. Advanced Micro Devices*, resulted in the award of $26 million in damages for AMD's infringement under the SCPA and several patents.
63. While semiconductor firms, particularly second sourcers, continue to study selected features, full copies of mask art are not practical anymore for the reasons stated. S. Kasch, "The Semiconductor Chip Protection Act: Past, Present and Future," *High Technology Law Journal* (1993).
64. The registration of mask works under the SCPA provisions has advantages over patent filings, which require the disclosure of proprietary information and a time-consuming search through prior art to assert validity. Mask work filing provides immediate registration at minimal cost without a time-consuming search.
65. The number of patents granted in the category "Semiconductor Devices and Manufacture" increased from 1,655 in 1981 to 5,427 in 1994. U.S. Department of Commerce: Patent & Trademark Office, "Technology Profile Report: Semiconductor Devices and Manufacture: 1/1969-12/1994," February1995.
66. P. Grindley and D.J. Teece, 1997. "Managing Intellectual Capital: Licensing and Cross-Licensing in Semiconductors and Electronics," *California Management Review*, 39/2 (Winter 1997): 8-41.
67. N. Rosenberg, "Uncertainty and Technological Change," in R. Landau, T. Taylor, and G. Wright, eds., *The Mosaic of Economic Growth* (Stanford, CA: Stanford University Press, 1996).

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