CHAPTER 2

The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry, 1947–1996

RICHARD N. LANGLOIS AND
W. EDWARD STEINMUELLER

Introduction

In the half century of its existence, the business of semiconductor manufacture has come to capture the popular imagination as few others have. Starting with only the most common of raw materials – silicon and aluminum – this industry constructs complex electronic systems performing functions that were science fiction only a few decades ago. Even so, the volume of literature on this industry would no doubt have been smaller if the technological and scientific leadership of the United States in that industry had not come under challenge by the emergence of international competition.

The decline of the global market share of American semiconductor producers in the mid-1980s suggested to many that the days of American dominance of science-based industries might be numbered. Although there is little evidence that international competitors had in mind the annihilation of the American industry, many nonetheless read the situation in terms familiar from the Cold War. The loss of American leadership in the semiconductor industry would be the first domino in a cascading fall of downstream electronic-systems industries.[1] Looking through the other end of this same telescope, America's foreign competitors asked the parallel question: How could one possibly succeed in *building* electronic-systems industries without developing a robust semiconductor industry of one's own?

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[1] Among the more hysterical versions of this thesis are Ferguson (1985) and Forester (1993). The latter, indeed, is testimony to the inertia of intellectual fashion, as the bulk of its assertions and predictions had already been falsified by the time the book was published. By contrast, Ferguson had essentially recanted his earlier views by that time (Ferguson and Morris, 1993).

The voluminous literature generated from the rise of foreign – especially Japanese – competition in semiconductors seemed to have one dominant theme: the United States must not merely learn from but closely imitate Japan. Most analysts assured us, implicitly or explicitly, that Japanese success reflected inherent superiorities in industrial structure and state policy, superiorities of a widely applicable and lasting kind. In its strongest form, the lesson from Japan was read in terms of the inevitable eclipse of the structures of entrepreneurial capitalism by some form of systematic planning, usually of the corporatist or state-corporatist variety.[2] A weaker variant simply indicted the American semiconductor industry and its domestic suppliers for excessive "fragmentation" and vertical disintegration. Writers like Ferguson (1988) and Florida and Kenney (1990) suggested that American faith in industrial districts like Silicon Valley had been misplaced and that only imitating the Japanese *keiretsu* structure would improve the performance of the American industry. This view was echoed by the prestigious MIT Commission on Industrial Productivity, which declared in 1989 that "the traditional structure and institutions of the U.S. industry appear to be inappropriate for meeting the challenge of the much stronger and better-organized Japanese competition" (MIT Commission, 1989, vol. 2, p. 20). The commission pronounced the American merchant semiconductor industry "too fragmented" and called for consolidation and rationalization.

This chapter offers a different, and perhaps even iconoclastic, explanation for the rise, decline, and resurrection of the American semiconductor industry. We argue that industrial leadership is a history-dependent process in which success rests upon the fit between exogenous (or quasi-exogenous) factors and the structures of knowledge, organization, and capability inherited from the past.[3] There is no one "optimal" industrial structure or policy regime independent of time and circumstance. In our story, Japanese success in the 1980s – like American leadership early on and like the renewed American success today – is a matter not of universal and time-invariant superiorities but of a complex of contingent factors and circumstances. There are certainly lessons from the Japanese success. But those lessons must be read carefully and in the proper context.

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[2] Corporatism, the coordination of control by an oligarchy of industrial interests, is the underlying hypothesis in Fallows (1994); state corporatism, corporatism under state direction, is the fundamental position of Johnson (1982). All of the studies that view Japanese industrial structure in terms of strongly unified purpose and relatively smooth coordination make the implicit argument that this structure for control is, or tends to be, inherently superior to the more divided and contentious structures prevailing in the United States.

[3] This theme is developed in greater detail and generality in Langlois and Robertson (1995), especially chapters 6 and 7.

Our perspective is informed by the view that competitive advantage ultimately resides in the industrial capabilities of the firms in an industry, even if those capabilities are conditioned on and affected by various background institutions and policies.[4] The significance of economic capabilities – what G. B. Richardson (1972), who coined the term, defined as the "knowledge, experience and skills" of the enterprise – is that they are most often hard to learn; tacit; unpredictable in the rate and direction of their acquisition; and often very difficult to abandon or forget.[5] It is precisely these characteristics of capabilities that make it very difficult for companies in this industry to relocate to positions of advantage when circumstances change. Because the better part of these capabilities evolve from the interactions between semiconductor firms and their customers and from the division of labor within the semiconductor industry, history matters.

Our story is thus one in which background conditions and starting points are as significant as corporate strategy and government policy. Corporate strategies, we will see, are often constrained by circumstance, and government policies often have effects very different from those intended. One centerpiece of our account is the prominent role we give to the extent and structure of end-use demand – a largely exogenous factor – in shaping the fortunes of companies and national industries.

Not surprisingly, we use history to convey our arguments. In what follows, we chronicle in order three major episodes of regional competitive advantage: the early rise of American industry, the challenge posed by Japanese firms in the late 1970s and 1980s, and the recent resurgence of American industry, coupled with the rise of new East Asian producers and growing internationalization. We close with a brief perspective on this history.

I. America's Rise to Dominance

The Invention of the Transistor

The invention of the transistor by Bardeen, Brattain, and Shockley at the Bell Telephone Laboratories after World War II is an oft-told story (Braun and Macdonald, 1978; Morris, 1990; Nelson, 1962). It was an innovation made possible by modern physics and intimately connected to basic research. Interestingly, however, the research was carried out not

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[4] Such background institutions and policies are what Nelson (1993) and Lundvall (1992) call "national systems of innovation."

[5] On the notion of capabilities see also Nelson and Winter (1982).

in universities but in one of America's premier corporate research laboratories.[6]

Even though the initial transistors were relatively primitive devices, their potential as a major invention was widely appreciated. AT&T sought and received patents for the first working transistor design, raising the prospect that the company would eventually be able to influence the entire spectrum of electronic industries. Despite this, AT&T immediately undertook a policy of broad public disclosure of the enabling technologies for producing transistors, announced widespread licensing of both original and subsequent transistor patents, and encouraged site visits to interested parties to assure the transfer of the technology to those interested in pursuing the development of the invention (Tilton, 1971, pp. 75–76; Braun and Macdonald, 1978, pp. 54–55).

AT&T had long pursued a policy of cross-licensing agreements, which allowed it to gain from the inventive efforts of others. Although AT&T had developed the transistor and begun using it early in telephone devices and circuits, it was still an extremely immature technology. By allowing access to the transistor, AT&T was betting, in effect, that the spillover benefits to telephony from tapping the capabilities of others would outweigh the forgone revenues of proprietary development (McHugh, 1949; Bello, 1953; Braun and Macdonald, 1978, p. 54; Levin, 1982, pp. 76–77). An AT&T vice president put it this way: "We realized that if this thing [the transistor] was as big as we thought, we couldn't keep it to ourselves and we couldn't make all the technical contributions. It was to our interest to spread it around. If you cast your bread on the water, sometimes it comes back angel food cake."[7] The consequence of this action was thus to create a large cohort of entrants intent on finding ways to commercialize the new technology (Mowery and Steinmueller, 1994). Few industries can claim such an early widespread diffusion of their core technology, which in this case generated intense rivalry to develop competitive advantage by leading in the improvement of the breakthrough innovation.

For the incumbent electronic-component producers, the vacuum-tube firms, the transistor was in large measure a competence-destroying innovation.[8] These firms nonetheless quickly saw the value of the device. At least in part, this was because the transistor remained undeveloped and

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[6] It will be a minor theme in this essay – albeit a theme articulated importantly by omission – that universities have played only an indirect role in the development of the semiconductor industry.

[7] Quotation attributed to Jack Morton, in "The Improbable Years," *Electronics* 41: 81 (February 19, 1968), quoted in Tilton (1971, pp. 75–76).

[8] A competence-destroying innovation is one that renders obsolete an organization's existing knowledge and capabilities (Tushman and Anderson, 1986).

even experimental, and much of the transistor work in the vacuum-tube firms took place in large R&D facilities not unlike Bell Labs. Moreover, although these firms produced vacuum tubes, they were diversified systems companies rather than specialists in tube production. Thus, although the transistor was competence destroying for the firm's vacuum-tube operations, it was competence enhancing for the firm as a whole. Nonetheless, as we will see, the near-term future in semiconductors did not belong to the established players but to smaller, newer, more-focused enterprises. Many of these benefited from personnel who left Bell Labs to pursue the development of the transistor elsewhere, establishing a pattern of personnel defection and spin-off that continues today in the United States.

For example, William Shockley left Bell Labs in the early 1950s for the San Francisco peninsula, where he founded Shockley Semiconductor Laboratories. Although his enterprise was never a commercial success, eight of Shockley's team defected in 1957 to found the semiconductor division of Fairchild Camera and Instrument Corporation, an organization of seminal importance in the industry. Largely through the efforts of Jean Hoerni, one of the eight defectors, Fairchild developed the planar process, a technology that allowed large-scale batch production of transistors. Almost immediately, Hoerni's colleague and fellow defector Robert Noyce would extend the planar process to the fabrication of multi-transistor devices – integrated circuits (ICs). The advantages of the planar process for transistor production were overwhelming and recognized immediately throughout the industry (Sparkes, 1973, p. 8). By 1968, Noyce and others had left Fairchild to found the next generation of semiconductor firms. As Saxenian (1994) and others have argued, the localization of many of these firms on the San Franciso peninsula created the kind of industrial district discussed by Alfred Marshall (1961), generating a self-reinforcing system of external economies.

The Role of Demand. The market for semiconductors began with the U.S. military, and it was the Cold War that nurtured this industry in its infancy. Although the transistor provided a practical means to make portable hearing aids and radios, its primary value during its early years lay in military systems, where performance rather than cost is often the deciding factor in adopting new technology.[9] Moreover, the nature of military – and later computer – demand affected the technological trajectory of development in the American industry. Because of its tractabil-

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[9] Indeed, Bell's haste in announcing the transistor was motivated at least in part by a desire to preempt any thought the military might have of classifying the technology (Levin, 1982, p. 58).

ity, germanium was the material of choice for transistors destined for consumer markets, where cost considerations dominated, and, as we will see, both Europe and Japan concentrated on this type of transistor early on. The silicon transistor, perfected by Gordon Teal (1976) at Texas Instruments (TI), was more expensive, but the stability of its electrical properties over a wider range of temperatures made it superior for military and space applications. Silicon also proved superior in digital switching applications, where speed was of importance.

Military demand for semiconductors provided several "spillovers" from the development of military devices to civilian applications. Much of this spillover was simply the consequence of accumulating a substantial practical knowledge base about transistor production using the continued revenue flow from military procurement.[10] Without this indirect research finance, American firms would likely have developed the technology at a pace and in directions similar to those of companies in Japan and Europe during this period. But military performance requirements in the United States stimulated the development of transistors with grown rather than contact junctions and encouraged the rapid ascendancy in the United States of silicon over germanium transistors. As Table 2.1 indicates, the unit production of germanium transistors outpaced that of silicon transistors through 1965. Throughout this period, production volumes increased and prices declined with greater experience. In 1957, three years after its first commercial production, the silicon transistor was still an expensive specialty item, the most important uses of which were military applications. The rapid price decline thereafter – much sharper than had been the case for germanium (see Table 2.1) – reflects the production advantages of the planar process for silicon.[11]

There can be little doubt of the importance of military and space demand for the pace and direction of technological change and cost reduction in this early period of the industry's development. Between 1955 and 1958, government procurement absorbed between 36 and 39 percent of industry output, a share that shot up to 45 and 48 percent in 1959–1960.[12] After a 1960 peak in which government demand was $258

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[10] Between 1955 and 1959, the prices of transistors for the military market remained four times greater (despite price reductions in both categories of demand) than those for the civilian market (Kleiman, 1966, p. 81).

[11] The physical characteristics of germanium made it unsuitable to the planar process.

[12] The share includes devices produced for the Department of Defense, the Atomic Energy Commission, the Central Intelligence Agency, the Federal Aviation Administration, and NASA (Levin, 1982, p. 60). The share of the consumption in the years 1952–1954, for which no data are available, was similar to that in the peak year, 1960, or about 50 percent of the market (Kraus, 1971, p. 91).

Table 2.1. *U.S. Sales of Germanium and Silicon Transistors (Nominal $)*

	Germanium		*Silicon*	
	Units (M)	Average Value ($)	Units (M)	Average Value ($)
1957	27.7	1.85	1.0	17.81
1958	45.0	1.79	2.1	15.57
1959	77.5	1.96	4.8	14.53
1960	119.1	1.70	8.8	11.27
1961	177.9	1.14	13.0	7.48
1962	213.7	0.82	26.6	4.39
1963	249.4	0.69	50.6	2.65
1964	288.8	0.57	118.1	1.46
1965	333.6	0.50	274.5	0.86

Source: EIA (1974, p. 87).

million, however, government expenditures began to be outstripped by commercial demand for semiconductors. Although the level of government expenditures between 1960 and 1977 fell below $200 million in only two years,[13] the government share of the market in the latter half of the period fluctuated between 8 and 12 percent.

Commercial semiconductor markets began to develop in the late 1950s. Table 2.2 indicates that by 1963 the computer industry had already generated substantial demand for semiconductors.[14] In that year, computer demand roughly equaled the entire consumer-electronics market for transistors. Despite the origins of the transistor in the communica-

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[13] The years were 1964 and 1971.

[14] This table reflects a methodology different from the one Levin (1982) used to determine the share of government consumption of semiconductor output. Dodson (1966) focused exclusively on transistors, a measure that raises the estimated average price of a semiconductor sold to the government. It is also likely that he underestimated the total transistor market, which would shift the shares of various demand segments. According to the Business Defense Service Agency, at that time a unit of the Department of Commerce, the value of transistor shipments in 1963 was $311.7 million or about $60 million (25 percent) greater than Dodson's figure. Despite these limitations, Dodson's is the best available study of the structure of final demand for this period.

Table 2.2. *Value of U.S. Transistors by End-Use, 1963*

Military		*Industrial*		*Consumer*	
Space	33.0	Computers	41.6	Car radios	20.6
Aircraft	22.8	Communications	16.0	Portable radios	12.6
Missiles	20.3	Test and measuring	11.7	Organs and hearing aids	7.3
Communications	16.8	Controls	11.5		
Surface systems	10.8	Other	11.5	Television	0.3
Strategic systems	8.8				
Other	6.7				
Total:	**119.2**		**92.3**		**40.8**
Percent:	**47.2**		**36.6**		**16.2**

Source: Dodson (1966, pp. 95–97).

tions industry, civilian demand for transistors in communications was lower than that for military communications.[15]

The Role of American Government Policy. Procurement demand was arguably the most important – and the most salutary – aspect of government policy toward the semiconductor industry in this period. But it was by no means the only aspect. The military provided direct support both for R&D and for production as well as indirect support through military systems contractors.[16] Military efforts to improve the uptake of semiconductor technology continued throughout the 1950s.[17] Table 2.3 presents some estimates of direct government expenditures for R&D and production refinement. According to a Defense Department report, the military also funded R&D indirectly through its defense systems contractors, to the tune of $13.9 million in 1958 and $16.2 million in 1959,

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[15] The U.S. consumer market for transistors was dominated by portable radio applications. Non-portable radios continued to be produced with vacuum tubes.

[16] Examples include R&D contracts to Bell (Levin, 1982, p. 67) and Army Signal Corps R&D and pilot manufacturing line contracts with Western Electric, GE, Raytheon, RCA, and Sylvania (Kraus, 1971).

[17] In that same year, the Signal Corps committed $14 million to fund "production refinement" at 12 firms and proceeded to spend a total of about $50 million on support for production engineering measures (PEM) between 1952 and 1964.

Table 2.3. *Estimated U.S. Government Direct Funding for R&D and Production Refinement, 1955–1961*

	1955	1956	1957	1958	1959	1960	1961	Totals
Research and development	3.2	4.1	3.8	4.0	6.3	6.8	11.0	39.3
Production refinement								
Transistors	2.7	14.0	0.0	1.9	1.0	0.0	1.7	**21.3**
Diodes and rectifiers	2.2	0.8	0.5	0.2	0.0	1.1	0.8	5.6
Total	**8.1**	**18.9**	**4.3**	**6.1**	**7.3**	**7.9**	**13.5**	**66.1**

Source: U.S. Department of Commerce (1961, p. 13, Table 8).

for example. The same report claims that government-sponsored R&D (both direct and indirect) accounted for about a quarter of all semiconductor R&D in those years (Tilton, 1971, p. 93).

These R&D and production-development activities were not as effective in pushing the industry along as were the fact and extent of government demand itself. All the major breakthroughs in transistors were developed privately with the military market (among others) in mind. Despite the $5 million in government R&D on silicon transistors, it was private work at Texas Instruments that yielded results (Teal, 1976). And the planar process, developed privately with the military market in view, rendered obsolete most of the production lines that the military had helped fund (Sparkes, 1973, p. 8).

The government tended to favor R&D contracts with established suppliers, notably the vacuum-tube firms. In 1959, for example, Western Electric and eight established vacuum-tube firms received 78 percent of the government's R&D funding despite accounting for only half of private R&D activity in the industry and only 37 percent of semiconductor sales (see Table 2.4). By contrast, the military was far less biased toward established firms in its role as buyer: in the same year, new firms accounted for 63 percent of all semiconductor sales, but 69 percent of sales to the military (Tilton, 1971, p. 91). The pragmatic policy of awarding work to those firms that could meet supply requirements was particularly important for encouraging new entry, both in the transistor era and in the subsequent development of the integrated circuit.

Competitors in the Wings: European and Japanese Developments. Especially outside the United States, it is common to hear the role of the

Table 2.4. *R&D Funding and Sales in the United States, 1959, by Type of Firm*

	Government R&D funds		Company R&D funds		Semiconductor sales	
Type of firm	*$ million*	*Percent*	*$ million*	*Percent*	*$ million*	*Percent*
"Old" firms	12.7	78	27.2	50	149.5	37
New firms	3.5	22	26.8	50	252.1	63
Total	16.2	100	54.0	100	401.6	100

Note: "Old" firms are Western Electric and eight vacuum-tube firms.
Source: Tilton (1971).

American military in the early semiconductor industry described as an implicit industrial policy accounting for much of America's rise to dominance in the industry, especially with respect to Europe. And there is certainly no disputing the importance of military demand for the growth of the American industry. On the other hand, however, European firms remained competitive in the market for germanium transistors through at least 1964. As we saw, the germanium transistor remained viable in Europe later into the 1960s because of the characteristics of that continent's end-use markets for transistors[18] (Malerba, 1985, pp. 75–80, 88–89). Table 2.5 suggests the relative sizes of the American, Japanese, and European industries in this period.

The incentive for European firms to keep pace with American developments was limited by several factors – the dominance of European consumer over computer markets, the persistence of larger vertically integrated systems firms who viewed transistors as a necessary input into electronic system products rather than as an end product (Malerba, 1985); and the effective closure of the market for American military and space contracts because of the military's "Buy American" policy and similar policies at NASA (Skole, 1968). European firms concentrated on indigenous European markets for consumer products and industrial applications and were not crowded out by American competitors. Neither international trade nor foreign direct investment was a major factor in this period (Tilton, 1971, p. 44).

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[18] In Europe, the other distinctive competence was in semiconductor power devices, including the silicon rectifier. Unfortunately for European producers, there were few technological spillovers from the silicon rectifier to other silicon semiconductor products.

Table 2.5. *Production and Consumption of Semiconductors by Country, Selected Years*

Country	Consumption (1956)	Production (1958)	Consumption (1960)	Production (1961)
United States	80	236	560	607
Japan	5	19	54	78
W. Germany	3	10	25	30
Great Britain	2	8	28	35
France	2	8	27	32

Note: $ million (nominal).
Source: Malerba (1985).

The follower strategy of European firms meant that their competitiveness hinged on the ability to adopt advances developed elsewhere. And the R&D capabilities of large European firms initially provided the "absorptive capacity" to follow closely new developments.[19] Significantly, the European firms tended to license technology almost exclusively from those American firms whom they most resembled and almost not at all from the American merchant houses (Malerba, 1985, p. 65). Without a large local military and computer market, integrated electronic system companies prevailed in Europe, resulting in the eventual dependence of these companies on foreign suppliers in the silicon transistor and integrated circuit eras.

Although the early origins of the Japanese semiconductor industry are broadly similar to those of the European, a few significant differences were to prove crucial in explaining the distinctive path of Japanese development in later periods. As in Europe, the principal producers of transistors in the 1950s and 1960s were diversified electronic system companies, including firms that had previously produced vacuum tubes, rather than companies that were principally specialized in semiconductor production. And, as in Europe, the main end-use for transistors in Japan in this period was consumer products rather than the military.

Unlike their European and American counterparts, Japanese firms engaged in – and the Japanese government subsidized – virtually no basic research during this period. The R&D they did undertake was geared

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[19] To use the terminology of Cohen and Levinthal (1990).

toward what Kodama (1995, p. 24) picturesquely describes as the "digestion" of foreign technology. The absence of a domestic scientific base forced Japanese companies to adopt a critical and wide-ranging search for new ideas from all sources. This practice was reinforced by Japanese trade policy. Like Europe, Japan responded to American competitive advantage with high tariffs; in addition, Japan imposed quotas and registration requirements (Tyson and Yoffie, 1993, p. 37). In contrast to European governments, moreover, the Japanese government essentially forbade foreign direct investment, thus allowing American firms to tap the Japanese market only through direct export or licensing and technology sales to Japanese firms.[20]

With this combination of policies, Japan was able to achieve a net export surplus in semiconductors from 1956 to 1968.[21] Fundamentally, this strong export position was a consequence of specialization. In 1963, Japanese system output was only $1.2 billion compared to $5.7 billion in Europe and $14 billion in the United States.[22] But Japanese companies developed the transistor as a commodity component for the rapidly growing transistor-radio market, an export market that Japan was able to retain despite much larger rivals in foreign markets.[23] This specialization became a disadvantage, however, as silicon began to replace germanium as the material of choice for transistors. Beginning in 1961, Japanese imports of transistors expanded at a 45 percent annual growth rate, eventually overtaking exports in 1968.

Japanese government policy toward the electronics industry focused on financing export expansion as well as attempting to channel foreign technology toward companies that were most likely to use it productively, a strategy reinforcing the position of incumbents that only a few companies, notably Sony, were able to bypass. The position of incumbents was also reinforced by the fact that Nippon Telephone and Telegraph

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[20] Japanese companies have typically supplied some 90 percent of the Japanese semiconductor market, whereas American firms – through imports or foreign direct investment – have supplied between 50 and 70 percent of the European market (Tyson and Yoffie, 1993, p. 34).

[21] Computed from Tilton (1971, p. 45). After 1968, Japan experienced a net import balance for eight years (Dosi, 1984, p. 255), or until nearly the beginning of the period of the Japanese challenge to U.S. dominance discussed later.

[22] The size of the Japanese final electronics production market is from Tilton (1971); that for Europe and the United States is from Sciberras (1977, p. 49). Sciberras cites a Texas Instruments estimate reported by Carrell (1968), an article Tilton (1971) also cites.

[23] The evidence for this is somewhat circumstantial. In 1957 and 1958, Tilton (1971) estimates, transistor radios absorbed two-thirds of Japanese transistor production, a share that fell moderately on an annual basis until it reached one-third in 1964 (p. 157). The years 1957 and 1958 are also the years in which Japan achieved its large net export position in transistors, whereas from 1965 export growth is essentially nil for four years (Dosi, 1984, p. 255).

(NTT), the state telephone monopoly, pursued a policy of buying only from four principal suppliers.[24] The Japanese government also sought increased concentration in the domestic computer industry – without much success. In 1970 there were still six mainframe producers, collectively holding a 50 percent market share in the Japanese domestic market (Fransman, 1990, p. 38). In short, although Japan did pursue industrial policies, it is not clear whether those policies bear direct responsbility for that country's industrial performance in this period. What is clear, however, is that the Japanese electronics industry was able to expand relative to that of the United States and Europe during the 1960s, attaining a level of about $3.25 billion by 1968 compared to Europe's $7.7 billion and America's $24 billion. A central feature of this expansion was that 70 percent of the market for Japanese semiconductor products remained in consumer electronics.

Because the Japanese vacuum-tube firms were much smaller than their American or European counterparts at the beginning of the transistor era, they had less to lose in moving to the new technology. As Tilton (1971, p. 154) notes, rapid growth "also helped create a receptive attitude toward change on the part of the receiving tube producers by reducing the risks associated with new products and new technologies and by increasing costs, in terms of declining market shares, to firms content simply to maintain the status quo." This meant that Japanese systems firms faced many of the same constraints, and adopted many of the same approaches, as the American merchant firms rather than those of the American, or European, systems houses.[25] Moreover, as Michael Porter (1990, pp. 117–122) has pointed out, the large number of actual and potential semiconductor producers in Japan led to a vibrant domestic rivalry that sharpened and focused Japanese firms. As we will see, this is in contrast to the "national champions" approach that was to develop in Europe.

The Integrated-Circuit (IC) Era

In 1958 and 1959, two Americans, Jack Kilby of Texas Instruments and Robert Noyce of Fairchild, were the first to devise practical monolithic circuits. Noyce's approach, based on the planar process that had revolutionized transistor production, was the more immediately practical. After

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[24] Fransman (1995) labels this policy "controlled competition." The principal suppliers were NEC, Fujitsu, Hitachi, and Oki.

[25] Unlike European firms, the Japanese firms sought and received licenses from Texas Instruments, Fairchild, and other American merchant firms rather than limiting themselves to arrangements with American systems houses.

struggling over patent claims, the two companies forged a cross-licensing agreement in 1966 that effectively gave them joint claim on the invention. Each company granted licenses to all comers in the range of 2 to 4 percent of IC profits (Reid, 1984, pp. 94–95). This practice reproduced and extended the technology-licensing policies of AT&T, again broadly diffusing the core technological innovation to all entrants.

Incremental technical improvement of the planar process helped set the paradigm or "technological trajectory" for the industry. Improving this process made it possible to increase the number of transistors per IC dramatically over time. Transistor counts per IC increased from 10 to 4,000 in the first decade of the industry's history; from 4,000 to over 500,000 in the second decade; and from 500,000 to 100 million in the third decade.[26] For the first two decades, the 10-million-fold increase in the number of transistors per IC was accompanied by modest increases in the cost of batch processing of a wafer, and almost no change in the average costs of processing the individual IC. This factor alone has been responsible for the enormous cost reduction in electronic circuitry since the birth of the IC and for the production of previously expensive electronic systems on a single IC. Reductions in the cost of components have lowered the cost of electronic systems relative to mechanical ones across a very wide range of applications and have reduced the price of electronic goods relative to all other goods and services in the economy – developments that have led to sustained high growth rates in the electronic systems and semiconductor industries and to changes in industrial structure in both industries.

The Development of the Industry: The Actors. The opportunity created by the IC during the period 1959–1966 produced a wave of new entry into the industry (Wilson et al., 1980, p. 14; Hannan and Freeman, 1989, p. 226). A significant feature of the transition was the disappearance of the vertically integrated American electronics companies that had led in the production of vacuum tubes and that had been able to stay in the race during the discrete semiconductor era. The market shares of those firms declined in the face of new entrants and the growth of relatively specialized manufacturers like TI, Fairchild, and Motorola. As Table 2.6 suggests, by 1965, the vertically integrated system firms had fallen from the top 5 slots in American semiconductor sales, and by 1975 all but RCA had fallen off the top-10 list.

Why did the vertically integrated electronic system firms do so poorly

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[26] As size of structures on the silicon crystal is reduced, it has become possible to build denser and more complex arrays of such structures on a crystal of a given size. This is the principal determinant of the increase in transistor count.

Table 2.6. *Leading U.S. Merchant Semiconductor Manufacturers, 1955–1975*

1955 *Transistors*	*1960* *Semiconductors*	*1965* *Semiconductors*	*1975* *Integrated Circuits*
Hughes	Texas Instruments	Texas Instruments	Texas Instruments
Transitron	Transitron	Motorola	Fairchild
Philco	Philco	Fairchild	National
Sylvania	General Electric	General Instrument	Intel
Texas Instruments	RCA	General Electric	Motorola
General Electric	Motorola	RCA	Rockwell
RCA	Clevite	Sprague	General Instrument
Westinghouse	Fairchild	Philco-Ford	RCA
Motorola	Hughes	Transitron	Signetics (Phillips)
Clevite	Sylvania	Raytheon	American Microsystems

Source: Mackintosh (1978, p. 54).

in this era? Wilson, Ashton, and Egan (1980) point out that the new leaders were either specialized start-ups or multidivisional firms (like TI, Fairchild, and Motorola) in which the semiconductor division dominated overall corporate strategy and in which semiconductor operations absorbed a significant portion of the attention of central management. By contrast, the semiconductor divisions of the integrated system firms were a small part of corporate sales and of corporate strategy, thereby attracting a smaller portion of managerial attention and receiving less autonomy.

This is consistent with the literature of management strategy urging corporations to cultivate their "core competences" and to recognize that deviation from these competences is risky (Teece, 1986; Prahalad and Hamel, 1990). Indeed, recent evidence suggests that specialized competence is important not so much in the core technology itself as in the complementary activities necessary to transform the technology into high-demand products (Christensen and Rosenbloom, 1995). Granstrand, Patel, and Pavitt (1997) argue in general that firms should not try to limit their core competences but rather should strive to widen those competences while retaining focus in complementary and downstream activities. Gambardella and Torrisi (1998) show that electronics firms in the 1980s did better when they narrowed their product focus while expanding their technological competences. Such product specialization is arguably of even greater value when market and technological opportunities are expanding rapidly along a well-defined trajectory (Patel and Pavitt, 1997, p. 153). American merchants in the integrated-circuit era arguably followed this advice: they expanded their technological competence in semiconductor design and fabrication while limiting their product diversification (relative to that of the large system houses) in a way that was shaped by the pattern of end-use demand. As we will see presently, however, the product diversity of American merchants did grow over time, to an extent that was to make them vulnerable to a challenge from even more narrowly focused Japanese firms wielding wide technological capabilities.

The Pattern of Demand. The price advantage of the integrated circuit compared with the transistor assured a relatively rapid diffusion of the new technology. It did not, however, immediately create major shifts in the electronic-system industries. During the first half of the 1960s, the methods for IC manufacturing were still under development and the technical characteristics of the ICs were limited, particularly for use in analog circuits.[27] But the technical capabilities of ICs were ideal for digital circuits, the major customers for which were the military (to which we return later) and the computer industry.

The 1960s was a period of rapid growth for the American computer industry. The leading firm, IBM, had built up its position during the 1950s by relying heavily on outside suppliers. In 1957, IBM had selected TI as its lead supplier, signing an agreement for "exchange of patent licenses, purchasing arrangements, interchange of technical information, and joint development" of semiconductors (Bashe et al., 1986, p. 402). Under this agreement, IBM designed what company biographers describe as the world's first automated transistor production line, which they disassembled in 1959 and shipped to TI (Bashe et al., 1986, pp. 400–402; Pugh et al., 1991, p. 64). By 1960, however, IBM had created its own components division, which geared up to make semiconductors for the phenomenally successful IBM 360 Series, announced in 1964.[28] By the 1970s, IBM's

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[27] Analog circuits involve the continuous variation of current or voltage, in contrast to the on-or-off character of digital circuits.

[28] IBM's decision to create internal capabilities in semiconductors and many other components was apparently based on a conscious perception of economies of scope between

dominance in computers had made it the world's largest producer of ICs. Thus the vertical division of labor in the United States became markedly different from, and more diverse than, that in Europe and Japan. Many small, highly specialized merchant firms dealing with relatively autonomous systems companies stood alongside a handful of large, vertically integrated captive producers.[29]

Merchant semiconductor firms faced basically two options. One class of product strategies involved making high-volume standard products, notably memories. Despite IBM's moves to convert from ferrite-core to semiconductor memory, this market continued to be relatively small until 1972. In that year, Intel's 1003 became the best-selling IC in the world, accounting for more than 90 percent of the company's $23.4 million in revenue in that year (Cogan and Burgelman, 1989). The other class of product strategies involved attempting to use the rapidly growing complexity of ICs in the large-scale integration (LSI) period to create differentiated products. For a time, American firms were able to do well with both sets of strategies.

The Role of American Government Policy. The other crucial influence on the American semiconductor industry continued to be the federal government, through its role as both an end-use demander and a supplier of research and development. Because of two technical goals – miniaturization and high reliability – the military was willing to pay the high prices the earliest devices commanded. Military use came to dominate other sources of demand for the early ICs.

Each of the U.S. military services had undertaken a research program in the area of miniaturization aimed at increasing circuit density.[30] In the uncertain world of innovation, there will normally be many different approaches that seemed promising ex ante but appear mistaken – or even silly – ex post. Nonetheless, it remains significant that the technologies pushed by the military were all ex post failures, whereas the successful paradigmatic innovation occurred at the hands of private

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component design and computer design. Especially in the era before large-scale integrated circuits, processing speed depended on the integration of component and system, and IBM wished to preserve the ability to adjust both component and system simultaneously instead of responding to autonomous changes in components fabricated – even at low cost – by outside suppliers. Moreover, in a world of centralized mainframe computers, reliability is crucial, and IBM wished to control directly as many determinants of quality as possible (Langlois, 1997).

[29] The other major American captive producer was AT&T. These two American captives also behaved differently than their integrated counterparts overseas in that they generally refrained from selling on the merchant market at all – because of legal constraint in the case of AT&T and of company policy in the case of IBM.

[30] These programs are documented in Kleiman (1966).

companies – Fairchild and TI – whose successful projects had received no government support. The most valuable input from the government may have been its keeping in the air knowledge of the military's fervent desire for miniaturization (Kleiman, 1966, pp. 203–204), an end-use need that was quite abstract and easy to convey. The specific programs themselves were costly not only in direct terms but also in terms of the resources diverted, especially at the companies like RCA and Westinghouse that participated most heavily, a participation that may have contributed to their falling behind in the IC era.[31] Overall, the government, including NASA, spent $32 million on IC R&D between 1959 and 1964, with 70 percent of that coming from the Air Force (Kleiman, 1966, p. 201).

The government also provided much of the early demand for the IC. Along with Westinghouse and RCA, Texas Instruments participated in the *Minuteman II* Program, the first major military use of ICs (Kleiman, 1966, p. 195; Levin, 1982, p. 62). And, while shunning military markets, Fairchild was the major IC vendor to NASA for the *Apollo* Project (Levin, 1982, p. 62). These early purchases hastened American firms down the slopes of their learning curves. And the government insistence on second sourcing sped the diffusion of IC technology. As IC prices fell, however, civilian uses, especially for the computer, quickly came to dominate government procurement (Table 2.7).

European Developments in the IC Era. Much of the technological gap that opened between European and American firms in the period of the integrated circuit was the result of the relative absence of the computer and military demand the United States enjoyed, although there were certainly other factors at work. The European semiconductor producers of the transistor era were mostly large vertically integrated systems firms. These firms naturally specialized – and were successful – in producing transistors to substitute for tubes in consumer and industrial applications. The strong growth in digital IC technology in the United States for computers and military applications was leading to what would become the next generation of components – components for which the capabilities of European firms were less relevant.

Indeed, in the early 1960s, the largest firms, including Philips and Siemens, were reluctant to switch from germanium technology, in which

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[31] Kleiman (1966, p. 187) reports, for example, that Westinghouse diverted some 50 professionals to the molecular electronics project. Of course, part of the reason that Westinghouse was willing to take on the project was that its opportunity costs of doing so were much lower than those of leading semiconductor firms like TI or Fairchild (Kleiman, 1966, p. 185).

Table 2.7. *End-Use Shares of Total U.S. Sales of Integrated Circuits and Total Market Value 1962–1978*

Markets	1962	1965	1969	1974	1978
Government	100%	55%	36%	20%	10%
Computer	0	35	44	36	38
Industrial	0	9	16	30	38
Consumer	0	1	4	15	15
Total U.S. domestic shipments (millions)	$4	$79	$413	$1,204	$2,080

Source: Borrus et al. (1983, p. 159).

they were skilled and successful and which was more useful in consumer applications than silicon.[32] These firms were also late to begin IC production, a technology for which they foresaw little demand. And, when they did begin IC production in the late 1960s, it was typically first in linear ICs for internal customers rather than in digital ICs, a field in which they met with little success. Philips, Siemens, and AEG-Telefunken retained strong positions in discrete devices and linear ICs.

Government policy in European countries played a significant role in the comparative lack of demand for digital ICs in the military, computer, and telecommunications sectors. The European computer industry was unable to achieve the output scale of American firms, notably IBM, who often produced in Europe in order to circumvent a 17 percent ad valorem tariff. In telecommunications, a history of national procurement in the larger European markets (France, Germany, Italy, and the United Kingdom) fragmented the market. The absence of significant military demand from Germany and the less-intensive development of avionics for the European military reduced the demand from this sector as well.

The situation in the computer industry is particularly relevant for comparisons with Japan. By the mid-1960s, Britain, France, and Germany had all begun efforts to foster national computer industries (Dosi, 1981, p. 27). As Bresnahan and Malerba (Chapter 3 in this volume) point out, many of those European (and Japanese) policies toward computers were aimed at forestalling IBM with preferential procurement policies as well as outright subventions. By subsidizing national computer makers, who

[32] This paragraph draws on Malerba (1985, pp. 105–124).

were motivated if not constrained to buy from national semiconductor makers, the European computer initiatives thus attempted to create some indigenous demand for logic ICs. Moreover, all three countries initiated R&D programs in computers, some of which spilled over into semiconductors.[33] As Tilton (1971, p. 131) notes, these programs tended to favor a small number of large established firms – to a much greater extent than had American military R&D. Indeed, European government policy in this period encouraged consolidation and rationalization. Especially in Britain and France, which did not initially have "national champions" the size of Philips or Siemens, a wave of mergers took place in both computers and semiconductors, with government approval and sometimes government instigation. This policy of consolidation had the effect of reducing indigenous competition in the face of penetration by subsidiaries of American firms and generated "champions" that proved unfit to take on the Americans (Tilton, 1971, pp. 131–132).

Japanese Developments in the IC Era. The early development of the Japanese IC industry is one of the few areas of IC industry history that has never received a complete examination.[34] Conflicting accounts of this period by Japanese and American executives were (1) that Japanese firms committed early to IC mass production[35] and (2) that Japanese firms remained dependent on U.S. sources of supply (Okimoto et al., 1984). By 1974, the Japanese output of ICs was valued at ¥125.5 billion, about $560 million at the exchange rate in 1974 (Bank of America 1980, p. 104). This compares with U.S. IC shipments in that year of about $2.1 billion (U.S. Department of Commerce, 1966 et seriatim).

Thus the situation in Japan in this period was in many respects similar to – and perhaps even more dire than – that in Europe. Japan had even less military demand than did Europe, and Japanese firms were even more heavily committed to the production of discrete (especially germanium) devices for consumer applications, in which the Japanese were highly successful and strongly export oriented. The Japanese firms were slow to make the transition to batch-produced silicon devices in the early 1960s, and, when they turned later in the decade to the production of bipolar ICs, they could not compete with Texas Instruments and National Semiconductor. Some Japanese firms accused the Americans of

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[33] Several of these programs are described in Dosi (1981, p. 27).

[34] The beginnings of a technical history are contained in Watanabe (1984). Although Watanabe discusses the development of the industry, all of his 87 references (all in the English language) are technical. A more comprehensive business history may be found in Nakagawa (1985).

[35] Watanabe (1984) dates Japanese IC production from the first quarter of 1962.

Table 2.8. *Worldwide Shares of Semiconductor and IC Sales by Region of Producing Company, 1978 and 1989*

	1978		1989	
	Semiconductor	IC	Semiconductor	IC
U.S.	59	74	43	45
Japan	28	20	48	47
Europe	13	6	11	7

Source: 1978: Braun and Macdonald (1982, p. 153); 1989: Integrated Circuit Engineering (1990, pp. 1-9 and 3-2).

"dumping" (Okimoto et al., 1984, pp. 14–15). Also, like the Europeans, the Japanese were concerned about the dominance of American computer makers, especially IBM, which held nearly 40 percent of the market during most of the 1960s.

From 1965 to 1972, Japan's policy toward the IC industry was largely focused on market reservation, support for the licensing of foreign technology, and domestic procurement by NTT. The market-reservation policy was largely one of preventing direct foreign investment, which meant that American firms were unable to replicate the pattern of foreign direct investment (FDI) that they had followed in Europe. By the time that this policy was dismantled with a round of liberalization in the mid-1970s, the first opportunity for American firms to repeat their European FDI experience had passed, as Japanese firms were soon to launch their challenge to the U.S. merchant producers.

II. The Japanese Challenge

During the 1970s, the integrated circuit reinforced American dominance of the international market for semiconductors. In the major producing regions, the United States held a two-to-one overall advantage over Japan in market share in semiconductors and a better than three-to-one advantage in integrated circuits (see Table 2.8).[36] A decade later, Japan had over-

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[36] The data in Table 2.8 are derived from Integrated Circuit Engineering Corporation (ICE), a U.S. market research firm that defines the "national origin" of semiconductor production as follows: "All figures that describe 'sales or production by geographical headquarters location' include all sales or production by a company regardless of where the

taken the United States in both semiconductor and IC share among the three producing regions, while the European share remained frozen.[37]

The loss of American dominance is striking. How and why did this happen?[38] The answer is to be found in the dynamics of competition between American and Japanese companies in the new generations of IC products introduced beginning in the late 1970s. This competition involved issues of productive efficiency, investment rates and timing, and design strategy. The success of Japanese companies was aided by the nature of end-use markets in Japan, the timing of market developments, and the patterns of investment by American and Japanese companies.

Challenging the Leader: Strategy for Overtaking an Incumbent

The vitality of the American IC industry during its period of dominance was its intense technological competitiveness, supported by its industrial structure. Competition among firms selling to the same customers meant that cooperative technological relationships within the industry were rare, that equipment suppliers were encouraged to offer highly differentiated products, and that the industry had not developed a unified position for lobbying the government. Moreover, because of the peculiar structure of the American industry, the largest producer (IBM) was a customer of both domestic and foreign manufacturers but was not itself a merchant.[39]

product is produced or sold. For example, all of Texas Instruments' semiconductor sales or production, including those from its Japanese and European facilities, would be listed in the North American semiconductor segment" (ICE, 1995, p. 1-1). ICE's data also include captive production volumes, the revenues from nonrecurring engineering costs of developing application-specific integrated circuits, and internal transfers.

[37] Table 2.8 includes the production of American captive producers (primarily IBM), which has often been excluded in other studies The estimated share of American captives in the world total amounted to 10 percent of the total semiconductor and 11 percent of the IC market (ICE, 1990). Excluding them suggests an even more dramatic decline of the U.S. position to 36 percent in semiconductors and 38 percent in ICs, with a 54 percent share for Japanese producers in both markets. Howell, Bartlett, and Davis (1992, p. 9) are among the authors who compare only American merchant companies to Japan. In 1989, they estimate Japanese share of the semiconductor market at 51 percent including other producers (European and Asian) and 38 percent for the United States.

[38] A sample of attempts to answer the question would include Borrus, Millstein, and Zysman (1982); Borrus (1988); Ferguson (1985); Howell, Bartlett, and Davis (1992); Prestowitz (1988); Semiconductor Industry Association (SIA) (1981, 1983); and Tyson (1992).

[39] In another sense, however, the structure of the American semiconductor industry was not peculiar at all. "The coexistence and complementarity of large and small technology-based firms has been a persistent feature of the US in major twentieth century industries" (Wright, 1999, p. 317).

Almost from its origins, the industry had been focused on growth rather than on profit margins. Indeed, the profitability of the industry collectively ran below the average for American manufacturing.[40] The prosperity of the industry was maintained through growth of product markets, a process that required continual investment in physical capacity and in research and development. This meant that American IC companies could not generate large cash reserves from retained earnings; moreover, as these companies were not typically divisions of larger organizations, they could not benefit from intraorganizational transfers of capital. The result was that, during periodic industry downturns, the industry reduced investment spending and laid off workers; in the upturns, the industry delayed in committing to new plant, delay that led to capacity shortages.[41]

In Japanese firms, IC production occurred within a vertically integrated structure similar to that of firms in Europe. But, for a number of reasons, the Japanese firms viewed it as crucial to enter international merchant markets. For one thing, outside customers would help ward off the sorts of internal demands that Malerba (1985) associates with the decline of the European industry. Rather than believing they were on the verge of overtaking American companies, the Japanese saw both their semiconductor and computer industries as relatively weak against IBM and perceived that a key feature of IBM's advantage was technology, specifically its position in ICs (Ferguson and Morris, 1993). The fact that Japanese IC producers were large companies in comparison with their American counterparts gave them the advantage that they were able to mobilize internal capital resources to make investments in the IC industry in a way that U.S. companies could not.

The strategy of the Japanese challenge could therefore be based upon an investment challenge with two elements, investment in capacity and investment in manufacturing quality. This left the problem of identifying which products were vulnerable to a challenge. Hindsight makes it

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[40] See Braun and Macdonald (1982, p. 148) for net earnings after tax as a percentage of sales for 1967–1977.

[41] American firms did, of course, have recourse to the arm's-length capital markets. And most economists would see this chronic "undercapitalization" of the industry as a sign that capital markets had "failed." In fact, of course, arm's-length capital markets and the internal capital markets of multidivisional firms are both institutions with pluses and minuses, and neither is sensibly judged against an abstract ideal standard. As we will see, the decentralization and independence of American firms served the industry well in many circumstances, both early and late in our story. But, because of what one might generally view as transaction-cost problems, arm's-length financing may be less adept in smoothing cyclical fluctuations than is internal financing. We include in this venture-capital financing, which is, in any case, typically used for start-up capital rather than for ongoing capitalization of mature businesses.

Table 2.9. *Maximum Market Share in DRAMs by American and Japanese Companies, by Device*

Device	Maximum Market Share (%)	
	United States	Japan
1K	95	5
4K	83	17
16K	59	41
64K	29	71
256K	8	92
1M	4	96
4M	2	98

Source: Dataquest, cited in Methé (1991, p. 69).

obvious that the emerging dynamic random-access memory (DRAM) of the early to mid-1970s was the most attractive market to challenge. At that time, Japanese producers could certainly have concluded that the DRAM market would be suited to the Japanese approach to manufacturing. The potential for the DRAM to become a standardized, mass-produced product had already been demonstrated by Intel's 1003, the 1K DRAM that established the market.

American firms continued to dominate in the early – 1K and 4K – DRAM markets. But an industry recession delayed the American "ramp-up" to the 16K DRAM, which appeared in 1976. Aided by unforeseen production problems among the three leaders, Japanese firms were able to gain a significant share of the 16K market. By mid-1979, 16 companies were producing DRAMs, and Japanese producers accounted for 42 percent of the market (Wilson et al., 1980, pp. 93–94) (see Table 2.9). This was a remarkable development. For the first time, Japanese companies were able to gain a significant foothold in the American market for a leading-edge device. The fact that this was achieved without a significant backlash from the U.S. government or a consolidated response from American IC or system manufacturers signaled that the American market might well be open.

The opportunity opened for Japanese producers in the 16K DRAM market had proved sufficient for them to advance to a position of leadership in the 64K DRAM. Their success relied upon manufacturing advantage and price-cutting. The Japanese fixed early upon a conservative design for their 64K DRAMs, which allowed them simply to scale up existing process technology. By contrast, the American firms insisted on radical new designs and new process technology, which increased development times and start-up problems (Borrus, 1988, p. 144). As a result, Intel, Mostek, and National encountered production difficulties, giving Japanese firms a head start down the experience curve.

Japanese dominance accelerated in the 256K (1982) and 1-megabit (1985) generations (see Table 2.9). The scaleup of 64K DRAM production had caused a very rapid reduction in price, which, combined with the general recession in the U.S. industry in 1985, caused all but two American merchant IC companies to withdraw from DRAM production[42] (Howell et al., 1992, p. 29). In 1990, American market share had fallen to only 2 percent of the new-generation 4-megabit DRAM.[43] (see Table 2.9).

The Role of Demand

As had been the case in the rise of the American semiconductor industry, the pattern of end-use demand was crucial in shaping the bundle of capabilities that Japanese industry possessed – as well as in narrowing and limiting the choices the Japanese firms had open to them. In this case, that end-use demand came largely from consumer electronics and, to a somewhat lesser extent, from telecommunications. Consumer demand helped place the Japanese on a product trajectory – namely, CMOS ICs – that turned out eventually to have much wider applicability.[44] And NTT's demand for high-quality memory chips for telecommunication switching systems helped nudge the industry into a strategy of specialization in high-volume production of DRAMs.

Japan was without a significant military demand that could provide a market to support specialized high-performance devices. Japanese computer manufacturers had attained a moderate success, with 1973 production of ¥472 billion ($2.15 billion). Nonetheless, the consumer

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[42] The exceptions were Texas Instruments, which produced in Japan, and Micron Technology, which produced in Idaho.

[43] Again, these figures do not take into account the sizable captive production at IBM and AT&T.

[44] MOS stands for metal-oxide semiconductor, a form of field-effect technology. CMOS stands for "complementary" MOS and NMOS (discussed later) for "negative" MOS.

electronics market of that year was far larger at ¥1,685 billion ($7.66 billion). Consumer electronics accounted for one-half of all electronic equipment production in Japan in 1973, a share that was to remain almost constant throughout the 1970s despite a 50 percent growth in the overall size of production.

The particular consumer product of greatest relevance in the early years was the desktop (and eventually the hand-held) calculator. Although this product may seem mundane, it created a very large demand for ICs: in the early 1970s, nearly 50 percent of the Japanese IC market went for desktop calculators (Watanabe, 1984, p. 1564). Calculators thus provided Japanese firms with a "product driver" that could be used to fund large-scale production of ICs (Borrus, 1988, p. 124). More significantly, perhaps, the calculator market started Japanese firms down the technological trajectory of CMOS production.[45] American firms favored the alternative NMOS technology for the early generations of DRAMs, largely because of its (initially) lower cost and because of conservatism about the technological risks of CMOS. Japanese firms chose to develop expertise in CMOS because its lower power consumption – useful in portable devices – had offsetting benefits in calculators and other consumer applications. But a technological change in the lithography process canceled out the cost advantage of NMOS, and CMOS turned out to have a steeper learning curve. By 1983–1984, the cost of CMOS had fallen below that of NMOS, and CMOS quickly became the clear technological choice for almost all applications. The Americans thus found that much of their previous experience with NMOS had become obsolete and that they lagged behind the Japanese in CMOS.

The Role of Japanese Government Policy

The VLSI Program is the most famous of the efforts made by the Japanese to deepen their technological competence to a level at which it could challenge American dominance. The program sprang from a key goal of Japanese (as of European) industrial policy: to create a mainframe computer industry in competition with, and in imitation of, IBM.

Both NTT and MITI (the Ministry of International Trade and Industry) initiated programs for improving manufacturing capabilities. The NTT project lasted from 1975 to 1981 and was funded on the order of ¥40 billion (about $180 million) (Callon, 1995, p. 37). Several major companies, notably Toshiba and Mitsubishi, who were not traditional suppliers to NTT, were left out, thus allowing MITI in 1976 to create

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[45] The remainder of this paragraph follows Ernst and O'Connor (1992, p. 66).

another project in which they could participate.[46] The MITI VLSI Project extended over the period 1976–1980. Total program expenditures are officially given as ¥73.7 billion (about $330 million), of which ¥29.1 billion ($130 million), or some 40 percent, was government subsidy. The two projects were organizationally distinct, although overall oversight of both was technically assigned to MITI. NTT's efforts were conducted at its own laboratories, whereas MITI's VLSI Project was based at a separate facility that combined researchers from participating companies, all of whom continued their own research programs.

In planning the VLSI Project, MITI saw joint organization in a single laboratory as politically valuable and pressed the companies to agree. This feature has attracted great attention and has been emulated in other consortia designs. It was also a feature that, by recent accounts (Fransman, 1990, p. 63; Callon, 1995, p. 57), the companies vehemently opposed. The companies reluctantly accepted MITI's joint laboratory organization as the price of the private research subsidies they really wanted (Fransman, 1990, p. 64). One consequence of the resistance is that only 15–20 percent of the total budget went to the joint laboratories; 80–85 percent went to private research in company laboratories (Fransman, 1990, p. 80).

The technological goal of the VLSI Project was to accelerate Japanese progress in increasing the transistor count in ICs. The initial target was development of techniques for fabricating a 256K device. This goal was hastily bumped up to 1 megabit (1M) when Matsushita, a company with no connection to the project, announced its development of a chip that already met those standards (Sigurdson, 1986, p. 53). Much of the research was focused on high-energy alternatives to the optical lithography techniques then in use[47] (Sigurdson, 1986, p. 83; Fransman, 1995, p. 162; Callon, 1995, p. 119). As it turned out, such techniques have not replaced optical lithography even today – although, as Henderson (1995) has pointed out, the lifespan of optical technology fooled almost everyone.

American Government Policy on the Eve of the Japanese Challenge

Between 1965 and 1984, U.S. government policy may be divided into two periods. As we saw, the first period (1965–1974) was one in which the

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[46] Five companies were official participants: NEC, Toshiba, Fujitsu, Hitachi, and Mitsubishi.

[47] Lithography is the "drawing" of the circuit pattern on the wafer, a process somewhat analogous to what a photographic enlarger does in a darkroom. High-energy techniques would use beams of electrons or even x-rays rather than light to draw finer lines.

integrated-circuit industry benefited from the same space and defense programs that had supported the transistor industry's growth. Federal demands for ICs during this period contributed to the rate of cost reduction, producing an externality for commercial markets. By 1974, however, growth in commercial markets for ICs had greatly diminished the ability of procurement to influence the industry: government demand had fallen to 16 percent of industry output (U.S. Department of Commerce, 1979, p. 44). This level was not increased, even with the increases in defense expenditure, in the 1980s.

During the second period, there was only one major defense program directed at the semiconductor industry, the very high speed integrated circuit (VHSIC) program. VHSIC's ambitious goal was to close the gap between military and civilian technology. Although this goal went unmet, the program did improve the capabilities of defense contractors in systems design.[48] During the late 1980s, the strategy of basing military systems on leading-edge commercial components was once again debated in the context of "dual-use" technology, with little effect on practice.

Throughout the period, the industry continued to benefit from American policies governing the re-importation of partially finished goods manufactured offshore and a generally supportive tax treatment of R&D investment. Thus, for approximately a decade (1974–1984), the American industry experienced what was essentially a laissez-faire policy.

European Developments

During the period of the Japanese challenge (1978–1988), European firms adopted policies aimed at staying in the race, including the development of products for consumer electronics, industrial, and automotive applications. The most important initiative in this period was the acquisition of American companies. Table 2.10 shows most of these acquisitions. With the exception of Signetics and Fairchild, the European acquisitions were small specialized companies or minority shares that facilitated technology exchange. Schlumberger's acquisition of Fairchild was spectacularly unsuccessful, leading eventually to the sale of the company to National Semiconductor after the American government threatened to block a proposed sale to Fujitsu.[49] By contrast, Philips's acquisition of Signetics has assisted Europe's largest IC producer in

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[48] See Steinmueller (1988a) for further discussion of the VHSIC program and of the problems of attributing a major supportive role in the later period to government – and, specifically, military – procurement policies.

[49] See Steinmueller (1988b) for an account of Fujitsu's offer.

Table 2.10. *European Acquisition of U.S. Semiconductor Companies*

Year	*U.S. Firm*	*European Firm*	*Share Acquired*
1975	Signetics	Philips (NL)	100%
1976	Silconix	Lucas (UK)	24%
1977	Interdesign	Ferranti (UK)	100%
	American Microsystems	Bosch (FRG)	25%
	Litronix	Siemens (FRG)	80%
	Advanced Micro Devices	Siemens (FRG)	20%
1979	Fairchild	Schlumberger (FR)	100%
	Microwave Semiconductor	Siemens (FRG)	100%

Source: Braun and Macdonald (1982, p. 176).

maintaining a relatively strong position, both within Europe and in international markets.

The other developments, less important only because of their limited outcomes, were the European Silicon Structures Initiative (ECU30 million) and the Siemens-Philips Mega-Projekt (DM5 billion). The former program was part of the Eureka Program, which was somewhat effective in upgrading European processing capabilities. The latter program was initially successful, providing Siemens and Philips with a commercial SRAM product. But this position subsequently eroded, and today Europe has a very small share of the international market for SRAMs (European Microelectronics Panel, 1995). Thus, European firm strategy continued to be one of survival through specialization, punctuated by ambitious, but largely unsuccessful, efforts to achieve a technological breakthrough that would propel them to a dominant position in a major semiconductor market.

III. The American Response

An American Resurgence

The year 1985 was the darkest period in American IC industry history, with record layoffs and with Intel, the flagship among American merchants, suffering losses exceeding its book value. Japanese firms had captured the DRAM market almost entirely, and prognostications widely heralded a Japanese move into – and inevitable dominance of – other categories of chip, including the microprocessor (Ferguson, 1985; Reich and Mankin, 1986). But 1985 was actually not the beginning of the end but the beginning of a turnaround. On April 9, 1992, a front-page *New York Times* headline read, "U.S. Chip Makers Stem the Tide in Trade Battles with the Japanese: Predictions of a Trouncing Have Not Panned Out" (Pollack, 1992). During this short period, the United States was able to restore a slight lead in its market share with Japan – a performance we can characterize as a "resurgence" of the American producers. This change of fortunes does not represent a strong reversal in the relative competitive strength of American and Japanese semiconductor producers, an across-the-board restoration of American dominance; Japanese producers remain strong, especially in the product areas in which their competitive position was achieved, notably DRAMs. Rather, the American resurgence reflects a combination of several factors of varying importance:

- A renewed emphasis on manufacturing and some success in improving productivity;
- Organizational innovation and specialization, allowing the American industry to take advantage both of its own structural advantages and of global manufacturing capabilities; and
- A favorable shift in the importance of those products in which American firms have specialized. We view this last factor as the most important of these three.

We examine these factors in turn, reserving the role of American government policy for separate treatment.

Manufacturing Improvements. As we saw, Japanese firms had been nudged by the character of the demand they faced onto the technological trajectory of CMOS – a technology that was to prove superior in cost and performance dimensions in most applications. In 1988, CMOS represented about 40 percent of the value of IC production; by 1994, it was responsible for 80 percent of production value (ICE, 1995). Because American firms had concentrated on NMOS technology, they lagged in converting to CMOS, and that meant that the American companies were engaged in a process of "catch-up" with their Japanese competitors in process technology. This seemed an insurmountable problem, as most American companies feared that DRAM production was the only means of improving or "driving" the state of the art in CMOS technology. In the end, however, this fear proved groundless. American companies were able to make CMOS circuits with sufficient quality, performance, and transistor counts to meet the competition using experience with logic and specialized memory devices such as SRAMs.[50]

What evidence is there that American firms improved their manufacturing productivity significantly? One piece of indirect evidence is that American firms were able to hold their market shares in a number of product segments, including application-specific integrated circuits (ASICs), where American and Japanese companies compete nearly head-to-head.[51] There is also more direct evidence.[52] One of the factors driving the success of Japanese firms in memory products in the early 1980s was the higher quality of the chips they produced. For Japanese chips, defect rates – the fraction of chips that prove to be defective – were probably half to one-tenth the rates for American products. By the second half of that decade, however, American firms had dramatically increased expenditures for quality control, imitating Japanese practices such as total quality management (TQM), greater attention to preventive maintenance, and automated process control and monitoring. By the early 1990s, American manufacturers had probably begun to match the defect levels of their Japanese counterparts. Intel reportedly reduced its defect rate by a factor of 10 (Helm, 1995). There is also evidence that American firms have improved manufacturing yield rates and direct labor productivity since the early 1990s.[53] This represents a closing of the gap, but it doesn't mean that American production facilities (or "fabs") have reached the levels of Japanese or even Taiwanese fabs, in part because American fabs operate at smaller scales on average and cannot take as much advantage of the economies of large production runs.

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[50] In part, the claim that the production of DRAMs was necessary as a process driver confused the properties of DRAMs with the fact of volume production. As microprocessors and other nonmemory chips began to be produced in greater volume (because of the growth of the personal computer industry, discussed later), those devices were able to serve as process drivers. Indeed, microprocessor chips are in many ways more complicated than RAMs. They typically require more layers, and that requirement helped give American firms, and their American equipment suppliers, advantage in (among other things) the complex technology of interconnecting levels (Langlois, 1999).

[51] Even here, American firms tend to specialize in the standard-cell approach to ASICs, which is more design-intensive and less manufacturing-intensive than the linear and gate arrays favored by the Japanese. Between 1989 and 1994, however, this specialization diminished somewhat as American firms lost 2 percent of share in standard cells but gained a point in linear and gate arrays (ICE, 1990, 1995).

[52] The remainder of this paragraph follows Macher, Mowery, and Hodges (1998).

[53] According to one study, the yields of American firms increased from 60 percent in 1986 to 84 percent in 1991. The yields of Japanese firms increased over the same period from 75 percent to 93 percent, implying that American firms narrowed the gap in yield rates from 15 percent to 9 percent (US GAO, 1992).

Specialization and Globalization. Nonetheless, the Americans' improved manufacturing capabilities were more than adequate in view of favorable structural changes and demand shifts. The abandonment of the DRAM market by most American firms – including Intel – was a dark cloud with a bright silver lining. When Intel led the world industry in almost all categories, it and many of its American counterparts faced a full plate of product alternatives. With the elimination of mass memory as a viable market, these firms were impelled to specialize and narrow their focus to a smaller subset of choices. As we saw earlier, a relatively narrow product focus coupled with a deepening technological competence can be an extremely successful strategy, as it arguably was in the early days of the industry. It is also, indeed, the strategy that Japanese firms leveraged to success in DRAMs.

The areas in which American firms concentrated can generally be described as higher-margin, design-intensive chips. For such chips, production costs would not be the sole margin of competition; innovation and responsiveness would count for more. And innovation and responsiveness were arguably the strong suits of the "fragmented" American industry. As Nelson and Winter (1977) and others have argued, a decentralized structure permits the trying out of a wider diversity of approaches, leading to rapid trial-and-error learning. And the independence of many firms from larger organizations permits speedier realignment and recombination with suppliers and customers. Building on existing competences in design (especially of logic and specialty circuits) and close ties with the burgeoning American personal computer industry, American firms were able to prosper despite the Japanese edge in manufacturing technology.

Another aspect of specialization that benefited the American industry was the increasing "decoupling" of design from production. Such decoupling is in many respects a natural manifestation of the division of labor in growing markets (Young, 1928); in this case, it was abetted by the development of computerized design tools (Hobday, 1991) and the standardization of manufacturing technology (Macher et al., 1998). On the one hand, this allowed American firms to specialize in design-intensive chips, taking advantage of an American comparative advantage that arguably arises out of the decentralized and "fragmented" structure of that country's industry.[54] On the other hand, it also allowed many

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[54] Perhaps surprisingly, the mid-1980s – that dark period for American fortunes – was actually the most fertile period in history for the start-up of new semiconductor firms, by a large margin. Most of these new firms were involved in design-intensive custom devices and ASICs (Angel, 1994, p. 38).

American firms to take advantage of growing production capabilities overseas.

"Globalization" has long been a trend in the semiconductor industry (Langlois et al., 1988), and American firms had long used "offshore" production as a strategy for cost reduction, beginning with outsourcing of assembly and packaging stages.[55] But the decoupling of design from production has enabled American firms to benefit from globalization without investing large amounts of their own money overseas. These "fabless" semiconductor firms are able to contract out production to "silicon foundries" around the world, especially in the Far East.[56] In 1997, the fabless sector generated revenue of almost $8 billion, with industry revenues projected to increase to $18 billion by the year 2000, nearly 6 percent of the total semiconductor market[57]. The Fabless Semiconductor Association – which represents the foundry users – began with 45 members in 1994 and now boasts some 170 members, most of whom are North American (Zajak, 1997; Macher et al., 1998). Aside from the usual benefits of specialization, the fabless-foundry arrangement increases flexibility and response time, as design firms can take advantage of plants already geared up to serve them. The foundries make it possible for chip start-ups to "jump on a freight train moving 150 miles an hour," as one industry executive put it (Engardio et al., 1996). Although the Asian foundries originally lagged integrated firms in production technology, the gap has closed from three years to six months (Zajak, 1997), and three Asian foundries are now operating at the cutting-edge line width of 0.25 micron (LaPedus, 1997b).

[55] The growing internationalization of IC production has led to confusion in the use of official trade statistics. This is not a new phenomenon. Steinmueller (1988a) observed that the attribution of value added between production of finished wafers and final IC devices was a matter of some dispute, since international transfers of ICs during the 1980s followed a very complex pattern: wafers produced in one country would be followed by packaging operations in a second country (often one with different rules of corporate taxation). The packaging operation would be followed by testing operations in the original producing country or yet a third country. Since markets for specific models of partially finished semiconductors are either nonexistent or very thin and controlled by closely related parties, the attribution of value for tax and tariff purposes is neither obvious nor unambiguous.

[56] As we point out later, most of the foundries are in Taiwan and Singapore, with others planned – at least before the recent Asian financial crisis – in such countries as Thailand and China. Israel also boasts a major foundry. Even American firms have gotten into the foundry business: IBM is acting as foundry for Cyrix's line of microprocessors, an association slated to end, however, now that Cyrix has merged with National Semiconductor. Recently, with overcapacity in the DRAM market, Korea is looking to enter the business (LaPedus and Robertson, 1997).

[57] Data from the Fabless Semiconductor Association and Dataquest, cited in Macher, Mowery, and Hodges (1998).

Table 2.11. *Worldwide Merchant Market Product Segments (Percentage)*

	1988	1994
MOS Memory	29	35
MPU and related	17	26
MOS Logic	23	20
Bipolar Logic	11	3
Analog	18	16
Other	2	<1

Source: Integrated Circuit Engineering Corporation (1989, 1995).

Shifts in the Pattern of Demand. Product design has once again become a major determinant of competitive outcomes. This is true not only in the area of custom logic chips and ASICs but – perhaps most importantly – in microprocessor unit (MPU) and related segments, also called the microcomponent segment.[58] Between 1988 and 1994, merchant IC revenues grew by 121 percent, from $41.3 to $91.5 billion. The strong growth in overall revenues has been accompanied by more rapid growth in microprocessor than in memory markets, as illustrated in Table 2.11. This evolution of the product mix in the industry has strongly favored American producers. In the microcomponent portion of the chip market, American companies accounted for 66 percent of world production in 1994, compared with a 29 percent share for Japanese companies.

The importance of the microprocessor segment has meant that a single company, Intel, is responsible for much of the gain of American merchant IC producers. In 1994, Intel accounted for 31 percent of world output in the microcomponent market, led by its strong position in microprocessors. Intel's strategy for recovery, begun in the 1980s, has proved remarkably successful. In the late 1980s, Intel consolidated its intellectual-property position in microprocessors by terminating cross-licensing agreements with other companies and, more importantly, began extending its first-mover advantage over rivals by accelerating the rate of new product introduction. These developments pushed Intel into the position of the largest IC producer in the world, with 1994 sales of $9.85

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[58] This segment includes not only microprocessors, but also microcontrollers (less sophisticated microprocessors that are used in embedded applications) and related "support" chips, such as memory controllers, that are necessary to assembling a microprocessor system.

billion, $1 billion more than the second largest producer, NEC. Although Intel dominates the microprocessor market, it is not entirely without competitors; it is significant that its principal competitors are also American firms. Motorola has long produced a rival microprocessor line linked to the Apple computer platform. And, more recently, Cyrix and AMD have mounted a strategy of producing Intel-compatible microprocessors to attack the low-end personal-computer market.

The success of American firms in microprocessors and related chips has been reinforced by trends in end-use demand. In 1989, computer applications took 40 percent of merchant IC sales, followed by consumer and automotive applications at 28 percent.[59] By 1994, the respective shares were 52 percent for computer and 23 percent for consumer and automotive applications. The worldwide changes have led to increasing specialization. North American use of ICs for computer applications soared from 15 to 24 percent of the total value of world merchant sales, while the Japanese IC market for consumer applications fell from 13 to 10 percent of world merchant sales. Thus, in contrast to rough parity (15 versus 13 percent) in 1989, an enormous gap has opened between IC demand for consumer and computer applications in the 1994 markets of Japan and the United States (24 versus 10 percent). Keep in mind that these figures are in terms of revenue, not physical units, and much of the reversal of American fortunes has to do with the high value per component of microprocessors and other design-intensive chips, as against the low value per unit of the mass-produced DRAMs on which Japanese firms long rested their strategies.

Macroeconomic factors have also played a role. In 1985, it took 240 yen to buy a dollar. In late 1992, the exchange rate stood at 127 yen to a dollar. Six months later, it was 106 yen to the dollar, and for most of the past five years the rate has hovered around 100 yen per dollar. Although good news for Japanese consumers and businesses purchasing foreign goods and services, the very rapid increase in the value of the yen was a major shock to Japanese manufacturing companies, including IC producers. The most important long-term result of the strong yen may have been the relative decline in Japanese consumer electronic production.

Economies of scale are key to the success of consumer electronics. Two factors have limited Japan's realization of such economies, although another factor continues to work in Japan's favor. First, the rapid expansion of Korea, China, and the Southeast Asian economies into consumer electronics has divided demand, a trend that is particularly significant

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[59] These and succeeding figures in this paragraph are from ICE (1990; 1995).

where margins are small on large-volume low-end products. Second, during the past decade, no major innovation like the videocassette recorder has emerged to create a rapid-growth demand segment.[60] The factor remaining in Japan's favor is the control of mass production of some key components for consumer electronics. Color television picture tubes, specialized ICs, flat panel displays, and laser printing engines are components in the consumer and business-equipment markets for which Japanese firms maintain competitive advantage and in which scale economies are important. But these components are all relatively expensive to produce, especially in an era of dear yen.

This was not the end of the bad news for Japan, however. Between 1989 and 1994, the share of Japanese IC demand for computer and datacom applications fell from 41 to 20 percent of the total worldwide demand for those uses. Meanwhile, the American share of total demand in the computer segment rose from 37 to 46 percent.[61] The change represents a very serious reversal for Japan in the computer market and, again, a movement from a position of rough parity to one of American leadership. Traditional trade theory would discount these changes in downstream markets, assuming that trade flows would adjust to follow international demand. This type of adjustment is not the case, and has never been the case, in the IC industry. Neither the American nor the Japanese market is fully "open" to such adjustments, and imports as a percentage of total demand would be exceptional at 20 percent. Over the past several years, American imports as a share of the Japanese domestic market have hovered around 14 percent; in the American market, which nearly doubled between 1992 and 1994, the share of Japanese imports fell from 21 to 18 percent (ICE, 1995, p. 1-31).

In part, Japanese IC producers (who are also typically computer producers) have been disadvantaged by their failure to develop a vibrant domestic personal computer industry. From a very strong position in the first 15 years of microprocessor developments and the prospect of leadership in personal computer production, Japanese firms have retreated to become producers of specialized computer components and have suffered a marked decline in their international market share. In part, this development reflects the structure of the Japanese computer industry. Because personal computers in Japan are the province of the large vertically integrated systems houses, those firms have – at least until

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[60] There are hopes that the digital videodisk (DVD) technology will have this role in the closing years of this decade.

[61] Computed from ICE (1990; 1995). This change is somewhat overstated, since the 1989 figures include data communications as well as computer applications, whereas the 1994 figures include only computer applications.

recently – maintained a strategy of rival incompatible systems (Cottrell, 1995). By contrast, the fragmentation and vertical specialization of the American personal computer industry led to far greater standardization, which allowed both a finer division of labor and the use of a wider network of capabilities (Langlois, 1992). In part, however, the relative decline of Japan in personal computers also reflects the strength of American IC and system producers in accelerating the pace of product innovation. This too may be a by-product of the more fragmented and decentralized – and therefore more nimble – structure of American industry. Moreover, while Japanese computer makers are being pushed by American innovativeness on one side, they are also facing threats to their manufacturing leadership from elsewhere in Asia, and the "sourcing" of many once-strategic components is now more footloose than it had been.

The Rise of Far Eastern Production

Japanese firms were not the only ones who could understand the economics of capacity investment or productivity in manufacturing; they were soon joined by Korean semiconductor producers and by larger American companies who matched Japanese productivity by the simple expedient of establishing Japanese plants. The result is a dilution of the control of capacity investment by Japanese producers, who, even if they could manage to agree on rationing capacity expansion among themselves, could not control the Koreans, who were determined to follow in Japan's footsteps toward the "sunrise" high-technology industry of IC production.

Korean entry was based upon an aggressive investment program and the hiring of American-trained Korean talent.[62] In 1984–1985, Korean companies spent nearly $1.2 billion to enter the market (ICE 1987, p. 2-42), only to arrive at the height of the 1985 recession. Despite this, and because of the long-term perspective of the leading companies, the Koreans emerged from the global recession with relatively modern facilities and a growing share of the market. In 1986 they produced an output of $336 million worth of ICs or about 1.2 percent of the world market (ICE, 1988, pp. 2-24, 1-4). Although relatively small, this was enough to be noticed, since much of Samsung's output was focused on DRAMs. By

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[62] "By recruiting heavily among South Korean expatriates at U.S. universities and Silicon Valley chip makers, companies like Samsung Electronics Co. were able to quickly assemble a core of experienced engineers. . . . 'When we have joint meetings with Samsung engineers, they're nearly all [like] Americans,' says one NEC engineer" (Hamilton and Glain, 1995).

Table 2.12. *Worldwide Merchant-Market Sales of DRAMs ($ Million)*

Company	*Country*	*1995*	*1996*
Samsung	Korea	6,462	4,125
NEC	Japan	4,740	3,175
Hitachi	Japan	4,439	2,805
Hyundai	Korea	3,500	2,300
Toshiba	Japan	3,725	2,235
LG Electronics	Korea	3,005	2,005
Texas Instruments	U.S.	3,200	1,600
Micron	U.S.	2,485	1,575
Mitsubishi	Japan	2,215	1,400
Fujitsu	Japan	2,065	1,350

Source: Integrated Circuit Engineering Corporation (1996, 1997).

1993, Korean companies were producing $4.77 billion in ICs, a world market share of 5.2 percent (ICE, 1995, p. 2-46), and Samsung, which produced more than half of this output, became the world's largest memory-chip producer (Hamilton and Glain, 1995). In 1995, three Korean firms were among the top ten producers of DRAMs in the world, selling almost $13 billion worth of ICs (Table 2.12).

In contrast to Korea, Taiwan has developed into a highly diversified producer of semiconductors, with significant and growing capabilities in design as well as in fabrication, both of mass-produced DRAMs and of specialty chips in silicon foundries. The island ranks sixth in the world in the value of integrated-circuit output, having increased production from some $400 million in 1989 to $2.2 billion in 1994. By the year 2000, that figure may rise to $9.4 billion or 5 percent of world output (Dataquest, cited in Marnet, 1996).

The Taiwanese industry has its origins in a porous environment that encouraged foreign direct investment, strategic alliances with foreign firms, and high mobility of engineers, especially to and from the United States (see Table 2.13).[63] Taiwan served for years as an offshore site for American manufacturers, especially in the areas of assembly and packaging. An indigenous semiconductor industry began in the mid-1970s when a quasi-governmental research consortium called the Electronic Research and Service Organization (ERSO) licensed technology from RCA. As it happened, RCA was a leader in CMOS technology; moreover, RCA soon left the industry, leaving ERSO with intellectual-

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[63] Much of this paragraph follows Chen and Sewell (1996).

Table 2.13. *The Growth of Semiconductor Design and Fabrication in Taiwan, 1988–1992*

	1988	*1989*	*1990*	*1991*	*1992*
Proportionate value of sector					
Design	7.1	13.9	13.9	14.3	13.7
Mask and fabrication	14.3	19.4	21.4	33.0	37.4
Assembly	78.6	66.7	64.7	52.7	48.9
Total value ($ Million)	1095	1465	1574	1898	2491
Annual growth rate (%)	—	33.8	7.2	20.6	31.2

Source: Chen and Sewell (1996).

property rights to the American firm's technology and a leg up on what would become the dominant technological trajectory (Chen and Sewell, 1996, p. 772). ERSO spun off a number of design houses and a company called UMC to assimilate foreign production technology. Both UMC and ERSO dabbled in DRAMs for the 4K through 64K generations in the early 1980s. It was not until late in that decade, however, that Taiwan gained ground in DRAMs, especially through a joint venture between TI and the Taiwanese computer maker Acer. In 1993, this plant reportedly had the highest yield of any TI DRAM plant in the world, including Miho, Japan (Chen and Sewell, 1996, p. 774).

Perhaps the most significant aspect of the development of the Taiwanese semiconductor industry, however, is its major role in "silicon foundry" production for American fabless semiconductor manufacturers. In the early 1990s, three design houses owned by American-trained Taiwanese integrated backward into fabrication (Chen and Sewell, 1996, p. 774). By 1996, Taiwanese foundries were handling 40 percent of the output of American fabless companies, with firms like Taiwan Semiconductor Manufacturing (TSMC), United Microelectronics, and Winbond Technology producing for American companies like Cirrus Logic, S3, and Trident (Engardio et al., 1996). Most Taiwanese foundries involve joint ventures with American fabless firms (LaPedus, 1997b). Indeed, the Taiwanese industry is in many respects less a competitor with the American industry than it is a symbiotic extension of it.

A number of other Asian nations are beginning to enter the foundry business as a way of entering the broader semiconductor industry. Chartered Semiconductor of Singapore, a partly government owned enterprise, is already a major player, and Malaysia, Thailand, and China all have plans for entry and expansion (Marnet, 1996; LaPedus, 1997a).

How this expansion will be affected by the recent financial crisis in Asia remains to be seen.

The Role of American Government Policy

Trade Policy. American trade policy in the semiconductor arena antedated the period of Japanese ascendancy. For example, it was the threat of American trade sanctions that helped motivate some of the 1970s liberalization of Japanese policies mentioned earlier (Dick, 1995, p. 49). In 1977, American semiconductor firms banded together into the Semiconductor Industry Association (SIA), which was successful in a number of trade initiatives, including the elimination of semiconductor duties in both the United States and Japan[64] (Yoffie, 1988). But American efforts did not acquire bite and urgency until the mid-1980s, when the Japanese takeover of the DRAM market became a dominant fact.[65]

The first salvos were fired on legal ground. In June 1985, the SIA filed a so-called Section 301 complaint with the U.S. Trade Representative, charging that restrictive access to the Japanese market constituted an unfair trade practice. Within weeks, Micron Technology – one of the two remaining American DRAM producers and the only one to produce in the United States – filed a petition with the U.S. Commerce Department charging that Japanese firms were "dumping" 64K DRAMs in the United States. In September 1985, Intel, Advanced Micro Devices (AMD), and National Semiconductor filed a similar complaint, charging dumping in the market for electrically programmable read-only memories (EPROMs).[66] That same month, Micron filed a private antitrust suit against Japanese firms. And, in an unprecedented move, the Commerce Department in December instigated its own investigation of dumping in 256K and 1M DRAMs.

Of the two issues – access to Japanese markets for Americans and "dumping" in American markets by Japanese firms – the latter was the more dramatic and motivating. "Dumping" refers to the practice of

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[64] The SIA also lobbied successfully for the Semiconductor Chip Protection Act (SCPA), passed in 1984, which was an attempt to protect intellectual property in chip designs at home and to encourage such protection abroad. Although chip protection was widely desired by the industry, the SCPA has largely proved irrelevant, and almost no cases were filed under it. As Risberg (1990) argues, this is because it is cheaper and faster to protect chip designs by proprietary process technology and first-mover advantages than by litigation.

[65] The following account draws on Dick (1991; 1995), Tyson (1992), and Flamm (1996), the last of which is by far the most detailed and definitive.

[66] EPROMs are "nonvolatile" memory devices in that, unlike DRAMs, they remember information even when the power is turned off.

selling below cost in a foreign market in order to drive indigenous producers out of business, thereby ultimately allowing the dumping firm(s) to raise prices and reap economic rents. This is the international variant of the strategy more generally called predatory pricing. It is controversial among economists whether such a strategy is ever rational (as one may pay the costs without ever reaping the benefits);[67] and it is far from clear in principle let alone in practice whether one can reliably distinguish this strategy from healthy competition. In the case of semiconductors, the problem is compounded by the fact that, because of the prevalence of learning-curve effects, pricing below cost – so-called forward pricing – is in fact the appropriate and desirable policy (Spence, 1981; Dick, 1991). Moreover, this was a policy pioneered in semiconductors not by the Japanese but by Texas Instruments, which used it to good advantage in the 1960s and 1970s.

Given the climate of the times, however, the Commerce Department and the International Trade Commission were favorably disposed to the American petitioners and began to announce penalties for dumping that were to be added like a tariff to the price of Japanese chips sold in the United States. This legal activity catalyzed Japanese producers, notably the market leaders, Hitachi and NEC, to cut back production and raise prices. Meanwhile, ongoing negotiations between the American and Japanese governments were beginning to coalesce into a price-control and output-monitoring scheme formalized as the Semiconductor Trade Agreement (STA), signed in September 1986.

In exchange for superseding the pending legal actions, the STA set up what was effectively a price floor for DRAMs and EPROMs shipped to the United States. The Commerce Department established so-called foreign-market values (FMVs) for each Japanese firm. These firms could undercut rivals so long as their prices did not fall below the relevant FMVs.[68] In order to implement the agreement, MITI was empowered to monitor prices and production of the affected chips as well as to monitor

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[67] This is largely because the higher postpredation pricing required to recoup the costs of predation are likely to encourage entry (or reentry). Whether such entry will in fact occur depends on the extent of the cost advantage provided by incumbency. In semiconductors, many have argued, the first-mover advantages that learning effects confer upon incumbents are sufficiently important to raise significant problems of entry, particularly in mass produced product segments. But the entry of Korea, Taiwan, and other countries into the DRAM market suggests that barriers may not in fact have been high enough to make predation a successful strategy.

[68] This was intended to allow low-cost Japanese producers to expand at the expense of high-cost ones and thus to allow the average price of Japanese semiconductors to decline; that, because of the formula used for calculating FMVs, would have the effect of lowering the price floor. Tyson (1992, p. 110) praises this provision on the grounds that it would limit the price increases from the STA and that, by limiting the expansion of high-cost Japanese

seven other categories of device. To do this, the ministry set up a special office that was widely understood to be coordinating as well as monitoring Japanese pricing and production. Another aspect of the STA called for improved access to Japanese markets for American firms, a demand that a "secret" side letter quantified as a 20 percent market share.

The accord functioned smoothly in the main, apart from a rift in 1987 over pricing in third-country markets that led the Reagan administration to impose retaliatory sanctions for a short period. Just before the STA was to expire on July 31, 1991, the two governments negotiated a replacement. Under pressure from American computer manufacturers, who had been hurt by higher chip prices, this accord weakened the provision for price coordination, insisting only that Japanese firms submit data that might be used for dumping claims. Instead, the new accord focused on access to the Japanese market, explicitly mentioning the 20 percent target.[69] This second accord was allowed to run its course and was not renewed in 1996.

What were the effects of the STA and its successor? As Fig. 2.1 suggests, it is extremely clear that prices for DRAMs stabilized by 1986 and began to rise, reaching a peak in 1988–1989. The price of EPROMs followed a similar pattern. Industry officials have claimed that the rents in EPROMs generated by the STA enabled Intel to develop the microprocessor line on which its current success rests[70] – and some have even claimed that many of the largest American companies would have gone bankrupt without those rents (Helm, 1995). Constructing counterfactuals is always a tricky business, however. What is clear is that the price rise in 1988–1989 benefited Japanese DRAM producers at the expense of consumers. One estimate places these "bubble profits" (as they were called in Japan) at $3–4 billion (Flamm, 1996, p. 277).

Can this transfer be laid at the door of the STA? The SIA (1990) has argued that the price increases were the result not of the trade accords themselves but of collusion among Japanese chip producers, a collusion

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producers, it would make it easier for low-cost American producers to penetrate the Japanese market. The extent to which competition among Japanese producers mitigated the effects of the STA is doubtful, and it is hard to see how a policy of encouraging cost competition in Japan would *help* American firms enter that market.

[69] The target was reached in the final quarter of 1992 but then fell below it in subsequent periods (Dick, 1995, p. 60). Flamm (1996, p. 279) has suggested that Japanese firms may have consciously chosen to cut back production in the EPROM market in order to increase American market share for political reasons.

[70] Andrew Grove of Intel has also asserted that the pressure the STA exerted on Japan to increase the penetration of American chips led Japanese personal computer makers to adopt Intel microprocessors, which they might not otherwise have done (Siegmann, 1993).

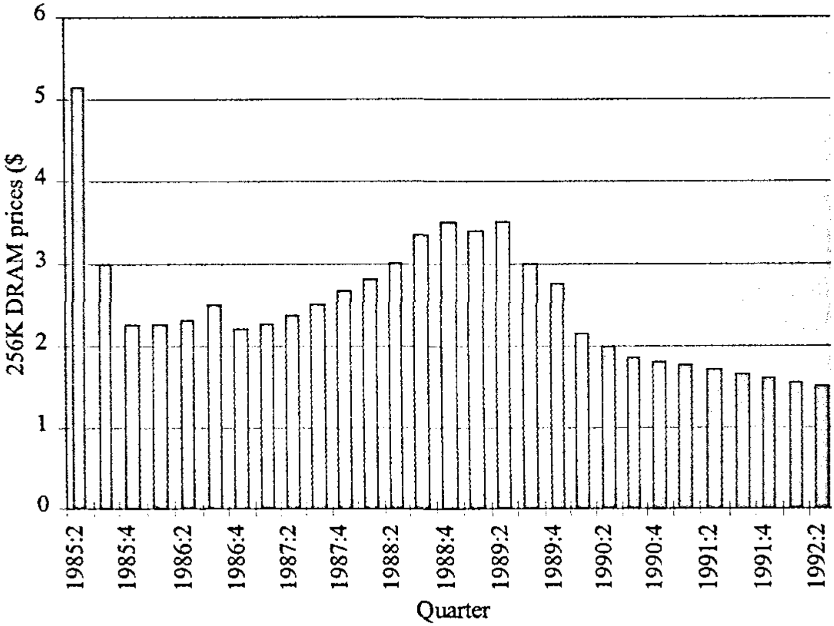

Figure 2.1. Average Selling Prices for 256K DRAMs. *Source:* Dataquest, cited in Tyson (1992, p. 115).

instigated by MITI months before the accord was signed. And it is true that chip prices in 1988–1989 were above the FMV floor, a result of cyclically high demand as well as of output restraint. But economists quickly point out that the STA and the legal actions preceding it were arguably the catalysts to the formation of the cartel, and it was the sanction of the STA that created at MITI a formal mechanism to police and manage that cartel. Indeed, it is a policy irony that, whereas proponents of managed trade typically saw coordination by MITI as one of Japan's unfair advantages, the STA actually strengthened MITI's coordinating role.

As with most complex policy interventions, the STA also had some unintended consequences. Early on, critics – and even some proponents – of managed trade pointed out that Japanese firms were plowing their bubble profits into research and development, which would strengthen those firms for further rounds of competition and the much-feared push into other semiconductor markets (Tyson, 1992, p. 117). Moreover, as Japanese firms are more vertically integrated than American ones, Japanese computer makers would have the advantage of internal transfer prices rather than market prices, giving them an edge over Americans in the computer arena.[71] It is largely this concern, indeed, that led Mowery and Rosenberg (1989, p. 114) to suggest that if "the Semiconductor Trade Agreement thus far is an example of successful 'managed trade,' it is hard to know what might constitute a failure."

In the event, however, the DRAM cartel generated a somewhat different set of unintended consequences – consequences much less happy for Japanese firms. By stabilizing DRAM prices and making that market so profitable, the cartel arrangement kept Japanese firms heavily invested in what was to become a low-margin commodity item. When the high prices attracted entry from Korea and Taiwan, prices and profits began to fall, and the cartel collapsed.[72] By contrast, American firms like Intel were arguably well served in the medium term by their failure in DRAMs, a failure that left them free to pursue high-margin logic and specialty chips that would be in high demand in the burgeoning American personal computer market.

Antitrust Policy and Research Consortia. As we saw, much popular and professional opinion circa 1985 attributed the relative decline of American competitiveness to the inherent inferiorities of American industrial structure relative to that of Japan. Widely touted aspects of the "Japanese model" were research coordination and collaboration in general and the VLSI Project in specific. As a result, much of the American policy response took the form of an attempt to encourage cooperative research – by indirect means as well as by direct subsidy.

On the antitrust front, both Congress and the Antitrust Division of the Justice Department sought to reduce legal obstacles to research cooperation among American firms. In 1984, Congress passed the National Cooperative Research Act, which weakened the brunt of antitrust law when applied to research joint ventures and allowed prospective joint-venture partners to register in advance with the Justice Department and the Federal Trade Commission.[73] For its part, the Reagan Justice

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[71] In fact, this possibility didn't materialize, partly because the cartel was short-lived and partly because the structural disadvantages of the Japanese computer makers far outweighed any advantages from cheaper DRAMs.

[72] In this case, the new entrants also faced trade pressure form the Americans. In 1992, Micron filed an antidumping case against three Korean firms, which resulted in penalties as high as 87 percent. In 1993, however, a Korean proposal for an accord patterned on the STA fell through, and the Commerce Department abruptly lowered the duties it had imposed (Dick, 1995, pp. 61–62).

[73] Specifically, the law weakened potential claims to actual damages rather than the treble damages allowed in other antitrust judgments; specified a rule-of-reason requirement rather than a per se rule, thus forcing courts to take into account the efficiency benefits of the venture; and required unsuccessful plaintiffs to pay court costs if the court

Department put in place new antitrust guidelines that recognized international market structure as a factor in the evaluation of horizontal mergers (White, 1985).

But the most significant instance of research collaboration in the 1980s was the formation of an industry consortium with substantial government funding.[74] In 1987, the Defense Science Board, a committee advisory to the American Department of Defense, issued dire warnings that the decline of the American semiconductor industry would have serious repercussions for national defense. The committee proposed a manufacturing facility to be jointly owned by industry and government. In the same year, a committee of the SIA representing 14 major semiconductor manufacturers issued a proposal for a research consortium to be funded by equal private and federal contributions. By the end of the year, the Defense Department agreed to fund such a consortium, with the 14 firms uniting as the founding members of the Semiconductor Manufacturing Technology Consortium (Sematech). The organization was funded at a yearly level of $100 million from federal sources and $100 million from dues assessed to members.[75]

Sematech set up shop in Austin, Texas, staffed importantly by personnel on secondment from the member companies. The goal was to develop cutting-edge production technology of use to consortium firms. By 1989, a large-scale semiconductor fabrication facility had been completed at Sematech headquarters in record time. Largely because of problems of appropriability and proprietary information, however, the Sematech members were unable to agree on an appropriate research program for

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declared their suit against a research joint venture to have been "frivolous, unreasonable, without foundation, or in bad faith" (White, 1985, pp. 43–44). It is not clear, however, to what extent the changes allayed the fears of industry or even reduced the level of antitrust scrutiny to which research joint ventures were subject (Grossman and Shapiro, 1986, p. 319).

[74] This account of the formation and goals of Sematech follows Grindley, Mowery, and Silverman (1994). Sematech was not the only consortium founded in this period. The Microelectronics and Computer Corporation (MCC), founded in 1982, is a for-profit organization whose members include some semiconductor firms and whose research agenda includes semiconductor technology, especially packaging (Gibson and Rogers, 1994; Thorpe, 1995). Also predating Sematech, the Semiconductor Research Corporation (SRC) is a consortium funded by private firms, by the Defense Department, and, recently, by Sematech. It concentrates on more basic research at universities. Lately, the Fabless Semiconductor Association has begun sponsoring cooperative efforts by its members (Macher et al., 1998).

[75] The original founding members of Sematech were Advanced Micro Devices (AMD), AT&T, Digital Equipment, Harris, Hewlett-Packard, Intel, IBM, LSI Logic, Micron, Motorola, National Semiconductor, NCR, Rockwell International, and Texas Instruments. Harris left the organization in 1992; LSI and Micron left in 1993. The dues required of each member amount to 1 percent of semiconductor sales revenue, with a minimum of $1 million and a maximum of $15 million.

the facility (Grindley et al., 1994, p. 730). As a result, Sematech quickly reoriented its mission away from developing cutting-edge process technology for and with member companies toward improving the capabilities of the American semiconductor-equipment industry and strengthening cooperation between those firms and the semiconductor manufacturers they serve.[76] This involved "contract R&D" with equipment suppliers, as well as programs to coordinate and set standards, in many cases through the offices of an organization called SEMI/SEMATECH that was set up at Sematech in 1987 to represent equipment makers.

The formation of Sematech is coincident with the turnaround of American fortunes in semiconductors, but few are willing to jump to the conclusion that Sematech somehow *caused* this resurgence. For one thing, the resurgence was already under way before Sematech had produced much in the way of research results. Moreover, it is clear that the factors outlined – the changing pattern of end-use demand, the appreciation of the yen, and the STA – must have primary place in an explanation of renewed American success. This is not to say, however, that Sematech has not proved useful to American industry, even if the mechanisms by which it contributed are hard to pin down (Grindley et al., 1994). Informal studies typically find that member companies are pleased with their association with the consortium[77] (Link et al., 1996). Irwin and Klenow (1996) found that Sematech probably increased the productivity of American R&D by reducing duplication, even if this meant a reduction in private R&D spending of some $300 million per year. And Link, Teece, and Finan (1996, p. 739) found not only that direct benefits to member companies exceeded costs but that "the benefits to member companies from research management and research integration, as well as the indirect benefits from spillovers, were more important than the tangible direct benefits flowing from research results." As in the case of the Japanese VLSI Project (Flamm, 1996, p. 103), then, the ultimate virtue of Sematech may lie not so much in the research it produced as in its role in reducing the transaction costs of research dissemination and in fostering closer "vertical" collaboration and coordination between manufacturers and equipment suppliers.

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[76] In 1989, only $30 million of Sematech's budget went into projects with equipment makers; by 1991, that figure was $130 million (Burrows, 1992); see also Link, Teece, and Finan (1996, pp. 743–744). Even more than semiconductor manufacturers, semiconductor equipment suppliers had been accused of "excessive vertical disintegration" (Stowsky, 1989, p. 243). On this industry generally see Langlois (1999).

[77] This presumably excludes the three firms that left the consortium, apparently over a disagreement with Sematech's redirection of attention toward equipment suppliers and away from direct R&D on cutting-edge fabrication (Irwin and Klenow, 1996, p. 327).

The Role of Japanese Government Policy

American concerns about the bilateral trade balance with Japan, especially with regard to semiconductor issues, emerged exactly when major changes were under way in the Japanese telecommunications and computer industries. In the telecommunications industry, NTT was to be privatized, providing deficit relief for the Japanese government and restructuring the Japanese telecommunication industry with the aim of accelerating progress toward the "information society." An incidental effect of these developments was to heighten competition among NTT's suppliers, who were also Japan's leading IC producers. These developments began in the mid-1980s and were complicated by the worldwide 1985 recession in the semiconductor industry. The effects of the recession were severe for the Japanese IC producers, in both semiconductors and electronic systems, creating losses of $3 billion, a development that may have contributed to the willingness of Japanese producers to agree to the Semiconductor Trade Accord.

The other major development of the 1980s was a reorientation of Japanese industrial policy away from support for current technology in the IC industry toward breakthroughs in advanced IC design and the computer industry. Japan's Future Electronic Device Project was organized within a larger program of research on new materials and had a very forward-looking agenda, including research on three-dimensional devices; on ICs for extreme environmental conditions (terminated in 1985); and on biochips (begun in 1986), which aimed at a complete paradigm shift in IC fabrication "to practical electronic devices using proteins."[78] Not surprisingly, none of these projects has had a significant commercial effect.

Support for the computer industry came in the form of the Fifth Generation Project,[79] which was based upon the premise that artificial intelligence was on the verge of commercialization with applications in natural language processing, speech recognition, and other domains. The project was to enable Japan to forge ahead in the computer industry, eclipsing both American system and component companies.[80] Although American industry took the Fifth Generation project more seriously than the Future Electronics Device project, it too proved to be an overly

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[78] Fransman (1990) outlines this agenda; the statement quoted is from Karube (1986).

[79] Fransman (1990) provides a detailed case study of the Fifth Generation Project, highlighting major disagreements about its direction as well as chronicling some of the technological difficulties in reaching its goals.

[80] Feigenbaum (1983), an expert in artificial intelligence, argued strongly that without an American response, the entire American information and communication technology industry was in peril.

ambitious effort at "forging ahead" of the United States, and, although the Japanese computer industry did succeed in making significant inroads in IBM's market position during the 1980s, the basis for this progress can be found in incremental improvements in manufacturing competencies rather than breakthrough technologies. Moreover, it became clear in the 1990s that chasing IBM was no longer a desirable goal in a world of open, modular, microprocessor-based computer systems. Many of the problems of the Japanese systems producers who, partly at the behest of the Japanese government, chased the holy grail of competitiveness in mainframe production mirror the problems that beset IBM itself early in this decade (Ferguson and Morris, 1993). Japanese companies generally, and NEC (the domestic market leader) in particular, failed to seize hold of the personal computer, a development that, as we saw, had major implications for the development of IC components.

Europe

The growing role of downstream markets in determining the success of semiconductor firms is further supported by the experience of European producers during the past 10 years. Although European companies have played only a peripheral role in the contest for competitive dominance between American and Japanese producers and the rise of the Koreans as major commodity producers, the European industry has been able to maintain its market share and strengthen its base by reinforcing its capabilities in linear ICs, including those involved in connecting analog and digital circuits. The strong position of European producers in consumer electronics at home and, through direct investments in the United States, in export markets has supported these developments. In addition to consumer electronics, European IC producers have developed the telecommunications and automotive sectors.[81]

During the last decade, European semiconductor research has continued to receive substantial public support, much of which has been channeled through the JESSI Program. This support has contributed to European producers' "staying in the race" by moving to smaller dimensions in IC fabrication. The current goals of JESSI to produce "chip sets" for advanced communication applications, especially for the digital

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[81] Europe is the world's largest automobile market, and European producers, despite a less-concentrated industrial structure than that of either the United States or Japan, dominate the European market. This dominance receives some help from protectionist measures in several countries, including Italy, where Japanese imports are severely limited.

communications protocol called asynchronous transfer mode (ATM), are closer to the market and therefore riskier. Of particular note are SGS-Thomson's relative rise as a "merchant" semiconductor company and the continued strength of Philips and Siemens, both of which are also system producers.

Summary

The American resurgence has been largely the result of the industry's ability to improve manufacturing and at the same time – and more importantly – to achieve a dominant position in the fastest-growing segment of the industry during a sustained period of growth. The resurgence is thus based upon both productivity improvements and innovation and reflects the success of American companies, and American industrial structure, in meeting the Japanese challenge. The resurgence has been strengthened by important changes in the structure of electronic system production in Japan and the United States, changes that have led to higher revenues for American IC producers. Intel in particular has benefited enormously from these structural changes, surging to a strong position as the world's leading IC producer from its near-bankruptcy a decade ago.

These structural changes, as well as evidence that the gap in productivity is closing, suggest that American firms will continue to be strong through the opening years of the next century, assuming that the American computer industry remains strong. Stronger demand for the products of the Japanese consumer-electronics industry would increase Japan's share of the world IC market, perhaps pushing Japan slightly ahead of the United States again. But the world has changed. The situation in which the United States and Japan were roughly at parity in the computer industry, with Japan having an additional edge from consumer electronics, has become one in which the two economies are increasingly specialized, the United States in computer-related systems and Japan in consumer-related systems. This structure of demand will support differentiation in domestic production that will reinforce the respective IC segments over time.

Concluding Perspective

At the risk of oversimplification, we can organize our conclusions in terms of three related themes: the importance of end-use demand, the effect of industrial strategy and structure, and the role of government policy.

End-Use Demand

The pattern of end-use demand for semiconductors has always had a distinctly regional character. And the source of that demand has had an important – maybe even dominant – role in shaping the fortunes of regional industries.

American firms benefited early on from military demand, when performance mattered more than price. This demand called forth technological innovations in silicon technology that proved widely applicable to nonmilitary markets and provided the American innovators with early-learning advantages. As military demand tapered off in relative terms, the American computer industry provided an alternative outlet that gave domestic semiconductor firms a specialty in digital devices and later in logic ICs. The Japanese challenge was also driven in many respects by the sources of demand facing Japanese producers. The advantages of CMOS in consumer applications – including, initially, electronic calculators – gave those firms critical experience in what would prove to be the dominant general-purpose technology. At the same time, NTT's demand for memory chips – and for high-quality chips in general – helped focus the Japanese industry into a strategy of specialization in DRAMs fueled by advantages in mass production. Most recently, American firms have benefited from their de facto specialization in design-intensive logic chips (including microprocessors) at a time when the (largely American) personal-computer industry is burgeoning and the (largely Japanese) consumer-electronics sector is declining. European firms have done best when they focused on indigenous sources of demand, which have tended to be more in consumer, industrial, and automotive sectors; they have done worst when, often at the behest of their governments, they have tried to compete against American or Japanese strengths.

Strategy and Structure

From the very beginning, the American semiconductor industry possessed a diverse industrial structure that relied far more heavily than does Japan's or Europe's on relatively small, highly focused firms, often grouped geographically and partaking of what Alfred Marshall (1961) described as external economies. This structure arose out of the open intellectual-property environments that attended the invention of the transistor and of the IC; the innovation-driven character of early military and computer demand; and the American institutions of spin-off and venture capital. Universities played a comparatively small – or at any rate indirect – role in this process.[82]

A decentralized structure served the American industry well during decades of world leadership. But once the maturity of business and technology began to stress and unfocus the competence of the leading American firms, that "fragmented" structure proved vulnerable to a focused attack by Japanese firms specialized in the mass production of high-volume devices. Japanese industrial structure proved effective in this challenge, as the more vertically and horizontally integrated firms could take advantage of internal capital markets and corporate competences in a capital-intensive and process-oriented business. Contrary to the dominant opinion a decade ago, however, this Japanese structure is not obviously superior for all forms of competition under all circumstances. In losing ground to the Japanese in high-volume production, American firms were forced to specialize and refocus. And the "fragmented" American system has responded well in both technological and organizational innovation in this new regime.

Government Policy

We conclude from history that government involvement has played a major role in the evolution of this industry, but that government intervention in the form of industrial and technological policy has had a more equivocal role, one in which success is far better remembered than failure.

American firms benefited greatly from the role of the American military in the early years. But it was the military's role as demander of semiconductors rather than its role as funder of R&D that proved crucial. Japanese firms did gain from the R&D subsidies of the VLSI program, even if the real benefits of that program may have lain in the coordination and collaboration, especially between equipment suppliers and manufacturers, it effected. And purchasing by NTT may have played a role analogous to that played for American firms by military demand. In general, however, we share the view of Porter (1990) that vibrant

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[82] The original invention of the transistor came out of a large corporate lab, and most important developments thereafter were driven by semiconductor firms. Saxenian (1994, pp. 41–42) and others have argued that universities like Stanford and Berkeley played a symbiotic role in the development of the Silicon Valley industrial district that bred much of the American semiconductor industry. But a close reading suggests that the importance of those universities lay less in basic research than in their own entrepreneurship and in their training of scientists and engineers for industry, a process that had already been set in motion by defense spending on space and military programs after World War II (Saxenian, 1994, pp. 21–24).

domestic competition among firms in Japan had far more to do with building technological competences than did any coordination from MITI or other government agencies. The 1986 trade accords may have given some American firms breathing space at a crucial time, but they also created some unintended effects, especially for Japan: by cartelizing and making profitable the DRAM market, the STA focused Japanese attention on what would become, with Korean entry, a low-margin commodity market. Sematech may have helped American firms in much the same way that the VLSI Project helped Japanese firms – by increasing coordination and collaboration between equipment suppliers and manufacturers. In the end, however, favorable demand shifts, specialization, and industrial structure probably had more to do with the American resurgence than did government policy. Europe has little to show for decades of government subsidy except survival. And European and Japanese programs to spur a mainframe computer industry both arguably misdirected the attention of domestic semiconductor firms away from their core competences.

If there is a positive entry in the ledger of government involvement, it may lie in the role of government in providing a credible signal and commitment to guide the domestic industry's strategic decisions. The prospect of early military demand in the United States played this role. So, arguably, did the VLSI Project and related policies in Japan, which created a common understanding and expectation about the path of strategy and technological development. Examined individually, the American policy initiatives of the mid-1980s – notably the STA and Sematech – may have fallen short of expectations. Nonetheless, the cumulative effects of the government's expressed willingness to act on the industry's behalf, in spite of political costs and potentially troubling precedents, is arguably a factor in its own right shaping the expectations of both American and Japanese IC producers as well as those of the IC producers of other nations.

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