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PARTICIPATION OF DEVELOPING NATIONS IN THE GLOBAL INTEGRATED CIRCUIT INDUSTRY: THE EXPERIENCE OF THE U.S., JAPAN, AND THE NIE'S

By: David Mowery
University of California, Berkeley
and
W. Edward Steinmueller
Stanford University

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Part I. Introduction: Problems and Prospects for the Developing World

The global microelectronics industry is virtually unique it its relative youth (less than four decades old), rapid growth, and in the ability of developing nations to enter the production of world-class systems and (in some instances) components for foreign markets. The industry is one of considerable interest to policymakers in the advanced, developing, and newly industrializing economies--indeed, the policy decisions made by various participants affect the viability or entry prospects of others. This paper reviews the development of the postwar microelectronics industry in the U.S., Japan, and a number of newly industrialized economies, in an effort to derive policy lessons from this experience for prospective and recent entrants into the industry. Recent policy initiatives in the U.S. and other industrial economies will affect this industry's structure and evolution, and these issues accordingly are discussed as well.

Governments and firms in developing and newly industrializing economies (NIEs) must address a number of issues in considering entry into the global microelectronics industry. These include (1) the ease of access by new entrants to international markets for microelectronic components; (2) the creation or sustenance of domestic conditions that contribute to the development of an indigenous microelectronics industry; and (3) the availability of international flows of technology and capital that will affect the development of an indigenous microelectronics industry. All of these issues will be affected by U.S. government policies designed to address current problems in the domestic microelectronics industry and by the policies of other industrialized nations.

Ernst and O'Connor argue in their recent survey[2] that recent changes in the international trade policies of developed nations have created greater impediments to the previously successful export-oriented strategies of NIE governments and firms, restricting

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[2] D. Ernst and D. O'Connor, Technology and Global Competition: The Challenge for Newly Industrializing Economies (Paris: OECD Development Centre, 1989).

opportunities for entry into this industry by developing nations. As economic integration among Western European economies has accelerated, the European Communities have adopted a number of policies (e.g., creative definition and aggressive enforcement of "antidumping" regulations) that have restricted access by foreign high-technology goods to this market. Similarly, the United States has during the past five years adopted a more aggressive "fair trade" stance in its bilateral and multilateral trade policies that includes a greater willingness to restrict foreign access to its market. For NIEs or developing nations contemplating entry into the microelectronics industry, these current and potential restrictions on access to the largest markets in the global economy may reduce the desirability of export-oriented development strategies, which historically appear to have been far more effective than import-substitution approaches to high-technology industrial development.

A second broad cluster of issues related to the creation or sustenance of domestic electronics in LDCs concerns the relevance of public policy "lessons" from the development of the U.S., Japanese, and NIE microelectronics industries. The development of the U.S. industry benefitted from the confluence of military procurement demand and R&D expenditures, antitrust policy, and intellectual property policy. In our view, however, the development of the U.S. industry did not result from a coherent and purposive government "strategy." Even the influence of military procurement and R&D policies on this industry's development was largely unintended and in some instances (e.g., R&D funding) can easily be overstated. Nevertheless, we believe that a close historical review of industry development and government policy in the United States yields important insights into the environmental conditions that are most conducive to successful industrial development in the high-technology sectors. Care must be taken, however, in applying conclusions about "lessons" from the U.S. experience to "latecomer" economies. Government policies that were effective or ineffective for the United States, the technological "pioneer" in this industry, may be irrelevant for economies engaged in technological "catch-up."

The hypothesis that effective "latecomer" policy may differ from that of the U.S. is bolstered by an examination of the policies and patterns of industrial development in the microelectronics industries of Japan, Taiwan, South Korea, and Singapore during the 1960-1990 period. In all of these economies, strategic industrial policies played an important role in the development of a domestic microelectronics industry. The contribution and essentiality of government strategy, however, is difficult to assess, because the focus of policy interventions differed considerably among these economies. For example, both South Korea and Japan adopted fairly restrictive policies with respect to inward direct foreign investment, and both governments utilized these restrictions as a source of leverage in international technology licensing negotiations. In Singapore and Taiwan, however, government policies on inward foreign investment have been much less restrictive. The role of import protection also varies across these economies.

The industrial structure of microelectronics production in recent entrants contrasts with the U.S. experience. Much of the growth of the U.S. industry reflected the entrepreneurial energies of new, relatively small firms that commercialized many microelectronics innovations. In contrast to these independent, merchant producers, however, both the Japanese and South Korean microelectronics industries are dominated by very large firms that are both diversified and vertically integrated to a much greater extent than most of their U.S. competitors. However, participation of large domestically owned firms is not a prerequisite to participation in the microelectronics industry. The Taiwanese microelectronics industry is populated by a larger number of relatively small firms and the Singaporean industry consists mainly of foreign-owned production and design facilities. Several important elements nonetheless do appear to be common to these East Asian economies and to the United States. These elements include intense competition among domestic firms throughout the development of the industry, and the substantial investment by public agencies in the production of a large pool of trained manpower.

Still another element of contrast with the U.S. industry's experience, and an important factor for consideration in decisionmaking on entry strategies for the

microelectronics industry, is the changing structure and technology of microelectronics component markets. There appear to be three broad classes of microelectronics components--"commodity," "design-based," and "application-specific" integrated circuits. These three product classes differ in their minimum efficient scale for production facilities, capital requirements for entry, and in the requirements for "linkages" between the producers of components and the designers of systems. For example, commodity IC production may be concentrated in a few enormous production facilities that manufacture for global markets. Although the design and production of "application-specific" integrated circuits (ASICs) may require more intensive communication between user and producer in the specification of products, production may still be carried out in completely separate and geographically distant locations, with few, if any, direct nonmarket links between producer and designer. It is therefore important to assess whether and exactly how "vertical" linkages between systems and components production are important. Finally, the significance of "horizontal" linkages among these product classes also are uncertain--do there exist economies of scope that favor firms that produce both ASICs and commodity components? Are these linkages equally important for all of these product groups?

The strategies of would-be entrants into the global microelectronics industry will be influenced by the changing international environment to a much greater extent than was true of the United States during the 1950s and 1960s or of the later entrants. An important element of this environment is the international flow of technology and capital from the industrial to the industrializing economies of the world. International foreign investment from industrial nations played an important role in the development of both NIE microelectronics industries and the collection of electronic system industries that provide a local market for microelectronics in South Korea, Singapore, and other East Asian economies. The OECD has noted in another study of NIE industrial policies that

> A potentially radical change between past and future trends lies in the fact that the diffusion of technologies is becoming increasingly disconnected from the trade in products which embody the technologies. Such an evolution may open new opportunities for those NIEs which are succeeding in the development of a technological infrastructure and an industrial organization which will allow them to

respond quickly to the evolution of world demand, especially in the fast-growing sectors.[3]

Despite this assessment, the same forces that have made industrial nations more willing to restrict access to their markets for some NIE exports also are changing industrial governments' attitudes toward technology transfer to foreign firms (see below for further discussion). Both the United States and the European Communities have launched large programs of financial support for technological development in their indigenous microelectronics industries which favor domestic sourcing and retention of technological advances. The relatively abundant international flows of technology and capital that have aided the development of NIE microelectronics and other high-technology industries thus shrink in the future. Our survey of the U.S. microelectronics industry accordingly devotes attention to the outlook for outflows of capital and technology from U.S. firms.

The microelectronics industry, like many other high-technology industries, currently exhibits a number of contradictory or countervailing trends in its global structure and environment. Even as this industry is becoming increasingly global in the scope of its markets and sources of technology, a number of industrial nation governments are adopting or considering the adoption of more nationalistic (or mercantilistic) policies toward technology transfer and economic activity. The number of nations and firms that have entered into production of components has grown, but so has the web of private "strategic alliances" and "managed trade" policies that could in the future reduce the intensity of competition among firms. The widening array of product lines and trajectories of development also is creating a range of new niches and opportunities for entry, although this expansion may also be increasing the costs and risks of entry. Finally, the experiences of previously successful entrants into this industry may be of limited relevance to governments or firms contemplating entry at this point in the industry's development. Sweeping generalizations about the outlook for this industry and for NIE or LDC governments and

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[3] OECD, The Newly Industrializing Countries: Challenge and Opportunity for OECD Industries (Paris: OECD, 1988), p. 8.

firms contemplating entry thus are likely to be incorrect or misleading. In the following chapters, we hope to illuminate the uncertainties and breadth of options that firms and governments will have to consider in the future. No single strategy will fit all product lines, all nations, or all firms.

Part II. The Development of Microelectronics in the United States, 1951-81: What "Lessons" for Newly Industrializing and Developing Economies?

Throughout the postwar period U.S. firms have played a major role in the global microelectronics industry, a role that for most of this period has been one of absolute dominance. A large literature has looked to the industry's history for lessons for public policy and managers in other industrial and industrializing economies.[4] The recent relative decline of U.S. microelectronics firms has also attracted considerable journalistic, scholarly, and official attention, and a number of public policy initiatives have been undertaken or are being considered to reverse the perceived decline.[5] This section of our report discusses industry development and public policy in the industry's early years. The more difficult period following 1981 is discussed separately in Section IV. Recent U.S. proposals for new public policies in R&D funding, intellectual property protection, antitrust, and trade policy that will influence this and possibly other U.S. high-technology industries are also considered in that section.

II.1. Government Policy and Industry Development in the U.S. Semiconductor and IC Industries, 1951-1981

The U.S. semiconductor industry began with the commercialization of the transistor during the 1950s and the growth of electronic components and systems industries. Many of the characteristics of the industry's subsequent development were established during this

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[4] Cite Franco Malerba, The Semiconductor Business, Madison: University of Wisonsin Press, 1985, U.N. Centre on Transnational Corporations, Transnational Corporations in the International Semiconductor Industry, New York: United Nations (ST/CTC/39), 1986, Dieter Ernst, The Global Microelectronics Industry, Berlin: Campus Press, 1984, Nancy S. Dorfman, Innovation and Market Structure: Lessons from the Computer and Semiconductor Industries, Cambridge: Ballinger Publishing Co., 1987.

[5] For example, see Thomas R. Howell, William A. Noellert, Janet H. MacLaughlin, and Alan Wm. Wolff, The Microelectronics Race: The Impact of Government Policy on International Competition, Boulder: Westview Press, 1988.

period, including rapid output growth accompanied by rapid technological change, extensive entry by new firms, distinct trajectories of technological improvement, and the growth of electronic system producers' demand for specialized semiconductor components. Table 1 contains data on the growth of transistor, diode, rectifier, and IC shipments during 1954-1971. The transition from transistor to integrated circuit components began with a slowdown in market growth in the transistor industry in 1961 that reflected growing problems of reliability in developing new systems with larger numbers of transistors. As the number transistors employed in a system grew, the probability of systems failure from the failure of a single component or interconnection increased exponentially. Continued growth in demand for semiconductor components required a new class of products whose price and features (e.g. greater reliability and fewer interconnections) would expand system application opportunities. Following its commercial introduction in 1961, integrated circuit products proved to be this new class of products and stimulated the resumption of industry growth.

Braun and MacDonald depict the historical context of the IC innovation as a response to the growing limitations of discrete transistors in more complex system applications:

> ...As long as each element had to be made, tested, packed, shipped, unpacked, retested and interconnected with others, it would be sheer individuality of components rather than technical or production limitations which would constrain improvement. The problem posed by the interconnection of components was particularly severe for, no matter how reliable the components, they were ultimately only as reliable as the joints connecting them and the generally manual methods used for wiring circuits. The more complex the system, the more interconnections were needed and the greater the chance of failure through this cause. Hence, the main obstacle to progress was a **tyranny of numbers**. By 1962, some large computers contained as many as 200,000 separate components and future systems that would require 10 million or so were envisaged. Not surprisingly, problems of reliability became serious with systems of this complexity. These could largely be overcome, as they were in the Minuteman project, by taking extreme care... but such measures

were not realistic in the commercial world. It was said that if all military components received the cossetting given to those in Minuteman, the expense would have exceeded the gross national product.[6]

The development of the integrated circuit in 1958 opened a new path for solving the "tyranny of numbers" problem and eventually led to rapid expansion in applications (and therefore markets) for semiconductor components. The IC's development was an extremely important breakthrough for the U.S. microelectronics industry and for this industry's customers, electronic system producers. Examining how this breakthrough was achieved provides some important clues about the role of government policy and the nature of technological change in the IC industry. The direct role of military-supported research proved limited while the path-dependent and cumulative character of technological development in the industry proved to be very important.

The integrated circuit, which made possible the interconnection of large numbers of transistors in a single semiconductor devices, was invented by Jack Kilby of Texas Instruments, a firm producing junction transistors. The technical feasibility of the IC concept rested on process innovations in diffusion and oxide masking technologies first developed for the manufacture of silicon junctions transistors. The U.S. Army's Diamond Ordnance Fuze Laboratory made important contributions to oxide masking technology. Other than this, a military research program in "molecular electronics" that had been initiated in response to the "tyranny of numbers" problem made no significant contribution to the invention of the IC despite $5 million in funding.[7] Mass production of the IC in turn required application of Jean Hoerni's planar process, a technique used in the batch production of junction transistors. Robert Noyce's application of the planar process to IC

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[6] Ernest Braun and Stuart Macdonald, Revolution in Miniature: The History and Impact of Semiconductor Electronics, 2nd ed. (Cambridge, Cambridge University Press, 1982), p. 99, emphasis added.

[7] T.R. Reid, The Chip, (New York: Simon and Schuster, 1984), pp. 120.

production was critically important in making commercial IC products and applications feasible.[8]

The IC innovation was fundamentally driven by commercial concerns (TI and Fairchild's search for a device that would expand the market of semiconductor devices), and rested on scientific knowledge and technology developed for previous generations of transistors. For the United States, therefore, the need for the IC product was apparent from experience in transistor application and the path to invention of the IC in the U.S. relied on prior transistor innovations. Developing countries have not had to recapitulate this history. For these "follower" economies, the need for IC components was apparent and technology transfer reduced any need for experience in transistor design and production. Nevertheless, such technological "leapfrogging" while possibly necessary, rarely has proven sufficient for the establishment of a viable IC components industry. The existence of a strong source of demand for ICs, typically located within the producer nation, also has been crucial. The U.S. military sector's greatest contribution to the early development of the IC industry arguably was made through its demand for these components.

In the U.S. IC industry, the structure of market demand greatly affected the path and the pace of innovation. The tyranny of numbers problem was especially acute, and the commercial rewards for its solution especially high, in computer system applications. The requirements of military computer systems offered the first opportunity to apply the technology. The Minuteman guidance system, for example, was a rugged, high-performance computer. Military and space systems, e.g. the Minuteman II and III and NASA applications, provided early demonstrations of the viability of the IC, commercial computer

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[8] Reid, op cit observes a marked contrast between Fairchild's commercially-oriented strategy and Texas Instruments' close relationship with the military. For TI, the invention of the IC immediately launched a search for armed service funding for development support. The Army offered TI funds to prove that the Kilby's IC was fully compatible with the Micro-Module program (the Army's version of the Air Force Molecular Electronics program). In 1959, the Air Force provided just over $1 million to TI for development of the IC. Reid, pp. 119-120.

applications quickly emerged for the new technology. As Kilby recounts: "From a marketing standpoint, Apollo and the Minuteman were ideal customers. When they decided that they could use these Solid Circuits, that had quite an impact on a lot of people who bought electronic equipment. Both of these projects were recognized as outstanding engineering operations, and if the integrated circuit was good enough for them, well, that meant it was good enough for a lot of other people."[9]

In 1969, after the use of ICs by IBM's competitors, Univac, Burroughs, and RCA in new mainframe computers, IBM re-designed its System 360, first introduced in 1964, to employ ICs. These developments as well as the early rapid growth of Digital Equipment following its introduction of a lower price "minicomputer," demonstrated that ICs could be employed for high-performance civilian applications.[10]

The proximity and prominence of computer systems applications in the U.S. created stronger incentives for U.S. producers to pursue the IC than was true in Europe. As Malerba (1985) has argued, the weak European computer industry and the dominance of semiconductor production by vertically integrated manufacturers of consumer electronic systems meant that European semiconductor producers pursued innovations in discrete components and failed to develop a strong presence in IC technologies. The expectation of a strong domestic demand for IC components appears to have been quite important in the pioneering innovative efforts of U.S. firms, none of which were themselves vertically integrated into system production, and proximity was therefore an important influence on the path and pace of technological innovation.

By 1966, ICs had overtaken transistors in commercial importance and the use of ICs in system designs had begun to restructure the demand for other semiconductor components.

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[9] Reid, op cit, pp. 121-122.

[10] Reid, op cit, p. 126

By the mid-1970s, the application of non-IC semiconductors for most system applications depended on the utilization of ICs. Tables 2 and 3 recount the growth of IC production between 1972 and 1982. During these years, the value of IC output increased at an annual rate of 20%. Rapid growth was accompanied by significant changes in the composition of output. The microprocessor, invented in 1971, accounted for $275 million in revenue by 1976, while revenues from earlier IC types, such as Diode Transistor Logic, began to fall in the late 1970s.[11]

The structure of the semiconductor industry changed very little during the 1960s. Of the eleven firms producing more than $15 million in transistors in 1960, only IBM and Western Electric produced semiconductor components entirely for internal consumption, and remain important "captive producers" to this day. System producers, including General Electric, RCA, and Philco, produced semiconductor devices for internal consumption and for sale to the external market. Each of the system producers had been important producers of electron-tube components and made a relatively successful transition to producing transistors. TI, Transitron, and Fairchild were among the first of the "merchant semiconductor producers," companies whose output was sold entirely to other firms. Merchant producers have come to dominate the commercial sale of ICs in the U.S. By 1971, National Semiconductor, Signetics, and American Microsystems had been added to the list of major merchant producers of ICs and ITT entered as a system producer that also sold in the merchant market. The concentration of the industry remained stable through the 1960s; four-, eight-, twenty-, and 50-firm concentration ratios were unchanged between

[11] Other changes in the mix of products are largely obscured by the classification system employed by the U.S. Department of Commerce for recording semiconductor output. For example, growth in shipments in aggregate categories of ICs such as TTL (transistor-transistor logic) reflect the growing use of particular TTL circuits for "gluing" together more complex ICs in increasingly complex systems. Within the TTL category, the output of some types of ICs grew at the expense of other types.

1963 and 1972.[12] During the 1970s, however, many of the firms that had made the transition from electron tubes to transistors proved unequal to the IC challenge, and exited from commercial (as opposed to "captive") production of components.

During the 1970s, the merchant IC companies that successfully pursued increases in the scale of IC integration grew more rapidly than other companies, which either failed to develop new, more complex products or focused on smaller "niche" markets. By 1980, five of the significant IC producers of 1960 had been reduced to minor status or had exited the industry. Four of the firms that exited were system producers but two of the largest remaining, IBM and AT&T were also vertically integrated captive producers, producing both ICs and systems. Throughout this period, merchant IC companies focussed most of their efforts on developing "standard" mass produced products that could be employed in a wide array of system applications Efforts to realize economies from vertical integration, if such advantages existed, required very large scale of system production. During the 1970s, the larger firms specializing in IC production, many of which exhibited modest degrees of vertical integration prospered. This group included TI, Motorola, National, Intel, Fairchild, Signetics, Mostek, and AMD. Alone of the electron-tube systems pioneers who entered the transistor market, RCA remained an important producer of ICs for defense applications, but was weak in commercial markets. The four new entrants on the 1980 list were Intel, AMD, General Instruments, and Harris. Intel and AMD entered the industry as specialists in IC production. The other two firms (Harris and General Instruments) were divisions of scientific instrument companies that consumed a relatively small proportion of their output internally. In 1981, the four firm concentration ratio was 49% and the eight firm concentration ratio was 67%, essentially unchanged from 1972. Overall, U.S. merchant producers expanded their share of the commercial IC market during 1960-1980 at the expense of vertically integrated U.S. firms that produced for both internal consumption and

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[12] Jerome Kraus, An Economic Study of the U.S. Semiconductor Industry, New School for Social Research, 1973, p. 114 and U.S. Department of Commerce, A Report on the U.S. Semiconductor Industry, Washington, D.C.: USGPO, September, 1979, p. 41.

commercial sale. This pattern of development contrasted sharply with that of the Japanese semiconductor industry during this period.

Internationalization of the industry accelerated in the 1970s. U.S. firms increased direct investment in offshore fabrication and assembly facilities in East Asian NIEs and in Western Europe (see below for further discussion). Acquisitions of U.S. producers by foreign firms also expanded. Signetics was purchased by the Dutch electronics giant Philips in 1975 and Fairchild was purchased in 1979 by Schlumberger of France, who sold it to National Semiconductor in 1986, after efforts by Fujitsu to acquire the company were blocked by the U.S. government on national defense grounds. Foreign acquisitions of smaller U.S. firms grew during the 1970s and 1980s. Japanese firms increased their investment in a number of U.S. start-up firms, but significant foreign capital also came from such NIEs as Korea. With the exception of the Fujitsu bid for Fairchild, the U.S. government has not discouraged foreign acquisitions in the industry.

The rapid growth of the U.S. IC industry from its origins to 1981 was affected by market, technological, policy-related, and internationalization factors, all of which are discussed in greater detail below. Among the market factors shaping the industry growth were the influences of "demand-pull" and "technology-push." In particular, military procurement created an early market demand for IC, one that was outstripped by commercial demand as the cost of ICs fell. Technological improvements anticipated by "Moore's Law" (see below) provided numerous new product design and application opportunities for IC firms supporting rapid growth and entry.

The IC radically shifted the "technological paradigm" (Dosi, 1985) for microelectronics components and accelerated turnover among firms that had shifted from tubes to transistors. The dynamism of the IC industry's structure and technological development was intensified by new methods for financing the entry of new firms into the IC and systems industries that increased competition in IC supply and expanded demand for ICs. In addition to military procurement policy, U.S. antitrust policy and a complex pattern

of process innovation prevented the development of strong intellectual property rights within the industry and supported the domestic interfirm transfer of technology. The U.S. industry expanded internationally in Europe through direct investment and in Japan through product export. U.S. firms also developed extensive offshore assembly operations, which supported the growth of East Asian electronic systems and microelectronics components industries.

II.1.a. *Military Demand and Early Market Growth*

Both discrete semiconductors (transistors, diodes, and rectifiers) and ICs derived a large share of their initial markets from military procurement. Table 4 shows the percentage of discrete semiconductor production devoted to "defense" production (including production for NASA, the FAA, and the AEC) in 1955-1968. Commercial demand for discrete semiconductors was also large in the early years of the industry, however, as these components were used in inexpensive hearing aids and radios that tapped a mass market. Military demand for discrete semiconductors peaked during the Minuteman missile program in 1960-62 and increased again with the Vietnam buildup of the mid-1960s. Defense demand declined as a proportion of output throughout the 1960s.

Table 5 shows the percentage of IC production accounted for by defense agencies and the average price of these devices in 1962-1968. The table reveals the high proportion of IC demand devoted to defense equipment and the high prices of ICs in the early 1960s. Sales volumes at initial prices were modest; the IC industry did not exceed $100 million in sales until 1966. By 1966, the average price of ICs had fallen to about $5. At these prices, commercial uses began to be attractive. Table 5 also reveals the modest size of the military IC market during this period. Military purchases of ICs during 1962-65, the period of unambiguous military dominance of the IC market, amounted to $140 million, less than 5% of the market for discrete semiconductor devices at that time. In view of its modest size, especially relative to the discrete semiconductor market, it is difficult to argue that military procurement was "indispensable" to the growth of a U.S. IC industry. Although military demand clearly aided industry growth and reductions in price, the small size and brief period of primacy of military demand within the overall IC market suggests that firms entering the IC industry were attracted by the potential for a larger, domestic civilian market.[13]

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[13] Other analysts believe that military demand nonetheless was an important influence on industry development. Grunwald and Flamm argued that despite the small share of total demand for semiconductor components, "military demand has probably pulled American (continued...)

In addition to providing an early market for semiconductor products, military procurement policies proved particularly beneficial to new microelectronics firms. Tilton noted that

> The defense market has been particularly important for new firms...Fortunately for them, the armed forces have not hesitated to buy from new and untried firms. In early 1953, for example, before Transitron had made any significant sales, the military authorized the use of its gold-bonded diode. This approval has been called the real turning point for the new firm. During 1959, new firms accounted for 63 percent of all semiconductor sales and 69 percent of military sales.[14]

Military procurement aided the early growth of other new entrants, including Fairchild and Texas Instruments. Established in 1957, Fairchild along with TI pioneered in the manufacture of silicon transistors. Fairchild's early growth relied heavily on military sales; 80 percent of its 1960 transistor output was destined for military applications.[15] These three firms were among many beneficiaries of a military procurement policy that did not discriminate against new entrants and thereby supported the growth of a diverse array of companies attempting to pioneer new technological advances in the industry. Military contracts frequently included incentives or generous provisions for the construction or expansion of production capacity, further reducing entry barriers for young firms. "Buy

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[13](...continued)
resources away from mass-market applications to custom military systems with much smaller production runs and smaller commercial potential. While of great value in developing certain types of basic research, these systems have offered fewer opportunities for developing automated production technologies... Both the military quality requirements and the scale of miliary systems have worked against the automation of assembly and testing by U.S. military contractors. J. Grunwald and K. Flamm, The Global Factory, Washington, D.C.: Brookings Institution, 1985, pp. 122-123.

[14] John E. Tilton, The International Diffusion of Technology: The Case of Semiconductors, Washington, D.C.: The Brookings Institution, 1971, p. 91.

[15] Herbert Kleiman, The Integrated Circuit Industry: A Case Study of Product Innovation in the Electronics Industry, D.B.A. Dissertation, The George Washington University, 1966, p. 169.

America" clauses in many military procurement contracts also provided a slight advantage for U.S. over foreign suppliers.[16]

Military procurement policy also influenced semiconductor industry structure by endorsing the practice of "second sourcing." Firms offering product innovations to the military were required to develop a second source for the product, i.e., a domestic producer offering an electronically and functionally identical product. As a purchaser of new, relatively untried components, the military employed second sourcing to reduce the risk that a system designed around a particular IC would be delayed by production problems or by the exit of a supplier. Second sourcing complemented the military's policy of allowing system producers to procure ICs from new entrants to the industry. To comply with second source requirements, firms exchanged designs and shared enough process knowledge to ensure that the second source component was identical to the original product. Although second source agreements stopped short of requiring a complete exchange of technical knowledge among participating firms, these agreements furthered the inter-firm transfer of many IC product and process technologies. Other major IC purchasers also adopted second sourcing policies, further accelerating the spread of IC technology. Military policy thus reinforced the effects of U.S. antitrust policies (see below) to speed interfirm technology transfer.

Although the IC almost certainly would have appeared and its applications in civilian markets would have expanded during (or possibly, slightly after) this period in the absence of military procurement demand, the innovation required the existence of both a substantial discrete component industry and a broad and diverse set of domestic market opportunities for system applications. By 1963, when IC production was valued at $16 million and almost exclusively for military applications, markets for the $242 million in transistor output were already quite diversified. Table 6 shows the value of transistor shipments in various

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[16] See F. Malerba, "Demand Structure and Technological Change: The Case of the European Semiconductor Industry," Research Policy 14, 1985, 283-297, p. 289.

application markets. Commercial computer and government missile/space applications dominate other categories, although consumer applications of portable and car radios accounted for 12% of output.

II.1.b. *Technological and Market Developments*

Because the expansion of commercial markets for integrated circuits depended heavily on the cost and the scale of integration of these components, technological advances in IC process technology were critical to growth in system applications during the 1970s. By using MOS transistors in IC fabrication, it was possible to dramatically increase the number of transistors per IC device. This trajectory of improvement began with the earliest devices, which contained only a few transistors and performed very basic electronic functions. Integration of larger numbers of transistors increased the number of electronic functions that could be incorporated on a single IC. With medium scale integration, electronic functions such as timing circuits could integrated in a single IC. Large scale integration made semiconductor memory an economically viable substitute for ferrite storage in computers and provided the level of complexity necessary for the innovation of the microprocessor. Improvements in the use of MOS transistors in ICs were the basis for the "law" first enunciated by Gordon Moore of Intel in 1964, who predicted that the number of transistors "integrated" in an IC device would double every year through the 1970s. "Moore's Law" has proven remarkably robust and accurate, as Figure 1 shows. The growing awareness of this seemingly robust trajectory of technological development also reduced the technological uncertainty faced by later entrants, including Japanese firms.[17]

Among the innovations necessary to pursue the trajectory of higher levels of integration, photolithography was central. Photolithography improvements increased the "resolution" for making circuit features, allowing progressive reductions in the physical size of individual circuit elements (transistors and their interconnections) and more circuit

[17] Gordon E. Moore, private communication, November 30, 1990.

elements for each IC. By 1971, advances in photolithography made it possible to put 6,000 components on a 6x6mm chip of silicon.[18] This increase in IC device density and functional complexity on each IC reduced the costs of constructing electronic systems, dramatically extending the range of applications for semiconductor technology. This expanding range of (largely civilian) IC applications drove industry growth through the 1970s.

A major impediment to the development of a commercial market for early ICs was their price. As noted in Table 5, the average price of integrated circuits fell dramatically during the 1960s. During the 1970s, the average price of individual ICs stabilized at approximately one dollar, but because the number of components increased according to Moore's Law, the quality adjusted value of ICs increased at a very rapid rate. Cost per transistor was falling at the rate of 50% per year and soon was measured in millicents. This dramatic reduction in the effective price of semiconductor electronics was largely responsible for the rapid output growth in the IC industry recorded in Tables 2 and 3.

The growth of markets for ICs can be divided into two basic segments, 1) higher value-added applications in computers and industrial electronic systems and 2) lower value added application in consumer electronics. The decade of the 1970s began and ended with U.S. producers of high value-added electronic systems in a strong position relative to international competition. In 1974 (see Table 7), the dominant customer for ICs was the computer industry, where IC replacements for ferrite core arrays in computer memories and development of faster and less expensive mainframe and minicomputer computer systems fueled rapid growth, prolific innovation, and numerous entrants. New entrants in the minicomputer industry like Digital Electronic Computer (DEC) opened competitive challenges to IBM's established position and appear to have stimulated technological change. Industrial markets, including specialized electronic system producers selling limited volume and therefore expensive instruments and control systems, as well as producers of less

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[18] Braun and MacDonald, Revolution in Miniature, op cit, p. 103.

expensive and larger volume instruments such as digital multimeters, also expanded their IC use during the 1970s. These markets, like computers, experienced rapid growth, prolific innovation, and numerous entrants with similar salutary effects on technological progress and competition.

The 1970s were, however, the beginning of a period of decline for the U.S. consumer electronics industry. This decline was important for the IC industry because radio and television equipment were second to computers in the share of total semiconductor demand throughout 1963-1972 and remained a distant second to computers in 1974.[19] As ICs permitted dramatic reductions in the parts count and price of television receivers, Japanese firms undercut the position of established U.S. television producers. By the end of the 1970s, U.S. television producers had lost considerable market share to Japanese producers and were in decline. In other consumer products that intensively utilized ICs, the U.S. firms proved incapable of sustaining efforts to lower system production costs by moving production offshore. By 1978 consumer producers accounted for a share of U.S. IC production that had declined by more than one-third in only four years. The relatively slow growth in applications of ICs in U.S.-produced consumer durables such as automobiles did not offset the declines in the U.S. consumer electronics sector's demand for ICs. The cumulative effect of these developments was to weaken the vertical links between IC producers and consumer electronic system producers, which increasingly were non-U.S. firms. U.S. IC firms faced better prospects in the production of new ICs for computer video displays than for television applications.

In retrospect, weaknesses in U.S. consumer electronics have been an important source of advantage for Japanese IC firms. These developments would not have been as significant if consumer electronics had remained a technologically unsophisticated market requiring only modest IC manufacturing capability. Instead, the development of video cassette recorders as well as sophisticated television and audio equipment offered

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[19] Grunwald and Flamm, op cit, pp. 43.

opportunities to design ICs that were both complex and offered higher value added to IC manufacturers (as well as enormous volume) than could have been predicted at the beginning of the 1970s. Japanese firms that occupied a strong position in consumer electronic ICs and systems at the beginning of the 1970s thus dominated a market that was to grow rapidly in size, profitability, and technological sophistication for the next two decades.

II.1.c. *Developments in Financial Markets*

In the 1960s and 1970s, innovation and entry in the IC and electronic system industries were aided by abundant venture capital. Most new firms during this period began with a relatively limited repertoire of products and a few substantially broadened their technological and market base. Venture capital made its greatest contributions to the growth of the IC industry when the capital requirements of entry and new product development were more modest than at present. Throughout the 1970s some $100-200 million of funds flowed into the electronics industry annually from the venture capital community, and much of this flow supported the growth of IC producers and equipment suppliers.[20] During the 1980s, while venture capital continues to play an important role in the IC industry, growth opportunities in electronic system production have absorbed a larger share of venture capital placements. Moreover, other high technology industries such as biotechnology and software have begun to compete with electronics investments for venture funds.

Venture capital supported the creation of many new firms, intensified competition within the industry and eroded the market power of earlier entrants. This abundant supply of venture capital and its augmentation by public equity offerings, relied on a U.S. capital

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[20] William J. Perry, "Cultivating Technological Innovation" in Ralph Landau and Nathan Rosenberg, The Positive Sum Strategy: Harnessing Technology for Economic Growth, Washington, D.C.: National Academy Press, 1986.

market of unsurpassed size, diversity, and liquidity. In the absence of this capital market, industry structure and technological development might well have assumed very different forms, as a comparison of the structure of the U.S. industry with those of Japan and Western Europe suggests.

In addition to intensifying competitive pressure, the proliferation of new firms broadened and diversified the range of technological options pursued within the industry. Venture capital-backed entry effectively decentralized decisions about the "right" solutions to specific technological or design problems. New firms often pioneered the process technologies or product design opportunities that might otherwise have been less vigorously pursued by incumbent firms. The resulting diversity contributed to rapid technological progress in the U.S. IC industry.

II.1.d. *Intellectual Property and Antitrust Policies*

The growth of the U.S. and global IC industries was affected in a number of ways by relatively weak protection of intellectual property. This weak protection was influenced by military procurement policy and by U.S. antitrust policy. The invention of the transistor occurred shortly before the filing in 1949 of a U.S. government antitrust suit against AT&T, alleging that "the absence of effective competition has tended to defeat effective public regulation of the rates charged subscribers for telephone service, since the higher the price charged by Western Electric for telephone apparatus and equipment, the higher the plant investment on which the operating companies are entitled to earn a reasonable return."[21] Under attack by the Justice Department, AT&T was reluctant to develop an entirely new line of business in the commercial sale of transistor products. The firm also may have wished to avoid any practice, such as charging high prices for transistor components or patent licenses, that would draw attention to its market power. Soon after the invention of

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[21] As quoted in John Brooks, Telephone: The First Hundred Years, New York: Harper and Row, 1976, p. 233.

the transistor, AT&T publicly disclosed the technology to interested firms. In April, 1952, the Bell Laboratories held a symposium open to all for a $25,000 admission fee that revealed the technology of the point contact transistor and explained progress in the manufacture of junction transistors.[22]

After considerable negotiation the antitrust suit was settled through a consent decree in 1956. The consent decree preserved Western Electric as a subsidiary of AT&T but stipulated that AT&T would be restricted to the production of telecommunications equipment. As a result, AT&T, which held a dominant patent position in 1956, adopted a policy of licensing its semiconductor patents at nominal rates to all comers. AT&T held by far the largest semiconductor patent position of any company in 1956.[23] The 1956 consent decree exerted an enormous influence on the development of intellectual property rights in the microelectronics industry supporting widespread domestic and international diffusion of semiconductor technology. Barred from the manufacture of transistors for commercial sale and forced to charge nominal rates for licensing the technology, AT&T required cross-licenses for access to its patents. As a result, virtually every important technological development in the industry was accessible to AT&T and all of the patents in the enormous pool created by the development of the industry were linked through cross-licenses with AT&T.

For AT&T, ownership of licenses for a broad array of patents facilitated the development and improvement of process technology for its internal needs. Process technologies developed by AT&T were regularly disclosed to others firms in AT&T-sponsored seminars. Other firms that filed patents for semiconductor technology chose to cross-license, not only with AT&T but among themselves. Since these firms were not bound by consent decrees, their liberal licensing policies are more difficult to explain, but these

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[22] Brooks, ibid, p. 54.

[23] John E. Tilton, International Diffusion of Technology..., op cit, p. 57.

policies may also have been affected by the AT&T consent decree. AT&T's enormous patent portfolio was released to prospective licensees as a result of the consent decree. Subsequent development efforts by these new entrants and licensees created new patents. The simultaneity of these subsequent inventions would have complicated the assignment of patent rights among the inventors, as in the case of Noyce's and Kilby's invention of the integrated circuit. As a result, many firms chose to cross-license rather than turn to the courts to determine patent validity and ownership.[24] The prevalence of cross-licensing, the absence of significant inter-firm patent royalty payments, and consequently rapid interfirm technology transfer, all have continued to the present.

Relatively liberal cross-licensing and rapid technology transfer, however, do not mean that intellectual property rights are unimportant in the semiconductor industry. Instead, patents are an important currency of technological exchange. Gordon Moore has noted that: "In order to make a semiconductor device, you probably use the patents owned by 20 or 30 companies. Each company tries to get enough of a patent position that it can trade with everybody, usually at zero or trivial royalty rates so no other company can put it out of business. The net result is that patenting has not had a strong impact on the industry."[25] Extensive cross-licensing has distributed production technologies widely within the semiconductor industry. If, as Moore suggests, cross-licensing requires a credible patent position, the practice may also have enhanced the incentives to innovate in the industry.

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[24] Kilby and Noyce's experience may also have been instructive. After litigation lasting a decade, the assignment was made to Noyce in 1970. By this time, however, Fairchild and T.I. had cut a deal which required new firms to license with both companies and the scientific community had acknowledged both men's contributions to the invention. See T.R. Reid, The Chip, op cit, chapter five.

[25] Gordon Moore, "Entrepreneurship and Innovation: The Electronics Industry," in Ralph Landau and Nathan Rosenberg, The Positive Sum Strategy: Harnessing Technology for Economic Growth, Washington, D.C.: National Academy Press, 1986, p. 426.

The liberal intellectual property regime spawned extensive cross-licensing and interfirm diffusion of new technological knowledge, but did not completely negate the value of intellectual property rights in the industry.

II.2. Evaluation of U.S. Government Policies Toward the IC Industry 1951-1981

Although no clear strategic intent is discernible within the complex web of U.S. government policies that supported the growth of the IC industry, one effect is apparent. Throughout the 1951-81 period, public policy consistently increased the range and number of technological alternatives that were explored by individuals and firms during a period of technological flux and uncertainty. The importance of diversity in the technological alternatives explored by firms in the early development of semiconductor technology stems from the role of the United States during this period as a pioneer in this technology. For the country, countries, or firms operating at the technological frontier, the pervasive characteristic of the environment is uncertainty.

Such genuine uncertainty is difficult to manage through a risk-minimizing strategy or other explicit strategy--the probabilities of different outcomes, even the range of possible outcomes, are unknown a priori. Efforts to direct the course of technological choice and exploration may be ineffective or even harmful in such an environment. Instead, exploration of numerous different avenues of technological development, combined with policies supporting rapid intra-national transfer of technologies and entry by new firms may illuminate the technological murk. In the U.S. during this period, the combination of defense-related procurement and R&D funding, early military development of technologies later employed in civilian applications (discussed in more detail below), low entry barriers, relatively abundant risk capital, and modest intellectual property protection, encouraged exploration of diverse technological alternatives within the microelectronics industry.

The previous section suggested that military procurement played an important role in building the IC industry. How important was military R&D funding in the innovative

process? Kleiman's study of military programs and policies in the late 1950s and early 1960s concluded that military R&D programs made little or no direct contribution to the development of IC technologies, noting, among other things, that the major corporate recipients of military R&D contracts were not among the pioneers in semiconductor technology, while the pioneering firms did so without R&D contracts.[26] The military's search for an effective means of microminiaturization was an important impetus for the invention of the IC, but this influence was channelled mainly through entrepreneurial expectations of a large military (and, eventually civilian) market for technologies that satisfied the demands of the Pentagon. The inventors of the IC, Noyce and Kilby, were aware of the military's interest in improved reliability, which most experts felt would require

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[26] According to Kleiman,

> "1) The concept of molecular electronics as espoused in the original Air Force proposal [setting a goal for micro-miniaturized components and a method of implementation] has not been realized. Its commercial value for any foreseeable application is very limited. For all practical purposes, the IC component of today is totally alien to the device conceptualized by the original molecular electronics proponents.
>
> 2) The material originally selected for use by the two firms that received initial funding in this area is not used at all.
>
> 3) The present techniques now being applied are attributable to a company that perfected the methodology without any support from government-sponsored R&D contracts.
>
> 4) The company that first demonstrated the IC concept did so as part of an internally-funded project.
>
> 5) The company to which the government has given the greatest R&D support is definitely not the market leader and is not consider to be the technical leader either.
>
> 6) The government's very aggressive R&D funding has not been matched by a similar zeal to incorporate the IC components in equipment and systems."

Kleiman, op cit, pp. 173-174.

a reduction in the number of components in electronic systems. TI and Fairchild, the inventors' employers, were heavily involved in production of transistors for military applications. The research strategy and funding provided by the military (as opposed to military procurement demand), however, did not materially affect the innovation process. Nevertheless, the restrictions on foreign access to the U.S. military market conveyed some advantages to relatively small U.S. firms.

Although military R&D funding did not affect the timing of the IC innovation, military procurement did encourage early entry by firms into the IC industry. Since considerable experience with IC production methods was required to reduce production costs, military demand played a major role in reducing component costs sufficiently to create a strong commercial IC demand.[27] Policies allowing the purchase of ICs from new companies and requiring second sourcing served to encourage entry and transfer technology among participating firms. The direction of government demand, concerned as the armed services were with highly reliable computer guidance systems, also was crucial in laying the foundations for the IC industry.

Government policy exercised less direct influence on the financing of the IC industry. The differential tax treatment for capital gains encouraged long-term investments in new entrants and the relatively liberal regulation of domestic capital markets distinguished the U.S. economy from those of Japan or most western European nations during this period. Neither of these policies, however, was directed solely at the IC industry. Nevertheless some of the structural features of the U.S. industry, especially the important role of new entrants and merchant producers, can be attributed in part to these policies. Government support for capital formation of a different sort during the 1950s and 1960s also was important to the development of this industry. Federal support for graduate training of scientists and

[27] From the beginning, TI and other firms were aware of the commercial potential of the IC. As one of its first demonstration projects, TI constructed a computer to demonstrate the reductions in component count and size that were possible with ICs.

engineers, funded under the G.I. Bill and the National Defense Education Act, significantly expanded the pool of technical expertise on which the semiconductor industry and the industries developing application of semiconductor technology could draw. The expansion of university research and training also contributed to an international scientific and engineering talent pool that made important contributions to the semiconductor industries of such NIEs as Korea and Taiwan. As the data in Figure 2 show, the expansion of federal fellowship support for graduate study in science after 1961 and engineering produced a significant expansion in graduate enrollment by U.S. citizens, just as cutbacks in this support after 1970 are associated with declining enrollment.

U.S. government policy toward reimportation of partially finished goods encouraged the growth of the offshore operations of U.S. firms in many East Asian NIEs. From the late 1960s through the 1970s, foreign direct investment by the U.S. IC industry was concentrated in two regions, Europe and East Asia. Investments in Europe on production facilities by U.S. IC firms served the needs of European producers of systems; little of the output from these plants was re-exported to other regions of the world. In East Asia, U.S. firms established assembly plants for ICs initially fabricated in the U.S., in order to reduce labor costs. Sections 806.3 and 807 of the U.S. tariff schedule allow the reimportation of goods manufactured in the U.S. and exported for further processing. Tariffs are assessed only on the value added abroad. In 1974-1978, reimports, a large share of the value of which is added offshore, accounted for 32-42% of U.S. IC sales.[28] This tariff-based incentive, however, had little effect on the establishment by U.S. firms of production operations in Western Europe. As we note below, Western European production operations focussed mainly on production for local markets and were motivated in large part by the relatively high tariff (17%) on semiconductor imports maintained by EC countries through much of

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[28] Computed from International Trade Commission, Competitive Factors Influencing World Trade in Integrated Circuits, Washington, D.C.: USITC Publication 1013, November, 1979, pp. 82, 94. Although these tables offer the value added overseas (the dutiable portion), the determination of this value is somewhat arbitrary. In 1974-1978, this amount ranges between 40 and 60% of the value of the reimports.

this period. Although foreign assembly operations helped U.S. firms keep the price of ICs low during the mid to late 1970s, foreign assembly may have delayed the development or utilization by U.S. firms of significant advances in process technology, e.g., automated assembly methods, such as wire bonders.[29] In addition, of course, the offshore activities of U.S. firms served to diffuse some semiconductor and system production technologies. As we discuss below, the stronger process capabilities of many Japanese IC firms have contributed to the U.S. industry's vulnerability to competition in the 1980s.

Government antitrust policy was another important influence on the early growth of the U.S. semiconductor industry. Diffusion of transistor product and process technologies almost certainly was not a goal of the antitrust policy of the Truman or Eisenhower administrations. Nevertheless, the 1956 consent decree that settled the AT&T suit prevented the one firm with a dominant patent position in semiconductor technology from setting royalty payments high enough to create barriers to the entry of the new firms that were the innovative and commercial leaders of the industry.[30]

II.3. Conclusion

The policies adopted by the U.S. government in the 1951-1981 period had the effect of increasing the diversity of technological endeavors in the semiconductor and IC industries.

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[29] R.N. Langlois, T.A. Pugel, C.S. Kaklisch, R.R. Nelson and W.G. Egelhoff, Micro-Electronics: An Industry in Transition, Unwin Hyman, 1989, note that Japanese IC firms were less heavily involved in foreign assembly operations, and argued that "Japanese firms have consciously chosen a strategy that emphasizes automated assembly. This is consistent with their emphasis on higher-volume standardized productions offered into the merchant markets." (p.57)

[30] The scope of the government's original suit may also help explain why IBM has chosen not to enter the commercial production of ICs in subsequent years. Proposals to dismember IBM are less plausible so long as IBM defends its vertically integrated structure by asserting that this structure is responsible for its domestic and international competitive strength, and avoids commercial manufacture of components.

Military procurement and antitrust policy were pro-competitive, encouraging the entry of firms, transfer of technology among firms, and the creation of fierce interfirm competition within the U.S. industry.[31] U.S. policies also helped the industry to internationalize its operations, contributing to international technology diffusion.

Nevertheless, this analysis of U.S. government policy suggests that public policy played a modest directive role. Although military funds were important in procurement and in underwriting the costs of investments in production capacity, their initially substantial role quickly faded. The industry's early growth was driven largely by demand for applications in commercial, rather than military markets. The commonality of military and commercial applications that characterized the early years of the IC industry facilitated the rapid overtaking of military by commercial demand. These military-civilian technological "spillovers," however, were fortuitous, rather than planned. The substantial military role in the early growth of markets did exert an important influence on industry structure, supporting the entry into the industry of relatively small firms and spawning the widespread practice of second sourcing. These too were collateral, rather than intentional, results of policy. Certainly, direct government support of R&D, an important channel for exercising a major directive influence, was of little importance.

The development of the U.S. semiconductor industry was heavily influenced, however, by government antitrust and human resource policies. Antitrust, as was noted earlier, contributed to the extensive cross-licensing of the initial, critical patents and to considerable interfirm transfer of technologies within the U.S. and global industries. Extensive cross-licensing meant that intellectual property played an important role as a "bargaining chip,"

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[31] The importance of a competitive market structure for industrial development is corroborated by studies of NIE industrialization, including Frischtak (1989), who notes that "...competition is a compelling force for industrial restructuring as firms shed outdated operations, introduce new product lines, and search for new markets. A competitive environment is thus the most effective way to stimulate modernization and structural change" (p.1). See C. Frischtak, Competition Policies for Industrializing Countries, Washington, D.C.: World Bank, 1989.

and during much of the industry's history did not apparently impede the diffusion of new technologies. Widespread diffusion also contributed to the entry of new firms and to the development of a intensely competitive domestic industry, which supported continued technological advance. Intra-national diffusion was aided by the substantial federal investment in university-based training of scientists and engineers, which rapidly expanded during the late 1950s and 1960s. The creation of a pool of high-level scientific and engineering talent greatly facilitated the development of semiconductor technologies and applications.

The U.S. experience does not support a strong directive role for government in establishing a microelectronics industry. Although the U.S. case may not be directly relevant in all of its dimensions to NIEs, several implications do emerge for NIE industrial strategies. Encouragement of domestic interfirm competition is an important means of spurring technological advance. Support for the development of the human resources that are so critical to this industry is essential. In the area of intellectual property rights, the history of the U.S. industry suggests that the creation of a domestic "level playing field," e.g., through widespread domestic licensing of patents (as in the liberal domestic licensing of foreign patents in Japan during the 1950s and 1960s) may support both substantial domestic diffusion and high levels of investment in technological advance.

Part III. The Experiences of Japan and the NIEs, 1960-present

The ascent of the Japanese IC industry from a position of relative technological backwardness in the 1960s to its current position of commercial and technological leadership is remarkable for several reasons. First, unlike other U.S. industries that have lost international market share because technological advance was moribund or market positions ossified, the U.S. IC industry has continued to be both technologically dynamic and competitively vigorous. Second, the U.S. IC industry actively internationalized its production and marketing operations and continues to have a strong position throughout the world. Third, the U.S. IC industry has strong ties to a very large and technologically dominate market for its output, the U.S. computer systems industry. Despite these advantages, by 1990 three Japanese producers NEC, Toshiba, and Hitachi had become the world's largest merchant IC producers.[32]

The competitive success of Japanese producers has greatly heightened interest in Japanese industry practices and Japanese government policies by nations that seek to reproduce Japanese success in "catching up" technologically and competitively. In this section, we examine features of the Japanese industry and policies of the Japanese government that have played a role in this "catch up" effort. This discussion serves to introduce the subsequent efforts of newly industrializing economies (NIEs) to reproduce the Japanese experience. It is followed by a more detailed examination in Section IV of the decline of the U.S. industry and its consequences, developments that are important determinants of the possibilities for the future of international trade and competition in the IC and electronic system industries. While none of the NIE's IC industries have yet reproduced either the context or results of the Japanese, several have developed viable IC

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[32] William J. McClean (ed.), Status 1990: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering, Inc., 1990, pp. 2-28,29 and 3-7. In estimated production value, however, IBM has continued to be the world's first or second largest IC producer. IBM was second in 1989, but ICE estimates that it has regained its number one ranking in 1990.

industries. The collective experience of these nations reveals several important conclusions and a larger number of unanswered questions about how other nations, including those with more modest economic and technological capabilities might develop IC and electronic system industries in the future.

III.1. The Japanese Experience

The starting point for the Japanese semiconductor industry, like that of U.S. producers was experience in production of discrete components. Japanese companies, however, lagged in building advanced ICs despite their early licensing of Fairchild's planar technology patents and their early use of Kilby and Noyce's IC patents. Much of this lag has been attributed to the Japanese focus on the desktop calculator market and consumer electronics rather than higher value added and more complex electronic system products such as computers.[33] Both the Japanese government and Japanese companies recognized that growth and development of the IC industry must be accompanied by moves toward more complex and higher value added electronic system products. In this respect, the principal target of industrial policy was IBM's international position in the computer industry rather than the U.S. IC producers *per se*. While IBM continues to hold a strong position in the Japanese economy, Japan is one of the few countries where IBM's share of the computer market has fallen below 50 percent.

Overcoming lags in the IC and electronic system industries required an intensive "catch-up" effort during the 1970s that focused both on IC process technology and developing the markets for more complex and higher value added products. In terms of government policy MITI's organization of the VLSI project and the development of the Japanese Electronic Computer Corporation are of central importance. In the practice of

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[33] See Michiyuki Uenohara, Takuo Sugano, John G. Linvill, and Franklin B. Weinstein, "Background" in Daniel I. Okimoto, Takuo Sugano, and Franklin B. Weinstein (eds.), Competitive Edge: The Semiconductor Industry in the U.S. and Japan, Stanford: Stanford University Press, 1984, especially pages 14-17.

Japanese firms, the growth of consumer electronics and computer production were key developments.

The VLSI project was organized by the Ministry of International Trade and Industry (MITI) in accordance with earlier extensive discussions between government and private companies that identified key technological gaps of the Japanese IC industry in the course of defining a vision of that industry's future.[34] The $200 million cost of the VLSI project was financed by long-term loans to be repaid from future semiconductor-industry profits. During its four year existence (1976-79), this project concentrated on improving the capabilities of participating firms in process technology.[35] The participating firms were also the five largest IC producers of the period--Fujitsu, Hitachi, Mitsubishi, NEC, and Toshiba. Over 600 patents resulted from cooperative research among these companies at a separate research laboratory. The VLSI project succeeded in recruiting high quality researchers from the participating companies to work in this detached research laboratory despite the fact that each the companies contributing researchers had to bear the opportunity costs of the temporary departure of these personnel.

Government policies supporting the development of the IC industry included industry development loans from the Japan Development Bank and private bank investments based on Ministry of Finance "advice" about the desired course of future bank investments in Japanese manufacturing.[36] These loans financed large scale investments in manufacturing

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[34] See Daniel I. Okimoto, "Political Context," in Daniel I. Okimoto, Takuo Sugano, and Franklin B. Weinstein (eds.), Competitive Edge: The Semiconductor Industry in the U.S. and Japan, Stanford: Stanford University Press, 1984.

[35] W. Edward Steinmueller, "Industry Structure and Government Policies in the U.S. and Japanese Integrated-Circuit Industries" in John B. Shoven (ed.), Government Policy Towards Industry in the United States and Japan, Cambridge: Cambridge University Press, 1988.

[36] See Okimoto, "Political Context" op cit.

capability at a time when the Japanese industry was attempting to develop a more dynamic computer industry.

Improving the supply capability of Japanese companies was, however, insufficient by itself. A policy encouraging demand for components also was needed. To serve this aim, the Japanese Electronic Computer Corporation (JECC) was formed. JECC aided in the domestic diffusion of computers by financing the purchase of domestically produced computers that were leased to Japanese business enterprises. Formation of these lease arrangements had two important ramifications. First, it reduced the risks of adoption of domestically produced computer systems for domestic firms. With a lease arrangement, systems that failed to meet user objectives could be returned and redeployed elsewhere. Second, it reduced the costs of computer purchase by providing users with a way to trade in smaller systems for larger systems and substituted for an extensive network of sales and support that is required for building markets in computer systems. The JECC leases also eased the risks of investing in capital equipment that was quickly outmoded in this technologically dynamic industry. These mechanisms served to accelerate the development of domestic computer markets and strengthen the vertical ties between computer producers and users. The resulting stronger Japanese demand for domestically produced computer systems provided a foundation for the growth of the Japanese IC industry.[37] The major role of the Japanese computer industry as a source of IC demand contrasts with the relatively weak presence of European-owned computer producers in the demand for Western European microelectronics components.

The Japanese challenge has attracted attention not only because of the success of government and private policies during the 1980s, but also because of contrasts between the structure of the Japanese IC industry and that of the U.S. industry. In Japan, the largest IC

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[37] See Steinmueller Government Policies... op cit.

companies are also the largest producers of electronic systems.[38] Revenues from electronic systems sales and from the internal use of ICs in system products provide Japanese IC producers with internal investment resources that are unavailable to U.S. merchant IC producers.[39] Japanese financial markets also may create more favorable conditions for external finance, offering firms debt finance at lower interest rates and allowing them to carry higher debt-equity ratios than U.S. firms. As a result, throughout the 1951-81 period and to a lesser extent in the late 1980s, the cost of capital appears to have been lower for major Japanese electronics firms than for their U.S. competitors. Although a portion of the differences in the domestic cost of capital for U.S. and Japanese electronics firms reflected different differences in capital market and firm structure, much of this difference can be attributed to a far more stable and effective macroeconomic policy environment in Japan. In other words, a critical factor in the growth of this and other Japanese high-technology industries had little if anything to do with government industrial, science, or technology policies.

Japanese IC producers appear to have gained competitive advantages from their particular approach to vertical integration. Vertically integrated Japanese firms, however, differ in important ways from the two dominant vertically integrated U.S. firms (IBM and Western Electric). Whereas the vertically integrated U.S. firms produce almost entirely for internal consumption, and purchase a minority of their internal requirements on the commercial market, Japanese producers typically sell two thirds to three quarters of their component production on the commercial market and purchase the majority of the ICs that they use internally. The internal demand for ICs in Japanese companies provides a stable

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[38] W. Edward Steinmueller, "International Joint Ventures in the Integrated Circuit Industry," Chapter 4 in David C. Mowery (ed.), International Collaborative Ventures, Washington, D.C.: American Enterprise Institute Ballinger Press, 1987.

[39] In addition to these internal resources, the Japanese government has organized and financed a series of successful cooperative research efforts in process technology beginning with the famous VLSI Program of the 1970s. See Steinmueller, "Industry Structure...," and Okimoto et al, Competitive Edge..., op cit for further information about these programs.

source of demand that allows fabrication facilities to run steadily, accumulating the learning that contributes to improved yields and lower costs. This internal demand also may lower risk in an environment of high fixed costs. Combined with their financial resources, Japanese companies' ability to reduce the risks of investment in capacity expansion and in new product development provides a formidable advantage in international competition.

The viability and importance of vertically integrated Japanese firms in commercial production of microelectronic components contrasts with the limited role of similarly structured U.S. firms in the production of commercial ICs, and suggests another potentially important contrast between the pioneer and follower economies in the exploitation of this new technology. Indeed, one might argue that the industry structure best-suited to pioneering the development of a new technology, one in which new, entrepreneurial merchant producers figured prominently, may be less useful for competition in a more mature stage of industry development. This issue is discussed below in greater detail.

As Figure 3 shows, Japanese firms throughout the 1987-79 period have invested far more as a percentage of sales in IC manufacturing facilities than U.S. firms. Japanese firms have specialized in advancing NMOS and CMOS process technologies by focussing on the production of Dynamic Random Access Memory (DRAM) devices. DRAMs account for 20-30% of the value of IC production. They are less difficult to design and test than other ICs with similar numbers of transistors and therefore may provide excellent opportunities for developing process technologies for other high-volume components. Furthermore, DRAM production experience and learning may offer significant spillovers to the design and production of other ICs.

An important factor in the Japanese industry's growth is the rapid expansion of systems applications for the classes of components in which Japanese firms are especially strong. Japanese firms have developed strong product and process expertise in CMOS technologies, which are widely applied in consumer electronics. As Figure 4 shows, CMOS has displaced NMOS as the dominant IC technology. Many of the Japanese companies that

have come to dominate CMOS production are also major producers of consumer electronics systems. Although the relationship between firm structure and innovative performance probably is an interactive rather than a causal one, it is likely that the rise of Japanese CMOS product and process technology once again may be linked to the vertically integrated firm structure characteristic of the Japanese industry. Japanese firms' process technology leadership in CMOS DRAMs has challenged the NMOS-based dominance of U.S. firms in memory products and raises the prospect that the leading Japanese firms will utilize their dominance of CMOS to forge ahead in the design of other IC products. U.S. merchant firms, with the single exception of Micron International, have ceased domestic production of DRAM products. During 1989, however, TI was the world's largest supplier of one megabit DRAMs from its Japanese production facilities.

The final factor contributing to the success of Japanese companies' catch-up efforts has been asymmetrical market access. Japanese IC companies have been able to retain a very high share of their own market while making significant inroads into the U.S. market. The failure of U.S. firms to penetrate the Japanese market has become increasingly noticeable as the Japanese industry has grown. Japanese production of ICs increased from $2.3 billion in 1978 to an estimated $20.3 billion in 1988.[40] Much of this growth resulted from expanded demand by Japanese electronic systems producers. Japanese domestic IC consumption in 1988 was approximately $15.8 billion.[41] A large proportion of the difference between Japanese domestic IC production and consumption is exported to the U.S., and a significant fraction of Japanese domestic IC consumption is exported to the U.S. embodied in electronic systems products.

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[40] For 1978, see Nomura Research Institute, The Microchip Revolution in Japan, Tokyo: Nomura Research Institute, January 7, 1980. For 1988, see William J. McClean, Status 1989: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering, Inc., 1989, p. 1-19. Growth is overstated because of the increase in the value of the yen during the past decade.

[41] McClean, ibid, p. 1-19.

Although the fact of asymmetry is indisputable, the reasons for it and consequences of it are not. U.S. firms and the Semiconductor Industry Association (SIA) have maintained that American access to the Japanese market is restricted by non-tariff barriers. Japanese firms and their trade association, the Japanese Semiconductor Industry Association (JSIA), have offered several explanations for the poor performance of U.S. firms in penetrating Japanese markets, including the quality of U.S. products, reliability of delivery, and "effort" in distribution. The evolution over an extended period of supply relationships among Japanese companies and the close relationships between industrial suppliers and purchasers in Japanese manufacturing also may have restricted U.S. firms' access to the Japanese markets. In recent years, U.S. firms have endeavored to adjust to these institutional differences. Whether these efforts have been sufficient to overcome barriers arising from national favoritism will no doubt continue to occupy a prominent position in public debate of this issue. Unofficial restrictions on Japanese access to the U.S. market also appear to be present,[42] and as was noted earlier, formal impediments have in the past restricted access by Japanese and European firms to the U.S. military market.

The ultimate economic effects of asymmetrical access to domestic IC markets are difficult to ascertain. If a domestic cartel were able to carve up the domestic Japanese market for different device types, Japanese firms could indeed exploit higher profits and learning in their production for domestic markets to support exports. The only well-documented actions approximating those of a cartel within the Japanese industry, however, are MITI's guidance to DRAM producers to meet the output and price targets of the U.S.-Japan Semiconductor Agreement (see below).

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[42] Andrew Pollack, "Big Chill on Asian Chips in U.S.," New York Times, September 6, 1988, p. 20, notes that "...the major American semiconductor companies have long had a tacit policy of preventing their distributors from selling products made by Japanese competitors. U.S. distributors face implicit threats of losing American product lines, which are more valuable than the Asian lines, if they take on an Asian supplier." Distributors sell about 30% of the semiconductors consumed in the U.S. market. Japanese firms, however, also sell ICs directly to larger accounts.

III.2. The NIEs Experience

The newly industrializing economies of East Asia, South Korea, Taiwan, Singapore, and Hong Kong have established dynamic domestic electronics industries during the past two decades. Table 8 displays the shares of GDP in these four nations accounted for by electronics production and the mix of products within each NIE's electronics output in 1987.[43] In all four of these economies, production of electronic components and systems accounts for a larger share of GDP than in such developed economies as the U.S., Japan, or the U.K.--in the case of Singapore, where electronics manufacture accounts for nearly 40% of GDP, the share of this industry in GDP exceeds the share of all manufacturing in U.S. GNP. Exports account for a large share of domestic production in all four economies, as domestic consumption of electronics products in 1987 ranged from 53% (Singapore and Taiwan) to 68% (Hong Kong).

The data in Table 8 also reveal contrasting patterns of specialization in electronics manufacturing among these four economies. South Korea is significantly more committed to production of semiconductor components and to consumer electronics (these two sectors account for more than 75% of South Korean electronics production in 1987) than any of the other three nations. Singapore and Taiwan, by contrast, have specialized in the production of computer components. Hong Kong's electronics industry is focused on the manufacture of consumer electronics products. South Korea and Taiwan are the major producers of microelectronic components, especially ICs (a subset of the "component" category in Table 8) among these four economies. All four of these economies entered the production of ICs relatively recently, following the establishment within each nation of an important industry in the manufacture of systems. Hong Kong has three IC companies while Singapore has one existing semiconductor plant (an SGS-operated factory producing power transistors) and a new IC fabrication facility (where National Semiconductor is a minor equity holder).

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[43] Table 8 is based on data in C. Dahlman, "Electronics Development Strategy: The Role of Government," unpublished MS., The World Bank, 1989.

The contrasts among these nations' electronics industries are matched by significant contrasts in industry structure and government policy, particularly in the treatment and economic significance of foreign ownership. Direct foreign investment has been important in the development of the electronics industries of Singapore and Hong Kong, both of which have had relatively liberal government policies toward foreign investment and, in the case of Singapore, policies that actively encouraged foreign investment in this sector. As a result, the development of the electronics industry, especially microelectronics, has occurred in these economies largely through the actions of foreign-owned firms. In Korea and Taiwan, by contrast, domestic firms have been more important, although foreign investment has been an important source of technology and expertise.

The Taiwanese electronics industry originated in the production of simple consumer electronics systems (e.g., black and white television receivers) in the 1950s and 1960s, gradually moving to higher-value-added consumer electronics (color televisions) and computer peripherals in the 1970s and 1980s. Much of the early consumer electronics production was undertaken on an OEM basis for foreign firms or within wholly-owned subsidiaries of foreign firms. Taiwan historically has maintained a more liberal policy towards foreign investment than South Korea, although formal approval of such investments was required for much of the postwar period.[44] During 1952-85, 423 applications for direct foreign investment in the Taiwanese electronics industry were approved by the Ministry of Economic Affairs, for a total inflow of $1.48 billion. U.S. sources accounted for roughly

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[44] Hou and San (1990) note that "...Taiwan has changed her policy toward FDI. In the past, the policy toward FDI could be described as 'encouragement with caution.' It has been stipulated in law that overseas Chinese and foreigners can only invest in certain sectors of the economy in Taiwan such as manufacturing, certain service enterprises, and scientific and technical research and development. However, the law also states that all foreign direct investment must be approved by the government. Therefore, the 'apply for approval' type of administration or 'positive list' scope of investment strategy was adopted by the government. To further encourage investors and firms to invest in Taiwan, the government made a bold move by changing the 'positive list' in the scope of investment into a 'negative list' in 1988." C. Hou and G. San, "National Systems Supporting Technical Advance in Industry--the Case of Taiwan," unpublished MS., 1990, p. 23.

33% and Japanese sources, 22% of this amount (Gee San, 1989, pp. 11-12).[45] According to San (1989), however, the role of foreign-owned firms has declined somewhat in importance in recent years within the so-called "information industry" sector, an extremely dynamic and important segment of the Taiwanese electronics industry: "In 1985, 16 of the top 30 information product firms were DFI firms; but this number fell to only 12 by 1987. In addition, from 1984's 57 percent share of total export value, DFI firms' share went down to 30 percent by 1987." (San, 1989, p. 9). Nevertheless, San (1989) concluded that their higher levels of R&D investment meant that foreign-owned firms remained important contributors to technological development in the Taiwanese computer industry.[46] In semiconductor components, Taiwanese firms have become active in the last five years in designing custom and semi-custom components, and six firms have been established to produce ASICs.

The historical origins of South Korea's electronics industry are broadly similar to those of Taiwan's. The industry's development has followed a rather different path in recent years, retaining a heavy emphasis on consumer electronics and recently expanding production of microelectronic components. As in Taiwan, direct foreign investment was regulated for much of the post-reconstruction period, and one recent review concluded that

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[45] G. San, "The Status and an Evaluation of the Electronics Industry in Taiwan," prepared for an OECD Development Centre conference on "Technological Change and the Electronics Sector--Perspectives and Policy Options for Newly Industrialising Economies," June, 1989.

[46] "...in 1986, the average total R&D expenditure of the 24 domestic firms was only NT$2.203 million while the 21 DFI firms has NT$25.004 million or about 12 times that of the domestic firms. However, considering that the scale of domestic firms is usually smaller than that of DFI firms, a comparison based on average R&D investment per employee would be more appropriate. Using this basis, although the result is still the same, the gap is smaller this time. Overall, it can be said that DFI firms are technologically more aggressive than domestic firms." (San, op cit, p. 18).

"Such investment has played only a minor part in the country's industrialization."[47] During 1962-81, the cumulative inflow of direct foreign investment amounted to roughly $1.25 billion, slightly more than one-twentieth of gross domestic investment in manufacturing. Rather than foreign investment, imports of capital goods and turnkey plants were important channels of technology transfer during Korean industrialization:

> Korea's policies concerning direct foreign investment (DFI) and foreign licensing (FL) were quite restrictive in the early years of industrialization, when technology was not a critical element and the mature technologies needed could be easily acquired through mechanisms other than DFI or FL (e.g., reverse engineering)...
>
> Consequently, the size of DFI and its proportion to total external borrowing were significantly lower in Korea than in other NIEs. For example, Korea's stock of DFI in 1983 was only 7 percent of the size of that in Brazil, 23 percent of that in Singapore, and less than a half the size of that in Taiwan and Hong Kong...Korea promoted technology transfer through the procurement of turnkey plants in the early years. For example, the chemical, cement, steel, and paper industries established in the 1960s and early 1970s, all resorted to the turnkey mode for their initial setup. But Korean firms assimilated imported technologies so rapidly that they managed to undertake subsequent expansions and upgrading with little assistance from foreigners.[48]

Although direct foreign investment accounted for a small share of domestic capital formation, its role nonetheless was significant in some sectors, such as electronics. Numerous analyses of South Korean industrialization emphasize the greater importance of foreign ownership in the newer, high-technology sectors.[49] In response to the changing

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[47] L.E. Westphal, L. Kim, and C.J. Dahlman, "Reflections on the Republic of Korea's Acquisition of Technological Capability," in N. Rosenberg and C. Frischtak, eds., International Technology Transfer, New York: Praeger, 1985, p. 185.

[48] L. Kim, "Korea's National System for Industrial Innovation," unpublished MS., 1990, p. 5. The unusually high shares of capital goods in South Korean imports during the industrialization period are another indicator of the extensive reliance by South Korean firms on "embodied" flows of technology; Kim notes that "Among NICs, the proportion of capital goods imports to total technology transfer was highest in Korea...," p. 6.

[49] See Westphal et al., op cit, who note that "DFI has been a particularly important vehicle for technological development in the establishment of much of the chemicals sector and, more recently, of major elements of the electrical and nonelectrical machinery sectors."

(continued...)

technological requirements of South Korean industry (as well as pressure from foreign governments), the South Korean government has adopted more liberal regulations for direct foreign investment, similarly to Taiwan.[50] Nevertheless, in high-technology "strategic sectors," restrictions on foreign investment are frequently accompanied with import protection, as the discussion by Mody (1989) of television and personal computer production points out:

> ...adequate protection was provided against imports and from foreign firms' manufacturing in Korea. Television imports were virtually banned until the early 1980s since televisions were a key product of the [Korean] conglomerates [chaebols]. More recently, as Korean producers entered the personal computer (PC) market, severe quantitative restrictions were placed on PC imports. Direct foreign investment by foreign firms in these products was also almost completely restricted.[51]

Mody argues that protection against imports and foreign investment in South Korea's "infant industries" was considerably more stringent than in Taiwan. The presence of several large and fiercely competitive Korean producers of import-substitutes, however, reduced the inefficiencies induced by protection in other economies (see below for further discussion). The large Korean chaebols have been able to enter the production of microelectronic components like DRAMs through their ability to negotiate joint venture agreements with foreign multinationals, to purchase technology licenses from foreign firms (here, the

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[49](...continued)
(p. 186), and conclude that "...the shift to new industries may imply greater dependence on direct foreign investment. Indeed, greater dependence on such proprietary transfers of technology is observed starting in the latter half of the 1970s." (p. 215).

[50] "...liberalization [in the 1980s] raised the share of Korea's 999 industrial subsectors open to foreign investment from 44 percent in the 1970s to 66 percent in 1984 and to almost 90 percent in 1988." See Kim, op cit, p. 18.

[51] A. Mody, "Institutions and Dynamic Comparative Advantage: Electronics Industry in South Korea and Taiwan," World Bank Industry and Energy Department Working Paper #9, 1989, p. 11.

declining fortunes of several small U.S. semiconductor firms played a crucial role[52]), and to absorb the enormous costs of entry into this capital-intensive sector.

The firm structure of South Korean and Taiwanese electronics firms differs dramatically. The South Korean electronics industry, like other export sectors, has grown through the investment and production activities of a small number of enormous, highly diversified firms, known as chaebols. The chaebols more closely resemble the prewar Japanese zaibatsu than they do the postwar Japanese industrial groups, inasmuch as these Korean firms are subject to much stronger central management control than are the constituent elements of Japanese industrial groups. The chaebol originated in response to stringent government controls on capital markets during postwar Korean industrialization. Credit rationing and restrictions on foreign currency convertibility favored the development of large firms that could overcome these capital market imperfections and that could successfully lobby the institutions that controlled capital availability.[53] In addition, these large firms were well-placed to negotiate turnkey investment projects and OEM production agreements with foreign multinationals in the shipbuilding, steel, and consumer electronics industries.

As of 1987, each of the four largest chaebol had sales of more than $12 billion, and were among the 50 largest industrial firms in the world. Each of these large but young firms

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[52] Kim (op. cit.) argues that "...most important of all [for South Korean entry into microelectronics components], there were a number of distressed small semiconductor companies in the U.S. that were ready to sell what Korea's chaebols needed most--chip designs and processes--in attempts to fuel cash for survival. Samsung Semiconductor's 64K DRAM...technology was licensed from Boise, Idaho-based Micron Technologies, enabling Samsung to hit the market with 64K DRAM some 18 months after the first Japanese ones became commercially available...In short, chaebols relied mainly on foreign firms for design and process technologies."

[53] Mody, op cit, notes that in South Korea, "Particular sectors and firms had preferential access to working capital and were charged lower interest rates...Until the early 1980s, the cost of borrowing was lower for heavy industry and for large firms." (p. 10)

remains under the control of its founding entrepreneur or his family. Mody (1989) estimated that electronics accounted for at least 20% of the total 1987 sales of Samsung, one of the most successful chaebol in electronics. High levels of producer concentration in the South Korean economy, however, do not appear to have produced widespread anticompetitive behavior. Indeed, the South Korean government appears to exercised some care to ensure that several chaebol were represented in strategic industrial sectors, in order that its efforts to encourage investment in these areas through restricting imports and foreign investment would not result in monopolization of domestic production.

Average firm size in the Taiwanese electronics and other sectors is much smaller than in Korea. Scitovsky notes that in 1981, the $10 billion in sales of Hyundai alone, one of the four largest Korean chaebol, exceeded the combined sales of the ten largest Taiwanese industrial firms. As in Korea, this characteristic of Taiwanese firm structure reflects government policy. During the reconstruction period of the 1950s, the Taiwanese government removed restrictions on domestic capital markets, resulting in high domestic interest rates and high savings rates.[54] In addition, such capital-intensive industries as chemicals, steel, and cement remained under government control. High rates of household savings and a reasonably open capital market appear to have improved relatively small firms' access to external finance, and encouraged the growth of numerous small firms, few if any of which are as diversified as the Korean chaebol. The contrasting structures of Korean and Taiwanese capital markets and industrial firms have been cited as one factor contributing to greater equality in the distribution of wealth in Taiwan, by comparison with South Korea.

The effects of these contrasting firm structures on performance in the electronics industry are difficult to determine. Mody argues that the smaller Taiwanese electronics firms historically have been quicker to respond to new opportunities, but that these smaller,

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[54] See T. Scitovsky, "Economic Development in Taiwan and South Korea, 1965-81," in L.J. Lau, ed., Models of Development, San Francisco: ICS Press, 1985.

less well-financed firms are poorly equipped to sustain competition against large foreign firms.[55] As a result, in such sectors of the electronics industry as telephone handsets or personal computers, the initially high market shares of Taiwanese firms have gradually been eroded by the slower, but well-heeled, South Korean chaebol, which have invested in capital-intensive production technologies that yield higher-quality, lower-cost products.[56] Moreover, Taiwanese firms have been slower than South Korean firms to enter the production of microelectronics "commodity" components like DRAMs. Even the ability of established Taiwanese firms to remain in such increasingly capital-intensive sectors as computer peripherals has been questioned by some analysts.

Nevertheless, the high levels of unrelated diversification associated with the chaebol structure proved to be detrimental to the performance of the American conglomerates of the late 1960s and 1970s.[57] As South Korean capital markets shed their imperfections and become more liquid, the advantages for individual firms of large size and political connections may decline. The chaebols' product lines are not based on any common technology, production capability, or marketing assets, beyond global name recognition in a few consumer product lines. Korean firms also have earned relatively low returns in the highly competitive DRAM components business. Based on the current evidence, it is

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[55] Many of the recent arguments about the competitive weaknesses resulting from the allegedly excessive fragmentation and small firm size in the U.S. semiconductor components industry's competitive struggles with Japanese firms are echoed in this debate over the relative merits of the South Korean and Taiwanese approaches to the electronics industry.

[56] "The niches that Taiwanese producers seek are new emerging markets. Thus, at the early stages Taiwanese firms have a competitive advantage; however, as the market grows to include larger firms, smaller Taiwanese firms are not able to remain competitive. They need to move on to a new product...Once the Koreans commit themselves to a product, they have greater resources and a greater incentive to add value or upgrade quality. Taiwanese firms have a lower incentive because they have the relatively easy option of moving on to a newer product." (Mody, op cit, p. 26).

[57] On the performance of these firms, see M. Jensen, "The Eclipse of the Public Corporation," Harvard Business Review, 1989, or the concluding chapter of A.D. Chandler, Jr., Scale and Scope, Cambridge: Harvard University Press, 1990.

difficult to single out either the Taiwanese or Korean firm structure as unambiguously superior for economic development. More likely, either approach can prove effective, if government policy supports a competitive, export-oriented domestic economic environment capable of sustaining high levels of physical and human capital investment.

All four of the successful East Asian NIEs have benefitted from government policies that combined intervention with a consistent effort (since the 1950s) to reinforce, or at least not frustrate, the operation of market forces.[58] Thus, in Taiwan, Korea, and Singapore, and more recently in Hong Kong, government policy has supported high levels of investment in a well-trained work force and in scientific and engineering manpower. Table 9 shows that South Korea, Singapore, Hong Kong and Taiwan are far ahead of other developing economies in the shares of the relevant populations enrolled in post-secondary educational programs in scientific and engineering fields, and exceed Japan in many of these shares.[59] Among these four NIEs, the less directive role of government in Hong Kong may be inferred from the somewhat lower shares of the urban population enrolled in such courses of study. Even Hong Kong, however, is ahead of such developing economies as Brazil or Mexico in these indicators of human capital formation.

Other government programs for technical support training of employed workers have been expanded in recent years in Taiwan, in order to offset the effects of capital constraints

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[58] As T.N. Srinavasan has argued in his comparison of South Korean and Indian economic development, "The lesson is not that the Korean government success is because the Korean government did not intervene in markets while those of China and India did. It is that the interventions in the Korean case did not distort incentives as much as those in India did." T.N. Srinavasan, "External Sector in Development: China and India, 1950-89," American Economic Review, May 1990, p. 116.

[59] C.J. Dahlman and C. Frischtak, "National Systems Supporting Technical Advance in Industry: The Brazilian Experience," unpublished MS., 1990, Table 5-5, p. 32. P.W. Kuznets, "An East Asian Model of Development: Japan, Taiwan, and South Korea," Economic Development and Cultural Change, 1988, S11-S43, presents similar data and arguments.

within the relatively small firms that dominate the electronics industry.[60] In this area and others, the potential contribution of human capital formation to the domestic adoption of advanced technologies, as well as its support for the domestic development of such advances, cannot be overemphasized. All four of these NIEs also have benefitted from their status as recipients of inflows of human capital, which in the cases of Taiwan, Singapore, and Hong Kong, involved the emigration of Chinese entrepreneurs from the mainland after 1949. In South Korea, the return of scientists and engineers trained and employed abroad also has contributed to indigenous technological development.

The governments of both South Korea and Taiwan have expanded their investments in R&D to support research and advanced training of scientists and engineers for their domestic electronics industries. In both economies, these research institutes have aided the indigenous development of advanced electronics components or peripheral technologies that has contributed to domestic firms' competitive strength. In Taiwan, where government expenditures account for 60% of total national R&D spending, two research institutes, the Industrial Technology Research Institute (ITRI) and the Institute for the Information Industry (III), have contributed to the development of the domestic electronics industry. The Electronics Research Services Organization (ERSO), affiliated with the ITRI, has been an important source of new technology and trained manpower for the domestic electronic components industry. ERSO has been the source of at least six "spinoff" companies engaged

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[60] "...more than 90 percent of firms in Taiwan are small and medium-sized in scale. Therefore, when conducting in-service training, these firms usually encountered problems such as a lack of instructors, insufficient teaching materials, and inadequate facilities. To solve this problem, the government set up two programs to assist these firms. First, it established public training institutes for the electronics industry's entry and middle level manpower. The training courses provided included maintenance of consumer electronics products for maintenance workers, industrial electronics engineering for technicians, and programming skills for CA/CNC programmers, etc....

"The second program was implemented by the government to meet its ambitious computerization project. it entails the vigorous education of higher level manpower in the field of computers." G. San, "The Status and an Evaluation of the Electronics Industry in Taiwan," OECD Development Centre, May 1989, p. 29.

in the fabrication of ICs, one of which is partly owned by Philips of the Netherlands (the Taiwan Semiconductor Manufacturing Corporation), the other five being domestically financed. These firms recently have joined forces with the ITRI to initiate a five-year program for the development of 16M DRAM fabrication technology. ERSO also provides a wide range of technical services to Taiwanese firms, and has supported the indigenous development of an important advance in computer peripheral technology that proved to be unobtainable from foreign sources.[61]

In South Korea, the Korean Institute of Electronics and Technology (KIET) and the Korea Electronics and Telecommunications Research Institute (KETRI), which absorbed many of the functions of KIET, were established after the creation of the Korean Advanced Institute of Science and Technology (KAIST), which also provides advanced training. These institutes, the first of which was founded in 1966, initially were staffed by scientists and engineers trained in foreign universities, with little familiarity with the technological problems of Korean industry and often far more interested in basic research than in the support of indigenous technological development and adoption of advanced foreign technologies. Over time, however, the focus of these institutes has shifted somewhat, from frontier scientific research to activities that could support the diffusion and adoption of technologies by Korean firms. In addition, the vastly improved in-house technological capabilities of Korean firms have made it far easier for the publicly financed research institutes to establish fruitful links with these firms. Indeed, Dahlman (1989) notes that a portion of KIET's semiconductor research facilities were sold to one of the chaebol in 1985, as these large firms expanded their independent R&D activities in semiconductors. The research efforts of the public research institutes have been devoted in several instances to

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[61] "ERSO is recognised as a good intermediary for technology transfers, since firms occasionally find it difficult to obtain licences. Tatung, for example, wanted to produce 30-megabyte hard disks, but failed to find a US or Japanese firm willing to licence it the necessary technology. As a result, it was forced to develop its own technology and was able to call upon ERSO for help." J.R. Chaponniere and M. Fouquin, "Technological Change and the Electronics Sector: Perspectives and Policy Options for Taiwan," OECD Development Centre, May 1989, p. 35.

reverse engineering of products manufactured abroad.[62] As in Taiwan, government research institutes also contributed to the recent development of advanced technologies that could not be licensed from foreign sources.[63]

Trade policy also merits attention in considering the factors contributing to growth in the electronics industry in these four economies. Any evaluation of trade policy in this context requires that one abandon simplistic categorizations such as "protectionist" or "liberal." Trade policy in the two largest economies, Taiwan and South Korea, has blended protection and openness in its treatment of imports and foreign investment. In both nations, this policy posture reflected economic and national security considerations at its inception. Singapore and Hong Kong, by contrast, have been relatively open to imports and foreign investment throughout the past 30 years. Nevertheless, there can be little doubt, however, that by comparison with trade policy in other developing economies (e.g., Brazil, India, Mexico), all four of these NIEs have since the early 1960s emphasized an outward orientation in policy toward flows of trade and other economic factors (i.e., investment and technology).

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[62] "In several sectors, a government research laboratory, on behalf of or in conjunction with one or several local companies, attempted to 'localise' foreign products based on technology new to Korea. This involved reverse engineering, the employment of Koreans trained overseas in foreign companies, and other methods." M. D.H. Bloom, "Technological Change and the Electronics Sector: Perspectives and Policy Options for the Republic of Korea," OECD Development Centre, May 1989, p. 21.

[63] "...work on the next generation of chips--the 4M DRAM--meant exploring the frontiers of semiconductor technology but also competing neck-and-neck with Japanese and U.S. companies. As the stakes have risen in the chip game, the field of players has grown smaller worldwide, meaning that few, if any, of those left in the game can be counted on to sell state-of-the-art chip design technology to Korean chaebols. So, Koreans had to tackle the 4M DRAM design alone. To avoid duplicate research and investment, the government stepped in and designated the R&D of the 4M DRAM as a national project. A public R&D institute played the coordinating role with three chaebols' participation." L. Kim, "Korea's National System for Industrial Innovation," unpub. MS, 1990, pp. 35-36.

Singapore, South Korea and Taiwan pursued conventional import-substitution policies through the 1950s, utilizing multiple exchange rates, tariffs, and quantitative restrictions on imports to support the growth of domestic industries such as textiles, steel, and chemicals. Indeed, as was noted above, in Taiwan the heavy, capital-intensive industrial firms spawned by these policies were often publicly owned. In all three economies, however, the early 1960s saw a dramatic shift in trade policy, albeit not one that could be described as substituting "free trade" for "protection." Rather than import substitution policies that supported production for the domestic market alone, all of these economies began financial liberalization (unification of exchange rates), some replacement of quantitative restrictions by tariffs, and the replacement of formal and informal impediments to export with incentives and subsidies for export production. In Singapore, foreign investment proved to be the engine of export-led domestic growth. In South Korea and Taiwan, protection against imports was gradually liberalized in a broad array of industries, and in both economies, restrictions on foreign investment more recently have been eased.

Nevertheless, restrictions on imports in such products as VCRs and personal computers remained significant in South Korea and Taiwan in the 1980s. Import restrictions in Taiwan relied more heavily on tariffs, in contrast to South Korea, and Taiwanese policy toward foreign ownership in "strategic" sectors appears to have become somewhat more liberal than is true of South Korea. Competitiveness in international markets was the benchmark against which the performance of domestic producers was evaluated by policymakers, in contrast to their counterparts in other developing nations. This orientation supported the intensely competitive domestic environment that offset some of the potentially anticompetitive effects of high levels of producer concentration in South Korea. The strategic trade policies of both South Korea and Taiwan now are being liberalized, in part because of pressure from major trading partners such as the EC and the United States. In both of these NIEs, as we have noted above, restrictions on foreign investment now may be less effective policies for developing high-technology industries, because of the difficulty of gaining access to the technology without some foreign participation.

Summarizing the public policy experience of these four NIEs, there appear to be much stronger elements of similarity among government policies than is true of firm structure or ownership within their indigenous electronics industries. In all of these economies, government policy has emphasized the engagement of domestic firms with the international economy, as producers of goods, users of technologies sourced abroad, or as recipients of foreign capital. Among other benefits, this outward-oriented policy has increased or sustained high levels of competitive pressure on domestic firms, preventing the "X-inefficiencies" and other deadweight losses associated with noncompetitive market structure and firm behavior. In the case of Taiwan, foreign-owned firms have accentuated this competitive pressure, with salutary effects. Government policy also has supported high levels of investment in physical and human capital. Finally, government policy has been highly flexible and responsive to change in both domestic and international economic and political factors.

What channels of technology transfer have proven to be effective in the development of the electronics industries of these four NIEs? Just as the discussion of firm and industry structure suggests that there is no single "optimal" path of institutional development, the experience of these economies suggests that there are a number of means for technology acquisition from foreign sources. South Korea has been successful in utilizing OEM agreements, turnkey plants, and imports of capital equipment to gain access to foreign technology.[64] These mechanisms have been somewhat less effective, however, in electronics, where joint ventures and licensing agreements with foreign firms are more common. Moreover, the outlook is for more of these "alliances" in electronics between chaebols and foreign multinationals. The feasibility of these alliances may be enhanced by

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[64] "Several things stand out in the Republic of Korea's pattern of technological development. One is the limited extent of reliance on proprietary transfers of technology by means of direct foreign investment and licensing agreements. Among formal transfers of technology, turnkey plants and machinery imports have played by far the greater role. Moreover, in only a few sectors, such as electronics, have exports depended crucially on transactions between related affiliates of multinational corporations or on other forms of international subcontracting." Westphal et al., 1985, op. cit., pp. 213-214.

the chaebols' enormous size and increasing experience in negotiating international technology-sharing agreements. An additional advantage for the South Korean chaebol seeking access to foreign technologies in high-volume semiconductor components is the willingness of small and medium-sized U.S. firms to sell their product and process technology. As and if the U.S. electronics industry spawns fewer of these startup firms,[65] however, this source of foreign technology could decline in importance. By comparison with steel or shipbuilding industries, however, obtaining additional foreign technology in the semiconductor components industry (especially in DRAMs) may entail a greater acceptance by South Korean firms of substantial control by foreign firms over their technological assets in joint ventures. An alternative approach, the development within these South Korean firms of a significantly stronger technology base, also is being undertaken, as in the 4M DRAM.

One of the most trenchant criticisms of the "Taiwanese model" for economic development raises the possibility that the relatively small Taiwanese electronics firms may face serious difficulties in negotiating access to foreign technologies through strategic alliances. Taiwanese firms have succeeded, however, in gaining access to advanced IC fabrication technologies in ASICs and smaller-volume components, access that has complemented efforts to strengthen the indigenous technology base. Moreover, the example of TSMC suggests that smaller size need not preclude access to advanced IC technologies through a strategic alliance.

In all four of these economies, direct foreign investment has been an important channel for technology transfer. In Hong Kong and Singapore, government policy has been oriented toward attracting such investment with few if any restrictions and modest performance requirements. In both Taiwan and South Korea, initially tight restrictions on foreign investment have gradually been relaxed, although they remain significant in selected

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[65] For a discussion of this possibility, see D.C. Mowery and N. Rosenberg, "The U.S. National System of Innovation," unpub. MS, 1990.

segments of the South Korean electronics industry. Nonetheless, comparing the experiences of these four economies and their respective government policies towards foreign investment suggests that the strategic employment of restrictions on investment access and performance requirements, when coupled with policies supporting exports and investment in human and physical capital, may produce greater technological and economic spillovers from foreign to domestic entrepreneurs and firms. The specific means through which technology is transferred may be less important for economic and industrial development than the indigenous human capital assets and orientation towards export or import-substitution that are created by public policies within the recipient economy.

This proposition is illustrated by the effects of the East Asian assembly operations of U.S. semiconductor producers, which contributed to the growth of an indigenous components or systems industry only where key complementary conditions were present.[66] Among the most important of these was the availability of skilled and technical labor in the host nation. Malaysia has hosted the largest assembly operations of any East Asian nation[67] but has little capacity in the production of other electronic systems and no IC fabrication facilities. The Philippines and Thailand also have not yet developed IC fabrication or significant electronic system production capacities while hosting assembly operations.

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[66] This conclusion is consistent with the findings of Dunning (1988) and Cantwell (1989), who analyzed the effects of direct foreign investment on British competitiveness. These authors found that foreign investment in Britain stimulated and improved the technological capabilities of British firms in the pharmaceuticals industry, even as foreign investment contributed to the decline in the technological and competitive underpinnings of the British auto industry. See J. Cantwell, Technological Innovation and Multinational Corporations, Blackwell, 1989, Chap. 4; and J.H. Dunning, Multinationals, Technology and Competitiveness, Unwin Hyman, 1988, Chap. 5.

[67] The following discussion draws upon William J. McClean (ed), Status 1988: A Report on the Integrated Circuit Industry (Scottsdale, Arizona: Integrated Circuit Engineering, Inc., 1988).

Finally, what can be learned from the experiences of these four economies concerning the technological linkages that are likely to be most supportive of economic dynamism and potentially, entry into semiconductor components production? There once again is almost as much contrast as similarity among the four NIEs in this dimension as in others, but several points stand out. In all of these economies, domestic production of electronics systems appears to have preceded entry into components production. Based on a comparison with the experiences of Malaysia, Thailand, and the Philippines, the history of electronics production in these four NIEs suggests that a history of systems production may be more important than semiconductor assembly operations alone for entry into components production. Indeed, assembly operations alone may fail to lead to expanded local activity in systems manufacture. Moreover, efforts to develop components production as a strategy to enter the manufacture of electronic systems are surely likely to fail. Components production, after all, historically has represented a rather small share of total sales or production in the electronics industry.[68]

The NIEs' history suggests that location is more important than the nationality of ownership of the systems production or assembly activities. In addition, the size and existence of any spillover effects depend critically on the supporting conditions created by public economic and human resources policies. Restrictions on foreign investment have played a modest role, but they appear to have been effective for development only when combined with these supporting policies.

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[68] "...although semiconductors represent the technological heart of IT, it is tempting--but highly misleading--to think of semiconductors as the cornerstone of industrialisation strategies for electronics. In financial terms, the semiconductor (SC) industry represents only a small proportion (less than 10%) of the IT industry worldwide. The SC industry is fiercely competitive and the financial and technological barriers to entry are formidable...As a result, most economies enter IT production through the application of SC to electronic and electromechanical products, rather than the manufacture of SCs." M. Hobday, "Semiconductor Technology and the Newly Industrialising Countries: The Diffusion of ASICs (Application Specific Integrated Circuits)," unpub. MS, 1989, p. 1.

The recent history of these NIEs' efforts to enter into components production also may shed some light on the strategic importance of vertical linkages among components design, components fabrication, and systems design and production within a single economy. South Korean firms have entered the production of components in part because of concern that the sources of value-added in consumer electronics systems increasingly were being captured by component producers, and in part because of concern over dependence on Japanese sources for the "commodity" components extensively employed in systems. Do these largely economic considerations have technological counterparts? Is "co-location" within the same economy of commodity component and systems design and development necessary for international competitiveness? Since the design and performance specifications of most commodity components are fairly standardized, it seems unlikely that component and systems designers must work together in the development of either components or systems. Moreover, there appear to be few if any learning and other spillovers between the production of commodity components and manufacture of high-volume consumer electronics systems. Nevertheless, the actions of the South Korean chaebol, which are being emulated by European producers of consumer electronics systems,[69] are based on the perception that such co-location is strategically valuable for competing at the technological frontier. Co-location almost certainly is unnecessary, however, for prospective entrants into systems manufacture (on an OEM basis, as a host for foreign-owned firms, etc.)--as we have seen, system production does not appear to require strength in domestic components manufacture.

Actions to strengthen a somewhat different vertical linkage have been pursued by Taiwanese firms in the ASIC market, where the rapid growth of independent and foreign-owned design firms now appears to have sparked the development of IC fabrication firms.

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[69] See M. Hobday, "The European Semiconductor Industry: Resurgence and Rationalization," Journal of Common Market Studies, 28, 1989, 155-186. It is too early to assess the ultimate effectiveness of the costly trans-European cooperative ventures that are intended to strengthen European firms' presence in high-volume components, although recent events suggest that this strategy may prove to be very difficult.

Especially in computer systems and related products, as Hobday (1989) has pointed out,[70] more and more of a given system's functionality and performance is located on the application-specific component. Co-location of ASIC development and systems development therefore may be quite important, and the rapid growth of ASIC design firms within Taiwan suggests that this technological interdependence affected firm strategies. The arguments for co-location of ASIC design and fabrication, however, are far less compelling. The very existence of independent ASIC design firms, of course, suggests that design and fabrication of these IC devices can occur independently of one another. This strategy, like the South Korean chaebols' vertical integration into DRAMs, is difficult to justify on technological grounds. Moreover, the economic arguments for Taiwanese entry into 16M DRAM production also seem questionable.

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[70] "Because so much of the finished IT system can now be embodied in ASICs, users may find that specifying a systems design becomes synonymous with specifying as ASIC design. In order to remain competitive in systems the user may have to engage in IC design." Hobday, "Semiconductor Technology and the Newly Industrialising Countries...", op cit, p. 18.

Part IV. Changes During the 1980s in Technology and Policy

IV.1. The U.S. IC Industry, 1981 to the Present

In 1981, the U.S. was the world's major exporter of semiconductor components. U.S. exports in 1981 included the export of finished semiconductors from the U.S. to Europe ($1.6 billion, 16% of U.S. production) and exports of partially manufactured ICs to East Asia for assembly.[71] By comparison, Japanese exports to the U.S. were $400 million, or 8% of Japanese production for 1981.[72] U.S.-owned plants also accounted for a significant fraction of European production. In other words, U.S. firms dominated international trade and international production of ICs in 1981.

By 1988, the situation had changed dramatically in two respects. First, U.S. producers no longer dominated international markets. Production of U.S.-headquartered companies amounted to $23.8 billion, or 42% of total world consumption, in 1988. U.S. domestic consumption of ICs in 1988 was estimated at $19.1 billion, with net imports of some $800 million from Japan. Second, Japan's semiconductor industry and consumption had grown more than fivefold. Japan had dramatically increased its export role in the world semiconductor industry. Figure 5 shows the evolution of national market shares in merchant semiconductor production from 1982-1988.[73] Erosion in the U.S. presence in microelectronic components production, however, was less dramatic than the decline in the U.S. presence in electronic systems. Table 10 shows the growth of electronic systems production by geographic area for 1984-1988. Japan accounted for less than one-third of U.S. production in 1984, but by 1988 had reached 56% of the U.S. level. Japan was not alone in making major advances in electronic system production during the 1980s.

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[71] Mel H. Eklund and William I. Strauss, Status 1982: A Report on the Integrated Circuit Industry (Scottsdale, Arizona: Integrated Circuit Engineering, Inc., 1982), p. 8.

[72] ibid.

[73] Excluding U.S. captive production has a major impact on the measurement of U.S. market share in international markets.

European electronic systems production grew during the 1980s as rapidly as Japanese output. As we noted above, the rapid growth of Japanese IC production is linked to rapid growth in Japanese production of consumer electronic systems.

A number of experts have cited these changes in the economic position of the U.S. IC industry as indicative of a loss of technological leadership to Japanese firms. This section discusses the role of financial and structural factors in the U.S. microelectronics industry's changing international position. Growth in the capital requirements of the IC industry can be briefly summarized in the following statistic: total investment in the U.S. industry was roughly $4.5 billion during the 1970s;[74] during the 1980s investment in capital equipment alone exceeded $18 billion.[75] Much of the increase in capital requirements reflects the growing cost of process innovation and manufacturing facilities. but the costs of new product development also have increased spectacularly. Although data for most products are unavailable, the development costs for Intel's leading microprocessor designs grew from $300,000 for the 8080, introduced in 1974 to some $100 million for the 80386, introduced in 1986.[76]

Investment in R&D alone in the IC industry averages 10-15% of firm sales, well above the R&D/sales ratios of any other high-technology industry.[77] The technological

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[74] Office of Technology Assessment, International Competitiveness in Electronics, Washington, D.C.: Congress of the United States, p. 273.

[75] Computed by authors from Integrated Circuit Engineering statistics on investments through 1988, which were approximately $16.5 billion. William J. McClean (ed.), Status 1989..., op cit, p. 2:39 and corresponding statistics in earlier years of ICs annual Status reports.

[76] Congressional Budget Office, The Benefits and Risks of Federal Funding for Sematech, Washington, D.C.: U.S. Congress, September, 1987, p. 81. Intel has announced the technological successor to the 80386, the 80486.

[77] See Nathan Rosenberg and W. Edward Steinmueller, "Why Are Americans Such Poor Imitators?" American Economic Review, May, 1988.

races to develop DRAM and other devices' process technologies are likely to require IC industry investment levels of 20% of sales during the coming decade. Moreover, as Flamm (1990) has noted, these enormous investments have little or no scrap value because of the specialized nature of the fabrication facilities, and have very short economic lives, because of the rapid rate of technological change in the industry.[78] These enormous and short-lived capital investments are most common in the high volume components such as DRAMs, and have resulted in higher levels of producer concentration in this segment of the IC industry.

Table 11 provides statistics on capital investment on plant and equipment in the worldwide semiconductor industry, which includes both discrete devices and integrated circuits. The years were chosen to minimize the effects of periodic recessions in semiconductor sales and capital investments. Increases in capital investment are recorded for each of the reported years. From 1979 to 1984, capital expenditures as a share of sales increased by almost 50%.[79] Some of the high-volume fabrication facilities installed in the early 1980s, such as those used to produce DRAMs, have slowed the rate of increase in capital expenditure per dollar of sales. This slowdown may be only temporary, however, resulting from the severe industry recession of the mid-1980s, which depressed capital expenditures in the U.S. and Japan.

Increased capital costs have made it more difficult for U.S. firms to sustain a strong position in process technologies and attract capital from external sources. Industry-wide returns on U.S. IC company investment have been modest. Since 1964, the ratio of net

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[78] See K. Flamm, "Semiconductors" in G.C. Hufbauer, ed., Europe 1992: An American Perspective, Washington, D.C.: Brookings Institution, pp. 229-230.

[79] The reversal of this trend in 1988 resulted from higher average sales prices (ASPs) for ICs and increasing productivity of some of the larger fabrication facilities. From 1982 to 1986, the ASP (factory shipments value divided by units shipped) was relatively constant at one dollar. In 1988, the ASP shot up to $1.25, partly as the result of DRAM price stabilization following the U.S-Japan Semiconductor Agreement. If ASPs had remained at one dollar, the ratio of capital expenditures to factory shipments in 1988 would have been 20%.

earnings to sales for many semiconductor firms has been below the average for manufacturing.[80] Moreover, given the high risks associated with this industry, merely average returns on sales are likely to be too low to attract investors. The extent of this risk is illustrated dramatically by the experience of Intel, a major merchant producer. Intel recorded a 50% return on stockholder equity in 1974, and a return averaging over 20% from 1971-1981, but almost went bankrupt in the 1985 recession when its losses were over 80% of stockholder equity.[81]

Increased firm size and industry maturity paradoxically may have hampered the ability of established U.S. merchant producers of ICs to obtain the capital needed to remain competitive. During the 1960s and 1970s merchant companies promised rapid sales growth and capital requirements per dollar of sales that were lower than those faced by the same firms today. In recent years, however, the returns on sales for many firms have declined and sales growth has become more volatile, even as capital requirements have soared. In addition, investors expected that a portfolio of young IC companies would contain one or more "winning" companies, companies that were able to develop broader product lines and rapid revenue growth. Leading companies are now large; each of the top four companies (TI, Motorola, Intel, and National) recorded sales of over $1 billion in 1987.[82] They no longer offer the prospect of comparably dramatic growth in revenues, which reduces the attractiveness of their equities to investors. Even as the availability of venture capital for first- and second-round financing of startup firms expanded during the early 1980s (Perry

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[80] U.S. Department of Commerce, A Report on the U.S. Semiconductor Industry Washington, D.C., September, 1979, p. 57. During 1964-77, the average earnings-to-sales ratio in the semiconductor industry was below the average for all U.S. manufacturing industry. Since 1981, the financial performance of some U.S. firms has improved (with the exception the severe 1985 recession), but many continue to earn returns well below the manufacturing average.

[81] William J. McClean, Status 1987: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering, Inc., 1987, p. 2:18.

[82] William J. McClean, Status 1988: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering, Inc., p. 2-1.

estimated that venture capital provided as much as $2 billion annually during this period), established semiconductor firms faced greater difficulties in raising capital.

Industry volatility has also increased. The entry of more and more producers of high-volume products (e.g., DRAMs)[83] has contributed to wider unanticipated swings in revenues and profits, even as rapid expansion of capacity now is more important to capture sales in cyclical upswings. Growing global capacity in high-volume component production has led many U.S. firms, including Intel, to exit from the commercial production of DRAMs resulting in higher concentrations in this segment. Although existing and recent entrants to U.S. merchant production continue to offer innovative IC designs, their ability to simultaneously keep pace with the capital requirements of process improvements and of new product development is uncertain, making it more difficult to obtain capital from external sources.

Several financial experiments have been attempted or are being considered to reduce the problems of sales volatility and financing constraints. IBM purchased and eventually sold a significant equity position in Intel, providing an infusion of cash for Intel's investment in technology development. Intel's continuing success in microprocessor development and in the development of microcomputer-related products may be a consequence of this infusion of capital. TI and other IC manufacturers have discussed long-term IC purchase contracts in the industry aimed at smoothing the cyclicity of demand, and TI has obtained funds for production capacity investment from major customers.[84] "Strategic partnerships"

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[83] The recent expansion of South Korean firms' production of DRAMs has placed considerable pressure on prices for these components; see J.M. Schlesinger, "Japan's Chip Makers Take Glut in Stride Despite U.S., Korean Price Competition," Wall Street Journal, 1/12/90, p. B4.

[84] Louise Kehoe, "Where the Fog Hangs Thick in San Francisco: Louise Kehoe Examines Reaction to a Radical Plan for a Market in Semiconductor Futures," Financial Times, June 1, 1989, p. 21. A recent article on U.S. Memories by Pollack notes that "Texas Instruments, one of the American suppliers [of DRAMs], has acknowledged that it has (continued...)

have also been announced between system and IC producers. Although these partnerships have focussed on financing new product development, rather than capacity expansion, and appear relatively modest to date, they offer the potential for increasing the investment resources of U.S. IC firms in the future.[85]

In addition to making it more difficult for many U.S. firms to finance innovation in product and process technology, higher development and capital costs have increased the importance of economies of scale in IC production. These economies of scale have two sources. Improvement in the yield of devices can dramatically reduce the unit cost of production.[86] Yields depend on process improvements, both in producing specific devices and in incrementally improving a production process for a number of different products. Considerable experience is necessary to realize yield improvements, and the most common measure of this experience is the cumulative volume of production of a particular product. Cost reductions stemming from this experience are referred to as "learning."[87] The second source of economies of scale in the IC industry is the increased fixed costs of product design, equipment costs, and market development. These costs do not depend upon the size of current or cumulative output. The unit cost reductions from learning and from distributing

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[84](...continued)
received investments from some customers in exchange for guaranteed chip supplies." A. Pollack, "Computer Makers Decide to Abandon Joint U.S. Venture," New York Times, January 13, 1990, p. 18.

[85] TI has established forward sale arrangements allowing finance of production capacity. Many merchants have accepted large product design contracts such as RISC (Reduced Instruction Set Computer) IC design contracts. In both cases, external finance for activities that the company would otherwise have pursued increase resources available for investment in production capacity and R&D.

[86] W. Edward Steinmueller, Microeconomics and Microelectronics: Economic Studies of the Integrated Circuit Industry (Ph.D. Dissertation, Department of Economics, Stanford University, 1987).

[87] The use of the term learning here mixes the application of additional resources for process improvement in high volume production with the more traditional meaning of learning, accumulation of knowledge through experience.

fixed costs over a larger output mean that the IC industry is a declining average cost industry over wide ranges of output.

Is the structure of the U.S. semiconductor industry, dominated (in commercial sales of components) by independent, specialized producers, outmoded? A number of experts[88] have argued that larger, vertically integrated firms that produce a significant share of their internal IC requirements as well as systems now are better positioned for global competition. Large size may enable these firms to bear the increased risk of product and process innovations more easily. By employing "tapered" vertical integration to force outside vendors to absorb all of the fluctuations in IC demand, then firms may also be able to exploit learning-related and scale economies more effectively. The vertically nonintegrated U.S. merchant producers thus may find it difficult to compete with larger, vertically integrated foreign firms. Although this argument has received much attention, it has surprisingly little empirical support. After all, a significant restructuring of the U.S. systems and merchant IC producer sectors resulting in greater vertical integration would be highly beneficial if this argument is correct. Despite the absence of any significant public policy obstacles to such a restructuring, however, it has not yet occurred, although some of the financial innovations discussed above are intended to provide some of the advantages of vertical integration. Indeed, the recent collapse of U.S. Memories, a DRAM production consortium financed by U.S. system producers, suggests that this form of quasi-vertical integration remains unattractive to U.S. firms.

Recent developments in the technologies of IC products and processes under any circumstances would have increased competitive pressure on U.S. firms. They have been combined with the rise of Japanese competition in ICs, however, which has intensified competitive pressure and has affected U.S. public policy debates and responses. International competition in the IC industry has been marked by investment races in the

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[88] M. Borrus, Competing for Control (Ballinger, 1988); C. Ferguson, "Computers and the Coming of the U.S. Keiretsu," Harvard Business Review, 1990.

production of standard products, a sector in which cost reductions achieved through economies of scale and learning are important. U.S. companies' initial technological lead has been eroded by Japanese companies that utilize greater financial resources, vertically integrated firm structures, and superior access to their domestic market to meet increasing investment requirements and reduce costs. U.S. firms have been able to hold part of their former dominance through continued innovation in design-based products. If the process know-how accumulated through the production of standard products becomes relevant to advanced design-based products, however, the strong position of U.S. firms in these markets could weaken. The development of new technologies for application-specific ICs may provide opportunities for alternative strategies for success in IC production. The outcome of competition among standard, design-based, and application-specific IC sectors is uncertain, however, as we note below. Current U.S. government policies nevertheless appear to have as their goal the restoration of U.S. dominance in commodity device production.

IV.2. U.S. Public Policy Responses

Since 1981, U.S. government policies towards the microelectronics industry have come under increasingly critical scrutiny as a result of political pressure from the industry and growing concern within some quarters of the U.S. government (notably the military establishment) over the apparent erosion of the U.S. industry's competitiveness. Despite the professed allegiance of the Reagan and Bush Administrations to free-market principles, a range of initiatives with potentially far-reaching implications for the structure and technological development of the U.S. microelectronics industry recently have been discussed or undertaken. These initiatives include changes in R&D funding priorities, antitrust policy, protection of intellectual property, and trade policy.

An important source of change in the competitive strength of the U.S. industry that has also affected U.S. policies is the shift in the relationship between military and commercial technologies. Military technologies (and therefore military R&D and procurement) may now be less fertile sources of commercial technologies than was true during the 1950s and 1960s. This issue is not easily resolved with the limited evidence available to us, but the perception among policymakers of the relationship between military and commercial technologies has changed[89] and important new policy initiatives have resulted.

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[89] A recent front-page story in the New York Times discussed the growing concern that "...the trends that hamper major commercial enterprises--lagging productivity, competition from imports, foreign ownership of American companies and inadequate long-term research--are damaging producers of weapons. In response, the Pentagon is beginning to argue for broad industrial policies that would benefit high-technology industries as a whole, hoping that the rewards would reach sectors of the economy that directly serve the military." (p. D22) The story describes a report by the Defense Science Board that recommended the "...formation of an 'Industrial Policy Council' that would be headed by the President's National Security Advisor and would recommend policies to bolster industries that support the military. At the same time, the report said, the Defense Secretary should be made a permanent member of the Economic Policy Council, the Cabinet's group for making economic policy." (p. D22). See J.H. Cushman, "Bigger Role Urged for Defense Dept. in Economic Policy," New York Times, October 19, 1988, pp. A1 and D22.

Broad similarity in civilian and military requirements was associated with significant spillovers in microelectronics in the early 1960s, when ICs were relatively simple collections of a few dozen transistors. Demands of both the commercial and military markets in the early years of the IC industry focussed on miniaturization, reliability, and ruggedness. In recent years, however, these requirements have diverged. Military semiconductors must operate at increasingly rapid speeds with very high reliability in harsh environments. Consumers do not expect their products to operate in temperatures exceeding 200 degrees Fahrenheit while being bathed in ionizing radiation. Military systems, however, must operate successfully in such environments. In part because of more stringent military specifications for components and in part because of a more exacting certification process, the costs of production of military components exceed those of civilian components.

Military needs also encompass cost effectiveness in R&D and procurement. As a result of the declining share of the market accounted for by the military and the increasing length of time needed to insert new devices into weapons systems, the U.S. is increasingly dependent on progress in commercial IC technologies. The Pentagon VHSIC (Very High Speed Integrated Circuit) R&D program was begun in 1979 to enable the armed services to exert more influence over the trajectory of technological development in the microelectronics industry. The VHSIC program was also intended to reduce the lengthening time period that elapsed between the development of a new component and the component's insertion into a weapons system.[90]

The VHSIC program focused on IC technologies that were within the mainstream of industry technological development, and therefore associated with commercial ICs. Although some research was devoted to technologies that are more often associated with

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[90] Larry Sumney, former director of the VHSIC program, noted that "A major concern of the military has been the unconscionable delay between the creation of a new technology and its application in operational systems. This 'technology insertion' gap has extended to 10 years or even longer." See Larry Sumney, "VHSIC: A Status Report," IEEE Spectrum, December, 1982, p. 35.

military systems, such as gallium arsenide (GaAs), most VHSIC research was in technologies with commercial roots. Sumney defended the dismissal of GaAs, a major target of previous DOD research, in the following comment:

> VHSIC is totally silicon-based, and VHSIC is aimed at returning DOD electronics to that mainstream. Gallium arsenide (GaAs) gates are faster than silicon ones, and GaAs microwave monolithic circuits could be used now in all military communication, early warning, and radar systems. But GaAs digital integrated-circuit technology is far less mature than silicon digital technology. Although the gap is closing rapidly, the VHSIC program includes no plans to develop GaAs chips at this time.[91]

The VHSIC program was partially justified on the grounds that it would generate large commercial spillovers and thereby strengthen the American position in an increasingly competitive industry. Thus far, however, the VHSIC program has yielded few commercial technologies, providing additional evidence that the military and civilian sectors of this industry confront increasingly divergent requirements. One reason for the limited spillovers is the current tendency of the VHSIC program, like other defense R&D programs in established technologies, to stress applied and development objectives, rather than basic research.[92] Combined with divergent requirements, this focus on development means that

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[91] Sumney, op. cit., p. 35.

[92] Fong's recent discussion of the VHSIC program's impacts (G. Fong, "Federal Support for Industrial Technology: Lessons from the VHSIC and VLSI Programs," prepared for the Office of Technology Assessment, U.S. Congress, 1988) concludes that "One of VHSIC's objectives--that of immediate system applications...has come to dominate all others. The program has become 'system driven' with emphases on technology insertion and on the analysis, demonstration, and construction of radar, sonar, communications, fire control, and guidance systems." (p. 94). This shift in emphasis, Fong notes, reduced the potential for commercial spillovers from VHSIC that might have resulted from greater involvement by the major commercial merchant producers: "...the demise of device technologies has undermined the program's third major objective, that of encouraging the participation of merchant semiconductor producers in defense work. The Pentagon wanted to reverse the growing division between commercial and military work in integrated circuitry, and reestablish the close Pentagon-merchant industry relations of the 1950s. A VHSIC program that promoted semiconductor advances was to be the device to bring the merchants back into the fold. Initially progress was made along these lines. But as device technologies (continued...)

the commercial spillovers of VHSIC are likely to remain modest. Moreover, the budgetary and performance pressures that have led the VHSIC program to focus more heavily on development than on basic research almost certainly will grow in the future and will force defense R&D in a wide range of microelectronics projects to focus on development, reducing their potential commercial spillovers.

The changing relationship between military and commercial technologies in microelectronics influenced the decision of the Defense Department to contribute as much as $600 million over six years to the Sematech (Semiconductor Manufacturing Technology) research consortium. Sematech, which includes 14 U.S. producers of microelectronic components as members, is dedicated to the development of advanced manufacturing processes for standard ICs such as DRAMs, not military components. Sematech also includes among its goals strengthening the U.S. semiconductor manufacturing equipment industry through directing procurement demand toward these firms, which are small and are not vertically integrated into larger producers of components and systems, in contrast to many Japanese producers of equipment. Sematech also may lead to greater interfirm cooperation in the development of standards for capital equipment and could provide a means for hard-pressed U.S. IC firms to broaden their portfolio of process research, pursuing research through Sematech that complements, rather than duplicating, their in-house activities.

Military funding for Sematech is based on two assumptions: (1) technological spillovers in process and product technologies and design now flow primarily from commercial to defense applications in these sectors; and (2) U.S. suppliers of defense technologies cannot survive without maintaining a strong presence in commercial markets.

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[92](...continued)
moved down the list of VHSIC priorities, the Pentagon concentrated its attention on the military system houses, rather than the semiconductor merchants." (p. 95).

Therefore, research subsidies to support commercial technology development within domestic consortia that exclude foreign firms are necessary for national security purposes.

This justification is very similar to that employed by Western European governments for their support of the Airbus Industrie consortium. Sematech and similar initiatives undermine the basis for U.S. opposition to foreign technology development subsidies. If the difference between U.S. and foreign technology subsidy programs becomes one of degree, rather than kind, the limits to foreign abuse of subsidies that are imposed by U.S. opposition and persuasion are likely to be eroded still further. As Nelson and others have pointed out, the efforts of other nations, such as France and Great Britain, to merge military and commercial technology development have not been successful in the aircraft and electronics industries, nor has a similar effort in the U.S. nuclear power industry yielded major commercial technological benefits.[93] In addition, the focus of Sematech on high-volume DRAM production technologies rather than custom application-specific chip designs, the consortium's unproven ability to transfer technological developments to member firms, and the political feasibility of using general revenues to subsidize the technological development of a group of U.S. firms at the expense of their nonmember U.S. competitors, all raise questions. Unlike many recent Japanese cooperative research projects, which focused on the development of generic, precommercial technologies, Sematech is developing manufacturing process technologies for commercial application. Equitable sharing and utilization of Sematech research results therefore may prove to be even more difficult than in many Japanese consortia.

Restrictions on foreign participation in Sematech and other U.S.-based research consortia, if any if not most of which involve significant public funds (in many cases from state, as well as federal, sources), will also complicate U.S. efforts to achieve another important goal, greater access to similar consortia in other industrial economies. Indeed,

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[93] Richard R. Nelson, High Technology Policies: A Five Nation Comparison, Washington, D.C.: American Enterprise Institute, 1984.

the reality of global technological interdependence and the futility of efforts to restrict international movement of technological and scientific know-how are well illustrated by the recent decision of Texas Instruments, a major participant in Sematech, to enter a technology-sharing joint venture with Hitachi of Japan, presumably one of the major technological threats to the firms participating in Sematech.[94] Efforts to impose strict limitations on international transfer or foreign participation simply fly in the face of this interdependence and are likely to undercut the effectiveness of the collaborative research ventures currently underway.

Stronger domestic and international protection for intellectual property also has become an increasingly important goal of U.S. policymakers and industry personnel. The Semiconductor Chip Protection Act (SCPA) of 1984 extended sui generis protection to the layout of transistors and wires on an IC. The SCPA made it illegal to duplicate IC designs directly, and empowered the President to extend similar protection to nations providing comparable protection to the products of U.S. manufacturers, was only one of several important steps taken during the past decade. The creation of the Court of Appeals for the Federal Circuit in 1982, which hears all appeals of patent-related cases, has almost inadvertently (through the judicial temperament of the current judges) served to strengthen the rights of patentholders considerably. The actual impact of these changes in the domestic environment of intellectual property protection is uncertain. U.S. microelectronics firms have pursued litigation against alleged foreign infringers of patents or (in the case of microcode) copyright more aggressively in recent years. Nevertheless, the SCPA does not prohibit "reverse engineering" of U.S. firms' chip designs, a far more common means to follow an innovative leader.

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[94] According to one account, "'Sematech is for manufacturing knowledge and expertise,' said Stan Victor, a spokesman for Texas Instruments in Dallas. He added that the purpose of the agreement with Hitachi was different, because it was a 'technology development' program meant to create the most effective designs for the 16-megabit [microprocessor] chip." T.C. Hayes, "Developing a Computer Chip for the 90's," New York Times, December 23, 1988, p. C6.

Intensified vigilance on the part of individual firms in the area of intellectual property has been matched by the efforts of the U.S. government to increase standards for protection of U.S. firms' intellectual property in international trade negotiations. Bringing intellectual property issues into trade policy provides a potentially powerful enforcement mechanism--restriction of access to the U.S. market for the products of nations deemed to provide insufficient protection. Section 337 of the 1930 Tariff Act and Section 301 of the 1974 Trade Act (the latter Section has been broadened considerably and intellectual property issues accorded greater weight in the 1988 Act) provide for restrictions on access to the U.S. market for products that infringe on patents or copyright, as well as market access restrictions for goods produced by nations not providing comparable protection. As the importance of intellectual property rights within U.S. trade has grown, U.S. trade policymakers have employed the threat of broad sanctions under Section 301 to bring about significant revisions in the intellectual property regimes of such nations as South Korea, Singapore, and Thailand. In addition, private firms' complaints to the International Trade Commission of alleged infringement have received increasingly sympathetic hearings, resulting in more frequent invocations of Section 337.

Intellectual property rights now are the object of multilateral trade negotiations as well. Frustrated with the limited coverage, weak standards, and minimal enforcement of intellectual property rights provided by major international agreements (primarily the Bern and Paris Conventions), the United States and other industrial nations have placed intellectual property rights on the agenda of the Uruguay Round of multilateral trade negotiations, a negotiation that spans 15 different areas. A successful outcome for these negotiations would for the first time make insufficient protection for intellectual property rights grounds for sanctions (including trade retaliation against the offending government) under the provisions of the General Agreement on Tariffs and Trade. Moreover, the GATT would be called on to define, through reference to other international treaties or existing national statutes, acceptable levels of protection and coverage of intellectual property rights.

Despite the considerable U.S. investment of political resources in the intellectual property question, the benefits of a successful outcome, especially in multilateral negotiations, may easily be overstated. Not all U.S. industries benefit equally from intellectual property protection, despite the high priority accorded by the U.S. to this goal in the Uruguay Round. Conventional instruments of intellectual property protection, including patents, trade secrets, and copyrights, are not always sufficient to enable innovators to reap the returns to their investments.[95] Stronger intellectual property protection, especially stronger domestic intellectual property protection, is a two-edged sword for U.S. firms. It provides market power to innovators on the one hand and stronger incentives to invest in innovation, on the other. Strengthening domestic and international protection for intellectual property does little, however, to aid the adoption and utilization of the results of research. As we noted earlier, weak protection of intellectual property within the U.S. microelectronics industry during its early development contributed to rapid intra-national transfer of technology and impressive innovative performance.

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[95] "For new processes..., patents were generally rated the least effective of the mechanisms of appropriation: only 20 percent of the lines of business surveyed rated process patent effectiveness in excess of 4.0 [on a 7-point Likert scale, for which 7 was the highest rating]. Eighty percent scored the effectiveness of lead time and learning curve advantages on new processes in excess of 4.3. Secrecy, though not considered as effective as lead time and learning advantages, was still considered more effective than patents in protecting processes. Patents for products were typically considered more effective than those for processes, and secrecy was considered less effective in protecting products than processes. Generally, lead time, learning curves, and sales or service efforts were regarded as substantially more effective than patents in protecting products. Eighty percent of the sample businesses rated the effectiveness of sales and service efforts above 5.0, but only 20 percent considered product patents this effective." R.C. Levin, A.K. Klevorick, R.R. Nelson, and S.G. Winter, "Appropriating the Returns from Industrial Research and Development," Brookings Papers on Economic Activity, 1987, 783-820, pp. 794-795. The authors found that semiconductor industry personnel gave product patents a rating of 4.5 on a 7 point Likert scale for which 1 was lowest and 7 highest, a rating almost equal to the overall sample of industries and one that was below the effectiveness ratings of product patents in the inorganic chemicals, organic chemicals, pharmaceutical, plastic materials and products, steel mill products, and medical instruments industries, (Table 2, p. 797).

Technology-intensive industries like semiconductors also challenge the historic focus of U.S. bilateral and multilateral trade initiatives on tariffs and border measures and on assurances of procedural regularity and national treatment for foreign firms. The instruments employed by governments in support of their high-technology industries, however, now extend far beyond the border measures (mainly tariffs) that have been the subject of most trade negotiations. U.S. goals in trade negotiations on non-tariff barriers and other trade-distorting policies generally focus on improving the operation of policy processes in foreign economies. Improvements in these processes, however, does not preclude the evasion of disciplines by using alternative instruments, e.g., government procurement to achieve the same ends. The procedural focus of these negotiations thus can weaken their trade-liberalizing effectiveness.

One alternative to focusing trade policy on transparent and nondiscriminatory processes is to stipulate outcomes, as in the U.S.-Japan Semiconductor Agreement, which fixes a price floor for DRAMs and allegedly[96] commits the Japanese government to ensure a specific market share in Japan for U.S. producers of these components. Similar "managed trade" agreements of this sort have also been hammered out in the auto, steel, and textiles industries.[97] They are supported by some analysts[98] because they provide stronger protection against allegedly predatory imports and may be more easily enforced. By restricting imports through some form of a quota or price agreement, these "managed trade" arrangements also provide higher profits to the affected foreign producers, which makes

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[96] The allegation has been made in C. Prestowitz, Trading Places, and in a number of journalistic descriptions of this Agreement.

[97] The Semiconductor Agreement's alleged Japanese market share target for US components, however, would represent a significant extension in the objectives of these agreements, referred to by Bhagwati as a VIE (voluntary import expansion). See J.N. Bhagwati, "Trade in Services and the Multilateral Trade Negotiations," World Bank Economic Review, 1, 1987, 549-569.

[98] See P. Choate and J. Linger, "Tailored Trade: Dealing with the World as it Is," Harvard Business Review, January-February 1988, 86-93.

such import restrictions more acceptable to them and reduces the possibility of retaliation against U.S. exporters. These agreements frequently result in higher prices and lower efficiency within the U.S. economy. Moreover, since the agreements tend to be renewed repeatedly (as in the case of the Multifibre Arrangement, which establishes quotas for the U.S. and other industrial nations' textile industries), these undesirable effects may persist for years, reducing pressure on U.S. producers to adjust to import competition.

The Semiconductor Agreement has been especially harmful to the U.S. electronics sector because of the new international division of labor in microelectronics and computer systems. U.S. computer makers now depend on foreign (mainly Japanese) suppliers of DRAM components, and new personal computer and workstation designs demand more memory components per unit. The sharp increases in the cost of DRAMs that resulted from the Semiconductor Agreement were a serious competitive impediment to U.S. computer producers, few of whom produce their own memory chips.[99]

Since most Japanese producers of personal computers are vertically integrated into memory production, the Semiconductor Agreement increased their profits from DRAM sales and provided them with significant cost advantages in components for competitive computer and workstation designs. Moreover, the profits earned in the DRAM market can be applied to the development of even more sophisticated computers in the future. The Agreement's alleged call for an increase in the Japanese market share of U.S. producers of microelectronic components and the more recent U.S. government pressure on Japan under the "Super 301" provisions of the 1988 Omnibus Trade Act appear to be associated with a greater number of strategic alliances and other collaborative ventures between U.S. IC

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[99] According to estimates in A. Pine, "Computer Chip Pact Backfires on U.S. Industry," Los Angeles Times, June 6, 1988, the price of 256K DRAMs has risen within the U.S. from roughly $2.60 at the time the Agreement was signed to more than $3.60 in June 1988. The price of 64K DRAMs rose from $.90 to nearly $1.40 during the same period. Prices in Japan for DRAMs remained constant or declined slightly during this period. A more favorable view of the effects of the Agreement can be found in D. Yoffie, "Chip Shortage: Don't Blame the Pact," Wall Street Journal, June 21, 1988, p. 36.

producers and Japanese electronics companies.[100] One result of these collaborative ventures is accelerated technology transfer from U.S. to Japanese and from Japanese to U.S. firms. If the Semiconductor Agreement thus far is an example of successful "managed trade" policy, it is hard to know what constitutes a failure.[101]

Antitrust policy which influenced the early development of the U.S. microelectronics industry, also has undergone considerable change in the last eight years. Pursuing an initiative launched by the outgoing Carter Administration, the Reagan Administration considerably relaxed enforcement of such prohibitions as applied to interfirm collaboration in precommercial research. This relaxed enforcement policy was codified in the National Cooperative Research Act of 1984 (NCRA), which was intended to remove remaining disincentives to interfirm collaboration in R&D. The NCRA facilitated the establishment by the semiconductor and computer industries of the Microelectronics and Computer Technology Corporation (MCC) and has been associated with the foundation of numerous other domestic research consortia. It is too early to evaluate the impact of the NCRA or to assess the effectiveness of cooperative research in the semiconductor and other industries; thus far, MCC has encountered serious problems. If collaboration, even in precommercial research, reduces the number and range of technological avenues that are being pursued by independent firms, one of the powerful forces for innovation and growth in the industry's early years may be weakened.

More recently, a number of proposals have been made to extend the relaxation of antitrust sanctions to joint production ventures in selected high-technology industries. This proposal, embodied in a bill introduced by Reps. Boucher and Campbell in March 1989, has

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[100] W.E. Steinmueller, "International Joint Ventures..." in D. C. Mowery, op cit, p. 139.

[101] For further discussion, see David C. Mowery and Nathan Rosenberg, "New Developments in U.S. Technology Policy: Implications for Competitiveness and International Trade Policy," California Management Review, 1989, and David C. Mowery and Nathan Rosenberg, Technology and the Pursuit of Economic Growth (New York: Cambridge University Press, 1989).

important implications for the microelectronics industry for at least two reasons. High-definition television (HDTV) has been cited as a technology whose commercialization would be speeded significantly through production collaboration among U.S. firms. A domestic HDTV industry allegedly would strengthen the U.S. microelectronics industry, because of its important "upstream" linkages to the microelectronics industry, which would supply extensive quantities of components.[102] Antitrust concerns had little to do with the recent collapse of U.S. Memories, Inc., a U.S. consortium for the manufacture of memory components, however, and the ultimate effect of the legislative proposals on interfirm collaboration and competitive performance is very uncertain.

U.S. government policy towards the microelectronics industry is currently in flux. Although definitive predictions of the policy structure are exceedingly hazardous, current trends point to (1) expanded reliance on cooperative research and, possibly, production ventures involving U.S. firms; (2) potentially greater impediments to transfers of technology, especially from publicly and privately funded research consortia; (3) greater resort to "managed trade policies" in dealing with other industrial economies; (4) increased scrutiny of military research and procurement policies for their commercial effects; and (5) growing concern with protection and/or development of downstream industries that are major consumers of microelectronic components.[103]

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[102] Precisely how a domestic HDTV industry (or consortium) would in fact increase demand for the microelectronic components produced by U.S., rather than Japanese or European firms, however, is far from clear. A complex, "domestic content" requirement mandating use of the components made by U.S.-owned firms, rather than foreign-owned firms producing in the U.S. or abroad, will be needed.

[103] Recent controversies over the Bush Administration's commitment to Sematech have revealed the breadth and strength of political support for this consortium. Nonetheless, the current Administration is unlikely to commit major sums to other commercial technology development programs, given the severity of existing budgetary constraints. Foreign access to existing basic and applied research programs may still be restricted, however, and the aggressive "fair trade" stance of the Reagan Administration also bids fair to continue. Finally, Congressional support for "new Sematechs" may yet force the hand of the White House and produce additional programs.

IV.3. Change in the Technological Environment

If declining average costs were all that mattered in the IC industry, Japanese advantages in financing increasingly costly product development and process improvement and in restricting access to the domestic Japanese market could be formidable. But the ability of firms to maintain significant market power in the IC industry has historically been limited by the diversity of products and processes and the rapid pace of technological change. Both of these factors make conclusions about the outlook for U.S.-Japanese competition (and the prospects for entry by firms from the NIEs and LDCs) in the IC industry uncertain. The competitive outlook in three product areas differs very substantially, and the strategic and policy requirements for developing a domestic capability in each may also vary. Several broad issues merit consideration in this discussion: (1) the extent to which there exist significant scope economies among these three classes of components, meaning that firms producing all three types will retain competitive advantages over firms that specialize in one or two; (2) the advantages of vertical integration between systems and components in these three product classes, and (3) the importance of geographic proximity of systems and component design production, regardless of the ownership of such capacity.

"Standard" products include ICs produced in volume that exhibit the economies of scale attainable through learning and investment in process improvement. The trade frictions between U.S. and Japan in the IC industry have focussed on standard products such as dynamic random access memory (DRAM) ICs. As noted earlier, Japanese success in process improvement and management has reduced U.S. merchant domestic production of DRAM ICs. Despite the large price increases that have resulted from the U.S.-Japan Semiconductor Agreement (discussed in the next section) only one U.S. IC producer is domestically producing DRAMs for sale in the merchant market.[104] U.S. firms have been

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[104] Texas Instruments and IBM produce significant quantities of DRAMs in their Japanese facilities. One American company, Micron, has produced DRAMs throughout the 1980s. The failure of other U.S. DRAM producers to resume production after the (continued...)

able to sustain production of many other standard products, however, and it is premature to conclude that Japanese firms' low production costs (and high profits) in DRAMs will yield strong competitive advantages in other standard product types. Moreover, the entry of other producers into DRAM production may eventually erode Japanese firms' market share and profitability in this product.

The second category of ICs is "design-based" products, a category that includes microprocessors and complex ICs with smaller production volume whose economic success is determined by product features as well as cost. In "design-based" products, the innovative design is the key source of value to the purchaser, who incorporates the device in a system product. Product innovation by U.S. firms has sustained their competitiveness in these products. Process leadership of Japanese companies in standard products, especially in CMOS-based DRAMs, may strengthen their capabilities in design-based CMOS products. If these process technology spillovers are important, Japanese firms may match their prowess in process engineering with product innovation across a broad front to extend their dominance in process technology to design based products. At present, however, the extent of such spillovers among different product categories is uncertain.

Design-based products include products that are technologically at the state-of-the-art in process engineering and design technique as well as products that lag behind the current frontier. Japanese firms have been particularly successful in gaining market share for design-based products that are not at the state-of-the-art for two reasons. These products are produced in substantial volumes, and therefore require advanced process technologies, a strength of Japanese companies. Second, and more important, many design-based

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[104](...continued)
"stabilization" of prices under the terms of the Semiconductor Agreement is quite puzzling, and suggests that the allegedly predatory "dumping" of Japanese DRAMs in the U.S. market may have had little to do with the exit by U.s. firms from domestic DRAM production. Even Micron, the remaining U.S. domestic producer, has encountered severe technical and commercial difficulties in its efforts to introduce a one-megabit DRAM chip to complement its 256K DRAM component.

products have close ties with particular classes of system products in which Japanese firms are also strong. These system products include consumer electronics, computer systems, computer peripherals, and "mechatronics." The vertically integrated structure of many of the Japanese producers of these systems strengthens the linkages between the development of design-based components and the development of the system products incorporating them. Vertical integration may be particularly important to the exploitation of these linkages, but this issue has not been examined empirically. Nevertheless, the exploitation of linkages between systems production and the development and production of this class of components may require that even an arms-length relationship between component and systems producers involve firms within the same nation, although even this weaker "requirement" is not demonstrated. If (and this is a large "if") these linkages function most effectively within, as opposed to across, national boundaries, then NIEs seeking to develop a domestic design-based components industry may need a vigorous systems industry. Alternatively, however, further developments in information technologies and computer-aided design and manufacturing systems may make it easier to exploit these vertical linkages across national boundaries.

A third category of IC products is "application-specific ICs" (ASICs). ASICs represent a broad class of product designs and process technologies whose common feature is their ability to perform complex computation and signal processing functions in a specialized applications. Generally, ASIC production volumes are much smaller than those for design-based products. ASIC production is growing rapidly. Figures 6 and 7 show that sales of ASICs are beginning to dominate the category of design-based ICs other than microprocessors. ASICs allow system producers to reduce costs and differentiate their system products by building a system with fewer and more sophisticated ICs. Because system costs can be reduced and system complexity can be increased using ASICs, an ASIC-based design may have fewer and more costly ICs, yet still be less expensive and more sophisticated than a system built with more numerous but less expensive ICs of other types. Competitive success in the ASIC market does not appear to depend on the accumulation of process technology expertise from mass production of standard devices. Competitive

success in ASICs appears instead to hinge on the speed with which new proprietary designs can be developed to meet customer needs. Volumes are sufficiently small in most ASICs that process expertise and yields are less critical. Among other things, the apparently modest importance of process expertise has meant that design and production of ASICs are often carried out by different firms, which need not be in the same nation.

Research on process technologies that will reduce the capital costs of production facilities is being pursued by both established firms and new entrants. As was noted earlier, the very high costs of facilities for mass production of standard devices create economies of scale in the production of these products, and in the face of capital market imperfections, may confer competitive advantages on large, diversified firms. These same economies do not apply to the smaller production runs of more numerous ASIC device designs. Many ASIC devices are currently expensive to produce and the substantial investments of U.S. and Japanese firms in developing ASIC production capabilities may be an effective entry barrier for NIE economies. It is also true, however, that technological advance may reduce the costs and facilitate international transfer of ASIC production technology. The market for ASICs, like that for many design-based products, is closely tied to production and development of systems products. Designing a system and designing an ASIC are activities in which proximity appears to confer important advantages.

Both U.S. and Japanese firms have made major commitments to ASIC production. The ASIC market requires close ties between system and ASIC designers, and both U.S. and Japanese ASIC firms have attempted to reduce the costs of such ties by establishing design centers throughout the world. In recent years, Japanese firms appear to have made larger investments in the U.S. market than U.S. firms have made in the Japanese market. At the same time, ASIC product design innovation and the development of software that allows users to set ASIC specifications and design ASIC-based systems are areas where U.S. firms have a technological lead. Investment in production capacity alone therefore is unlikely to determine the outcome of this competitive struggle.

Cost reduction and design improvements in each sector are relevant for the balance among the three sectors. During the LSI era, when ICs had 10,000 logical "gates," standard and design-based ICs won the competitive battle, largely due to the usefulness of microprocessor-based designs that made standard devices "customizable." The outcome during the VLSI era, where ICs have 100,0000 to 1 million gates, is less certain. A general purpose IC innovation comparable to the microprocessor has yet to emerge from the development of VLSI capabilities. Instead, customized design and flexible manufacturing methods may support prolonged competition between design-based and application specific ICs with only moderate impact from mass produced standard products such as DRAMs.[105] The current strength of U.S. firms in ASICs therefore may not be threatened by Japanese dominance in "commodity" products such as DRAMs. Moreover, if such players as Korea or the Europeans elect to subsidize or otherwise achieve parity in memory production, Japanese firms may face severe competitive challenges in the product area that they currently dominate. Indeed, recent accounts suggest that in 1-MB DRAMs, the pressure on profitability resulting from the entry by Korean firms is causing Japanese producers to resist capacity expansion.[106]

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[105] See Carver Mead and Lynn Conway, Introduction to VLSI Systems, Reading, Massachusetts: Addison-Wesley Publishing Co., 1980.

[106] J. Schlesinger, op cit.

Part V. Implications for Developing Nations

The previous sections offer a foundation for examining two questions; (1) what lessons from the experience of the U.S., Japan, and the NIEs are relevant to developing nations' choices about government policy, technological development, and industrial evolution? and (2) what are the implications for developing nations of current and prospective changes in U.S. trade and technology policies?

Regarding the first area, caution must be exercised in applying "lessons" from the experience of any of the nations that have previously developed IC industries. U.S. experience in pioneering the industry, Japan's role developing a strong internal market for computers and a strong export position in consumer electronics, and the export orientation and success of NIEs offer lessons that may prove less relevant for subsequent "follower" firms. Although a genuinely directive government role appears to have been lacking throughout most of this industry's development in the U.S., this should not be taken to deny the evidence that such a role has been more effective in "follower" nations such as Japan and the NIEs. These nations can benefit greatly from careful monitoring and learning from the experiences of the pioneers, whose progress serves to reduce the uncertainty concerning appropriate technology strategies. Certainly, the experience of Japan and the NIEs suggests that monitoring and learning from the experiences of technology leaders can inform government technology development strategies.[107] Nevertheless, although the strategic choices of follower nations can be informed by the experiences of the pioneers, the problems of implementing directive government policies remain enormous.

In each of the nations that have developed IC industries, vertical ties between IC production and domestic electronic system producers have played a major role. In the U.S. producers of transistors sought innovative solutions to difficulties in component applications,

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[107] See D.C. Mowery and N. Rosenberg, Technology and the Pursuit of Economic Growth, Cambridge University Press, 1989, Chapter 8, for additional discussion.

and the result was the IC. In Japan and the NIEs in which IC production capabilities have developed a strong domestic (albeit foreign-owned, in some cases) system industry preceded he growth of components production. Where a domestic system industry was either slow to embrace microelectronics or lacking altogether, as in Western Europe, IC production capabilities were slower to develop. Finally, a portion of the decline in the commodity segment of the U.S. IC industry is linked to the decline of U.S. consumer electronics systems producers.

Developing nations are not likely to be able to support a large military demand for domestically produced components, nor will they be able to enter production of advanced, IC-intensive systems in competition with production from Japan, Taiwan, Singapore and (in computer areas) the U.S. Success for developing nations is most likely to flow from developing (or attracting foreign-owned production of) specialized subsystems and OEM products.

If an export-oriented strategy building upon "niche" products is the appropriate entry strategy, what role is domestic IC production likely to play? The experience of both Taiwan and South Korea indicates that it is possible to develop a dynamic and successful electronic system industry without significant domestic IC production. Both of these nations, however, now are building IC production capabilities, suggesting that such a capability is likely to be needed eventually. The industrial structure of electronic system producers in Taiwan is unusually ^T, suggesting that the coordination problems for creating domestic IC production might have delayed this capacity relative to other nations with more concentrated electronic system industries. In Korea, development of export capabilities for electronic systems also preceded domestic component production, and the very large scale of enterprise offered an opportunity to develop world class IC production facilities that also could participate in export markets. Between the extremes of Taiwan and Korea, Singapore and Hong Kong have built smaller electronic system and component production capabilities simultaneously and have arrived at an internationally competitive position in electronic systems without developing a strong components export capability. For developing nations, the critical

lessons from NIE experience is that the most important question to be resolved is the point of entry into export markets and, once such an opportunity is identified, the extent of available investment and human resources will determine the degree of commitment to component production. Most evidence suggests that systems production should precede components manufacture, and further suggests that human capital investment is crucial.

There are several developing countries where an export orientation is not a pre-requisite for electronic system production. Economies such as India, China, and Brazil offer internal markets sufficiently large to replicate the earlier experience of the U.S. and Japan in producing electronic systems in sufficient volume to create the necessary scale for a domestic components industry. The problem these countries face is the opportunity cost of developing these domestic components industries rather than allowing foreign direct investment or imports. In creating protected domestic industries, these nations are likely to provide incentives for their domestic producers to extract rents from domestic customers that will indefinitely delay their entry into international markets. Despite significant export markets within South America, this has occurred in Brazil. India also appears to have developed according to this scenario. The recent repudiation of the informatics strategy in Brazil will offer evidence about the export opportunities for other nations and may accelerate the liberalization of other developing nations. Within a trade liberalization strategy, developing nations have the opportunity to adopt Japanese strategies of graduated domestic subsidies and import tariffs that decline over time to build infant electronic system industries.

Regardless of the size of domestic markets, entry into international market competition appears to be a necessary element in any strategy for developing an electronic system and component industry. There are several reasons for this conclusion. First, because only a few nations can develop <u>all</u> of the needed capital equipment, component, and system production industries, substantial imports will be required for any nation with a significant electronics industry. Second, participation in international markets provides producers from developing nations with information about future electronics industry

developments to improve their capabilities and remain competitive. Laboriously building a domestic production capability that lags substantially behind broad trends in international markets is a dangerous strategy in an industry with rapid price declines and performance improvements. Even with a substantial domestic price advantage, imports with marked performance improvements are likely to displace domestic production. Moreover, because moderate economies of scale appear to exist for many electronic system products, the absence of export participation may condemn firms to producing at levels below efficient scale. In addition, of course, an export-oriented industry that is capable of producing internationally competitive systems will be vastly more beneficial for domestic users of these systems. A major source of economic benefit derives from the widespread domestic application of these technologies that display dramatic declines in cost/performance ratios. Third, participation in international markets provides an opportunity for firms to identify partners for joint ventures and other cooperative ventures that can further their domestic and export activities. Even limited success in international export markets is a palpable demonstration of competence and an invitation to explore possibilities for technology transfer, licensing, and joint activities. For most developing nations, participating in export markets will require importation of technology. Here, our assessment is that opportunities are more constrained than during the period when Japan and the NIEs developed successful entry strategies.

A key question for developing nations (as well as for many NIEs), noted earlier, concerns the availability of foreign technology through licensing. A number of developments suggest that the international technology licensing policies of U.S. firms may become more restrictive. A number of U.S. firms believe that they have been too generous in licensing foreign (especially Japanese) firms that have become major competitors. In addition, as was noted earlier, the U.S. government has adopted a tougher stance on protection of U.S. firms' intellectual property. There are two central issues regarding the outlook for technology licensing: cost and availability. Historically, the costs of licensed technologies have been based on the extent of use; high fixed-cost barriers have not been significant. Nonetheless, uncertainty remains about the degree to which the past accurately prefigures the future.

Availability may be a less serious potential problem. A great deal of proprietary process and product technology is embodied in capital equipment that is traded freely (with the exception of goods covered by export controls).

Historically, enforcement of intellectual property rights has not been a major impediment to technology transfer through licensing. Infringement actions generally have been filed retroactively, with license fees assessed as infringement came to the attention of the owners of technology, and punitive damages awards historically have been modest. As was noted earlier, formal intellectual property protection also is fairly porous in many instances; most production technologies can be acquired through the purchase of capital equipment. Joint ventures or strategic alliances between firms from industrial nations and NIEs may be able to solve the potential issues of infringement and technology transfer simultaneously. In short, trade in technology is likely to be less liberal than it was when Japan and the NIEs utilized imported technology to develop their capabilities. Fortunately for developing countries, technological developments have created greater flexibility in entrant strategies. In particular, ASIC and other customer specified designs for ICs have expanded the range of entry opportunities for new entrants throughout the world.

ASICs offer potential entrants the possibility of creating differentiated IC components and using these unique components to develop economically differentiated system designs. Developing such differentiated system designs may provide a basis for import substitution strategies that do not require protection of domestic markets. Whether this potential can be realized is unknown at present and will be a major issue for business and economic research in the coming decade. Industrial nations that have become major exporters of electronic system products have relied heavily on their large domestic markets to recoup product development costs. ASIC technologies may make it possible to dramatically reduce system design and production costs, allowing for the development of system products that use ASIC components for much smaller domestic markets. If this prospect is realized, smaller economies will be able to develop components and system products that are effective substitutes for internationally traded products in the areas of industrial automation

products, scientific instruments, telecommunications subsystems, and data processing subsystems. The startup costs of component production may be recouped from the profits of system production. Sustained comparative advantage is likely to require vertical coordination between component and system production in recognition of the importance of proximity in component and system design and production. Achievement of this goal, however, may require close coordination of component and system design, development, and production. Such coordination may in turn depend on close geographic proximity. Moreover, any ASIC-oriented strategy will require a sophisticated domestic systems design and production capability. In addition, substantial investment in the development of a domestic engineering manpower pool must precede any such effort.

The development of ASICs and associated design and production technologies will have differential impacts on the importance of geographic proximity for various activities. First, the proximity of the component and system designers makes it possible to develop components customized to a specific system application. Proximity may now be attainable at lower cost for developing-nation and NIE firms because of the development of engineering workstations that facilitate exchange of data between system and components designers and may reduce the importance of vertical integration of component design and manufacture. Second, the proximity of component design activities and component production allows more rapid "prototyping" of components and enhances the feedback of information from the component production process.[108] U.S. ASIC firms maintain that domestic production facilities provide them an important advantage in competing with Japanese producers that have made major investments in U.S. ASIC design centers but have not yet established ASIC fabrication facilities in the U.S. Developing nations planning to export highly innovative system products may need domestic ASIC production facilities to assure timely delivery and maintain the proprietary content of their component innovations.

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[108] Although ASIC production processes are supposed to be accurately modeled by automated design systems, the practical design of all but the most simple ASICs is accompanied by an iterative refinement of design based on actual production experience.

The costs of ASIC production facilities in the 1990s are likely to fall, but may still remain too expensive for many developing nations to create a domestic production capability. Nonetheless, the importance of short development cycles and rapid delivery means that in spite of the technological potential for ASICs to reduce the importance of geographic proximity of IC design and production activities, commercial realities mean that such proximity will remain important for entry into ASIC-based differentiated system production. The prospects appear good, however, for entry by developing nation producers into the manufacture of "commodity" systems that do not rely on ASIC for performance or functionality.

Previous experience with foreign-owned assembly and other production facilities in East Asian economies provides little guidance on the importance of local ownership, as opposed to domestic location, of facilities for the design and fabrication of microelectronics components. Is ownership essential to the development of a viable microelectronics-based industrial sector, or can direct foreign investment serve as a sufficient vehicle for technology transfer and industrial development? Many of the "spillovers" associated with a local microelectronics establishment, such as the development of a domestic technological infrastructure, presumably depend much more on the location, rather than on the ownership, of the assembly or production facilities. Especially in the case of an industrial strategy that focuses on ASIC-based, differentiated systems, some restrictions on foreign investment (e.g., accepting only partial foreign ownership) may be necessary in order to preserve the responsiveness to local system producers that appears to be essential to the viability of this strategy. In other words, rejection of an import-substitution strategy that relies on restrictions on goods trade need not preclude entirely the selective and judicious use of controls on foreign investment. As was noted earlier, most East Asian NIEs, including Hong Kong, have employed similar policies in their domestic microelectronics industries. Nonetheless, in view of the costs (distorted investment flows and potentially excessive reliance on public borrowing from international capital markets) associated with such investment restrictions, they must be employed with considerable care.

If the "lessons" of the U.S., Japanese, and NIE experience for developing nations' semiconductor industries are complex, so too are the implications of current and prospective technology and trade policies for the future of this industry in the NIEs and developing nations. The international trade regime in this industry appears likely to move toward "managed trade," as the U.S.-Japan Semiconductor Agreement has recently been supplemented by an agreement between the European Communities and Japan governing the pricing of memory chips. This changing environment has two offsetting implications. To the extent that these agreements cover only pricing, the resulting price floor in the major markets for commodity components creates opportunities for entry. If agreements on pricing are accompanied by quotas, however (something that has not occurred but that is likely), the trade regime in semiconductors might come to resemble those in steel or textiles, and entry by firms not already active in the industry and able to negotiate quotas accordingly would become more difficult.

Regardless of their specific form, trade restrictions mean that access to industrial nations' markets will be more difficult in the near future. Firms not already active in semiconductors, like their counterparts in textiles, may find that profitable export opportunities will require that they focus on products not covered by international quota or price agreements. These will likely be ASICs or other "design-intensive" products, rather than commodity products, such as DRAMs. As we noted earlier, experience in producing standard products <u>may</u> convey significant technological and competitive advantages on firms seeking entry into ASIC design and production. Such experience does not appear to be indispensable, however (e.g., Taiwanese firms are operating successfully in ASIC design with little if any experience in design or fabrication of standard devices), meaning that constrained export opportunities for standard components need not preclude entry into ASICs. Moreover, quota systems may focus on particular stages of intermediate good production, for example the may induce DRAM producers to integrate forward into the production of memory sub-systems to avoid restrictions on imports of DRAMs as components.

Access to U.S. semiconductor product and process technologies may also become more difficult. The possibility of restrictions on the foreign transfer of the results of federally funded basic research in public and university laboratories is a real one. Many U.S. firms are now more reluctant to license their semiconductor product or process technologies than previously was the case. At the same time, however, the forces that are driving growth in international collaborative ventures will not abate in the future, and these will create opportunities for technology transfer through various types of alliances. Indeed, entry into the semiconductor and other high-technology industries may be greatly assisted by the development of such alliances between firms from industrial and developing nations. Nonetheless, access to technology through either a license or a strategic alliance will require that prospective recipients develop acceptable regimes of intellectual property protection, strong indigenous science and engineering manpower pools, and managers who are alert to the possibilities in international markets. One potential policy that has received relatively little attention in many developing nations' efforts to develop international alliances in the formation of consortia of domestic firms to create the critical mass needed to be a credible participant in an international strategic alliance. This policy obviously is only advisable when domestic firms are quite small in size. Such a policy has the added benefit of diffusing foreign technological and managerial expertise among several domestic firms, which may compete in other domestic markets or after the dissolution of an international strategic alliance.[109]

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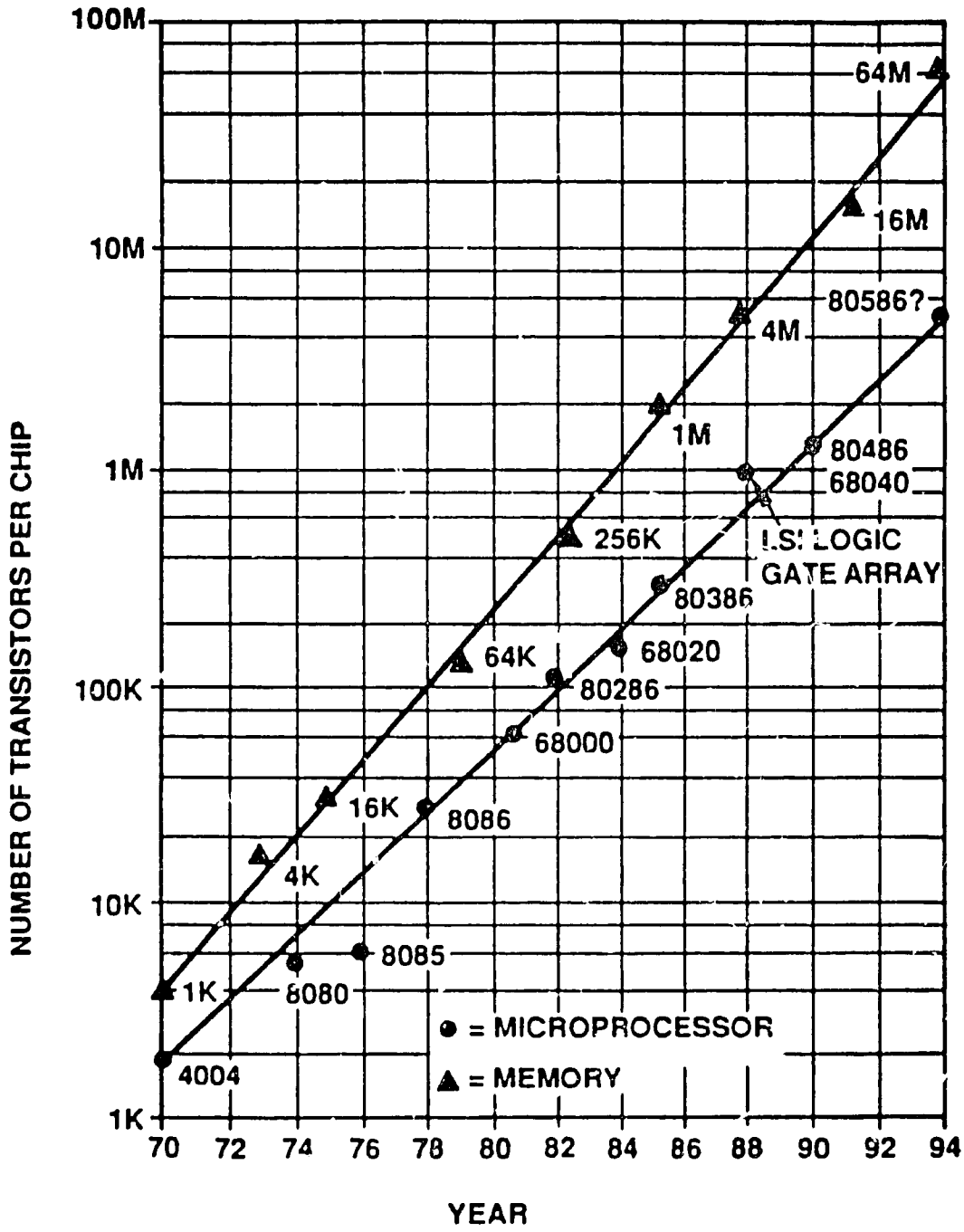
[109] Liberal domestic licensing of foreign technologies may not be feasible for all NIEs, in view of growing opposition from developed country governments to compulsory licensing requirements. Nonetheless, many NIE firms, especially those serving large domestic interests face much more intensive competition among developed nation firms and therefore may be able to choose among several alternative sources for licensed technologies. In such an environment, competing NIE firms may be able to source technology from different developed nation enterprises, preserving domestic competition. This outcome may require aggressive enforcement by NIE governments of competition policies that prevent the accumulation of market power by a single firm.

A final channel through which technology transfer from the U.S. has been fairly significant in this industry in the recent past, direct foreign investment, may well decline in importance in the future. This development reflects a number of factors, including (1) increasing automation of production operations and the related decline in the share of production costs accounted for by direct labor; (2) U.S. macroeconomic policies and low domestic savings rates, which are likely to continue to reduce the foreign exchange value of the dollar and to encourage a net inflow of foreign capital into the U.S.; (3) growing fixed costs and the higher risks of new product development, reducing the attractiveness to U.S. firms of direct foreign investment as a strategy for access to foreign markets; and (4) the prospect of increased restrictions on access to a unified Western European market after 1992, creating strong incentives for U.S. firms to locate additional direct foreign investment in that market. Firms thus may well have to rely on alternative channels for access to U.S. technology, including licensing and alliances. In addition, access to the U.S. and European markets is likely to require that these firms pursue some type of direct foreign investment strategy.

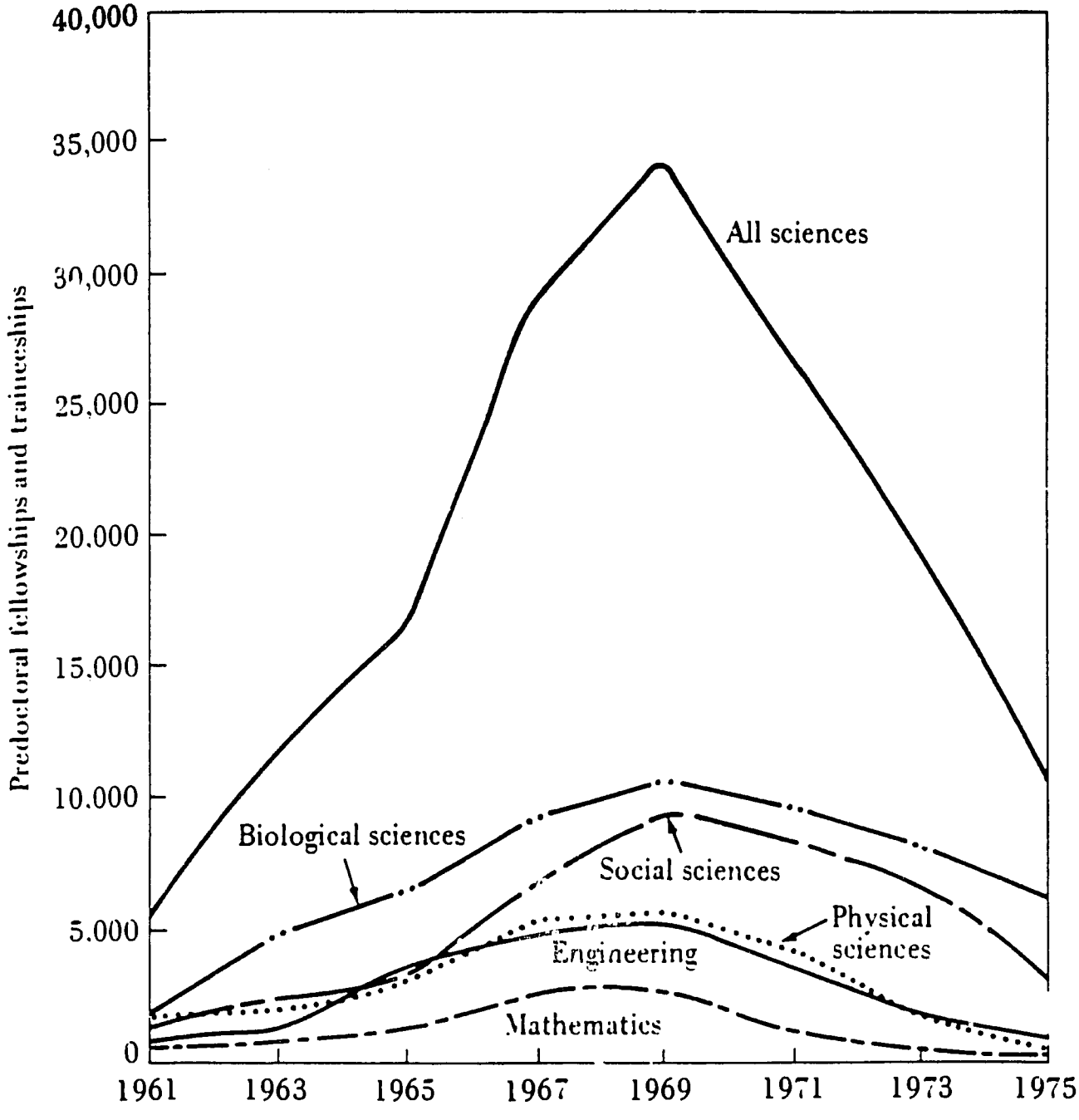
Government strategies for the development of an indigenous semiconductor industry inevitably must take into account the increased importance of international flows of technology, capital, and goods, factors that were far less important in the environment within which the U.S. semiconductor industry developed. These changes in the structure of the international economy mean that an autarkic strategy, if it ever were feasible, now is not. "Outward-looking" strategies that encourage indigenous technology development, the transfer of technology to domestic firms from abroad, and exposure of domestic firms to the pressures and discipline of competition (preferably international competition) are essential. Government agencies may be better able to make the technological judgments needed to formulate industry strategies that were U.S. government agencies in the 1950s, but they are not likely to be more adept at implementing such strategies. For this reason, government policies that attempt to "fine-tune" industry structure or strategy are ill-advised. Instead, intervention of a more generic sort, aiding the diffusion of technologies, supporting the development of human capital, and maintaining access by NIE firms to the markets of the industrial nations, ultimately may prove more effective.

Figure 1



MEMORY INCREASE = 1.5/YEAR
MPU INCREASE = 1.35/YEAR

Figure 2



Federal predoctoral fellowships and traineeships by field, fiscal year 1961–75. *Source:* Office of Technology Assessment

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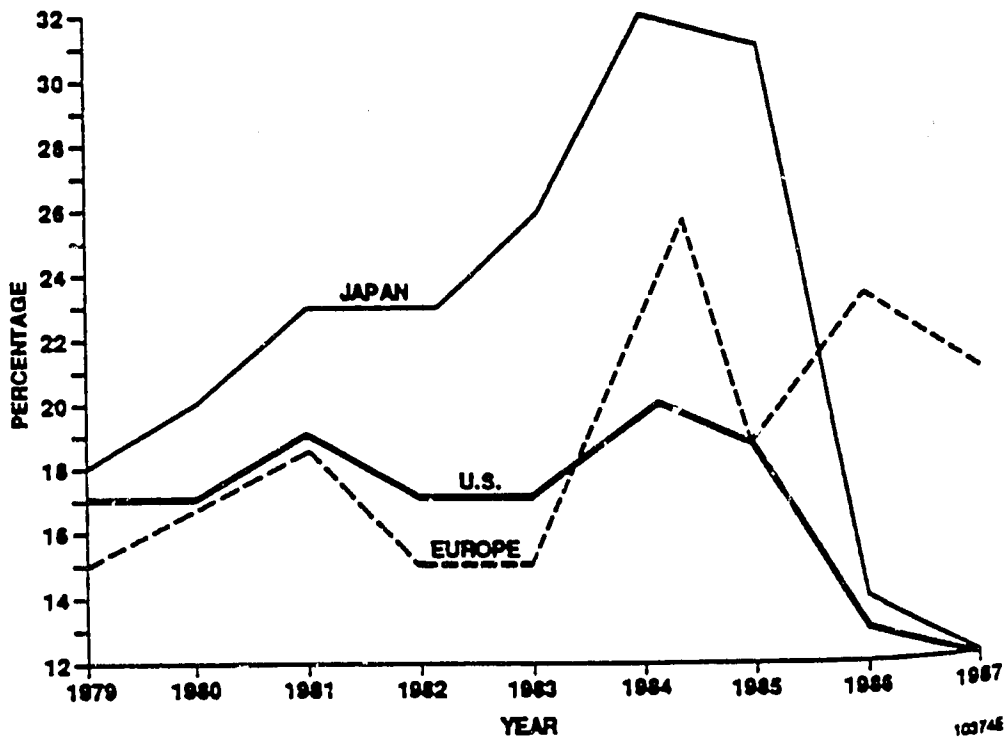
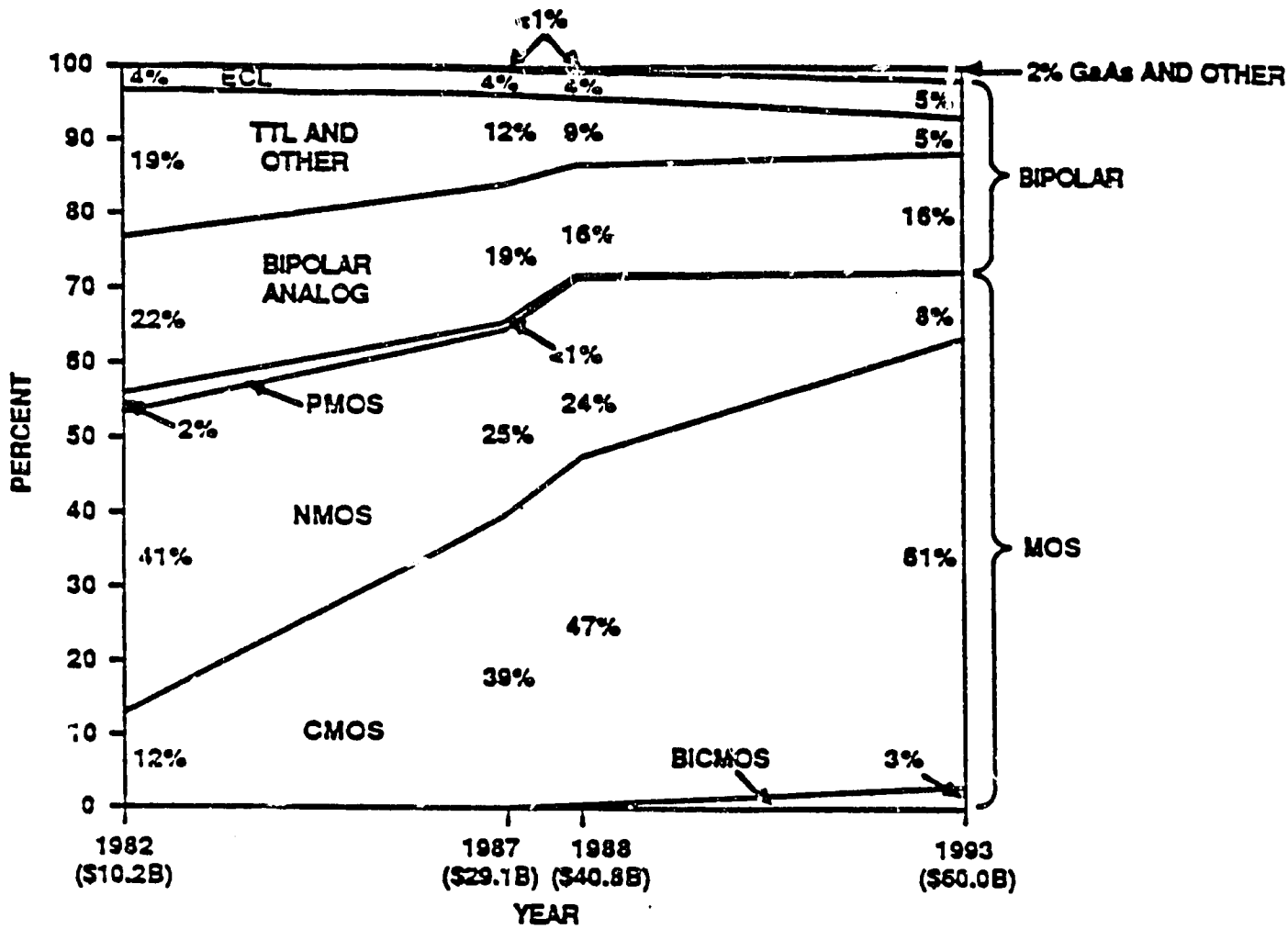
Figure 3



Capital Expenditures as a Percentage of Semiconductor Sales

Source: William J. McClean, Status 1988: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering, Inc., 1988, p. 2-27.

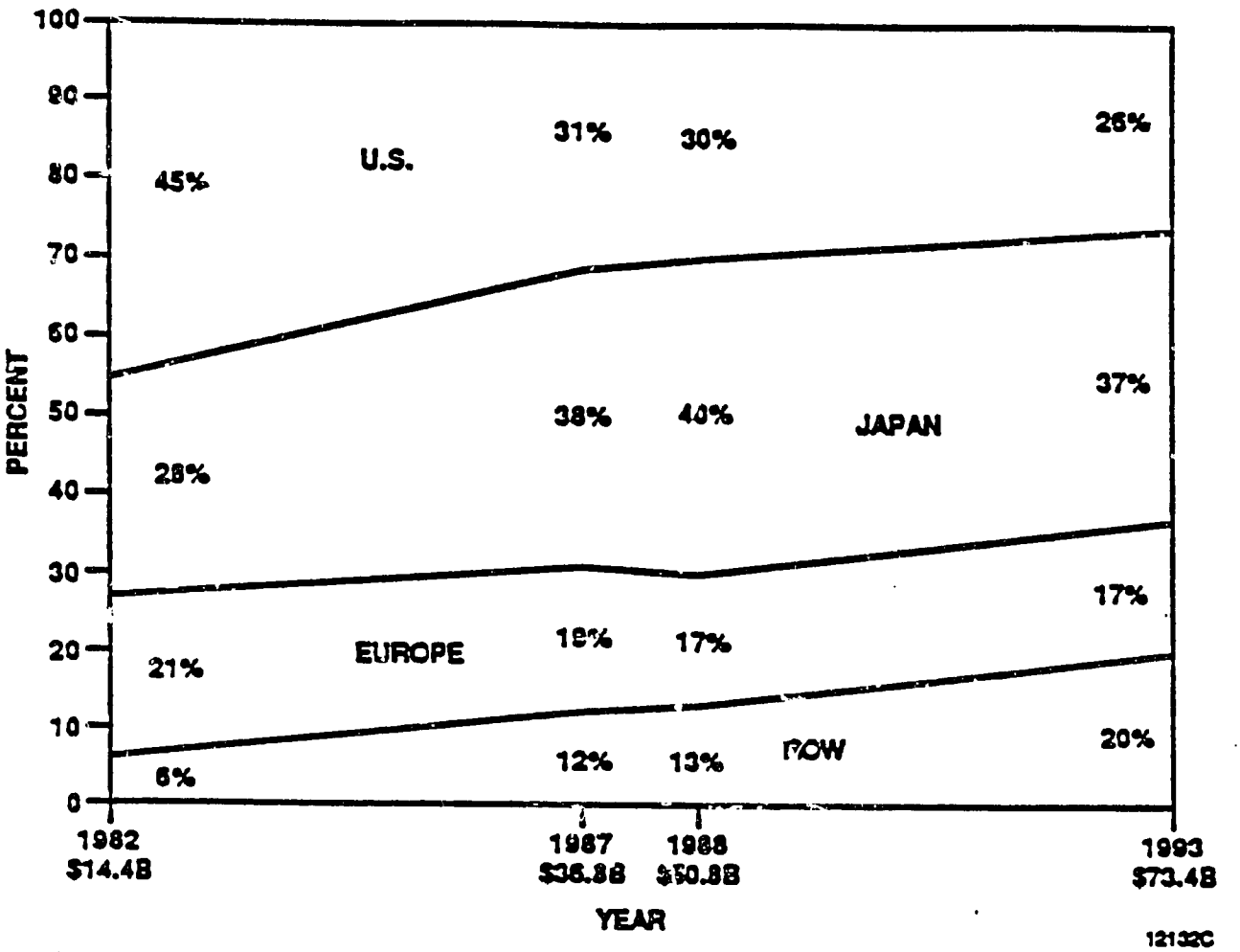
Figure 4



1982 - 1993 IC Technology Trends (Dollars)

Source: William J. McClean, Status 1989: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering Inc., 1989, p. 5-2.

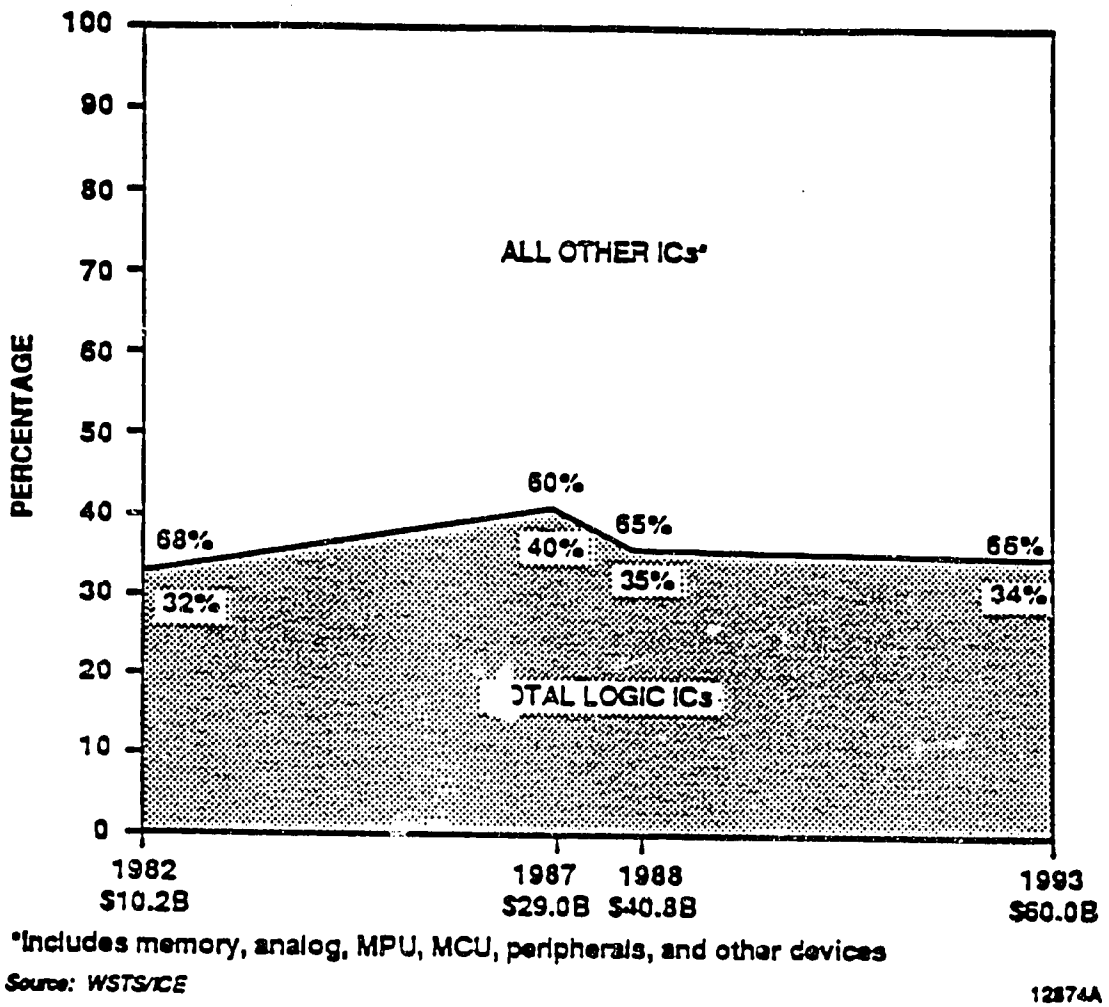
Figure 5



Worldwide Merchant Semiconductor Market

Source: William J. McClean, Status 1989: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering Inc., 1989, p. 1-20.

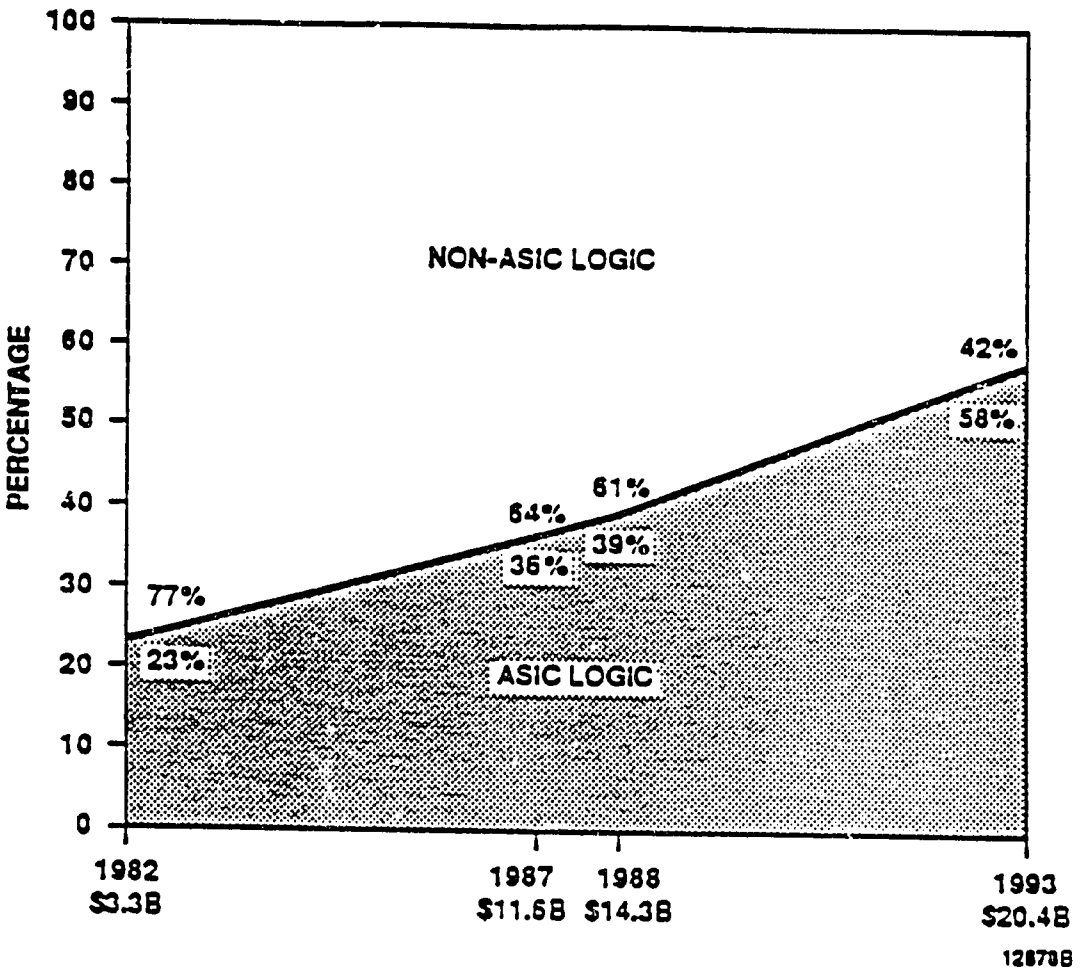
Figure 6



Total Logic Market versus Total IC Market

Source: William J. McClean, Status 1989: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering Inc., 1989, p. 4-3.

Figure 7



Logic Market Breakdown

Source: William J. McClean, Status 1989: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering Inc., 1989, p. 4-4.

Table 1

U.S. TRANSISTOR, DIODE, AND INTEGRATED CIRCUIT SHIPMENTS

Year	TRANSISTORS Units (M)	TRANSISTORS Value ($M)	DIODES AND RECTIFIERS Units (M)	DIODES AND RECTIFIERS Value ($M)	INTEGRATED CIRCUITS Units (M)	INTEGRATED CIRCUITS Value ($M)	Total Value ($M)
1954	1.3	5.1					5.1
1955	3.9	13.0	28.1	27.0			40.0
1956	14.7	40.0	48.0	50.0			90.0
1957	27.8	68.0	66.0	83.0			151.0
1958	46.1	112.0	74.8	98.0			210.0
1959	83.5	228.5	129.4	166.5			395.0
1960	131.8	313.9	197.6	228.0			541.9
1961	193.0	316.2	312.0	248.6			564.8
1962	258.2	303.5	424.3	267.7			571.2
1963	302.9	311.7	627.1	282.3	4.5	46.2	640.2
1964	395.0	323.1	762.1	312.0	13.8	141.9	777.0
1965	631.7	425.9	1072.6	379.4	95.4	317.1	1122.4
1966	877.3	504.3	1520.8	470.9	165.0	491.8	1467.0
1967	792.1	434.5	1461.1	444.4	178.8	505.0	1383.9
1968	551.7	426.6	1618.8	420.1	247.3	567.8	1414.5
1969	1249.1	472.1	2099.7	464.0	423.6	750.7	1686.8
1970	976.9	410.9	1866.0	421.1	490.2	887.9	1719.7
1971	880.7	340.7	1473.1	346.4	635.2	814.7	1501.8

SOURCES: 1954: Electronic Industries Association Yearbook.

1955-1959: U. S. Department of Commerce, Business and Services Administration (BDSA), Semiconductor, U. S. Production and Trade, February, 1961.

1960-1971 BDSA, Estimated Shipments of Selected Electronic Components, annual issues.

Table 2

U.S. IC Shipments ($000)
1972 - 1975

	1972	1973	1974	1975
Hybrid Thick Film	n/a	182,003	273,883	117,821
Hybrid Thin Film	n/a	27,121	51,493	79,671
Hybrid Other[1]	n/a	46,191	41,163	35,716
Total Hybrid	236,981	255,315	366,539	233,208
Digital				
DTL	n/a	43,736	48,353	28,372
TTL	n/a	283,111	325,566	251,111
CML/ECL	n/a	93,627	96,912	59,761
MOS	n/a	414,917	486,796	651,726
Other Digital	n/a	407,185	521,868	237,666
Total Digital	757,521	1,242,576	1,479,995	1,229,136
Analog	143,488	226,041	264,337	233,795
Total ICs	1,137,990	1,723,932	2,110,971	1,696,139

Source: U.S. Department of Commerce, Bureau of the Census, Current Industrial Reports: Selected Electronic and Associated Products, 1965 - 1971.

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[1] Hybrid for 1974 - 1975 excludes devices that are exclusively passive (i.e., do not contain semiconductors). This category includes devices such as resistor networks constructed with thick film (silk screen) techniques.

Table 3

U.S. IC Shipments ($000)
1976 - 1982

	1976	1977	1978	1979	1980	1981	1982
Hybrid							
Thick Film	198,420	178,986	219,971	287,584	280,103	378,045	434,672
Thin Film	103,943	136,383	180,394	256,375	322,458	245,264	215,790
Other	41,119	31,206	41,357	51,833	75,819	173,571	204,029
Total Hybrid	343,482	346,575	441,722	595,792	678,380	796,880	854,491
Digital Bipolar							
DTL	33,868	33,712	26,820	25,272	21,826	13,961	8,482
TTL	302,582	397,744	550,876	926,140	1,286,449	1,143,565	1,123,849
CML/ECL	84,209	85,173	131,890	135,536	120,269	199,160	190,270
IIL (1)	25,096	24,834	12,650	34,924	28,750	30,067	59,732
Microprocessors	--	--	19,123	36,999	57,212	73,747	320,348
Other	448,515	248,524	411,959	370,987	538,864	528,428	441,081
Total	894,270	789,987	1,153,318	1,529,858	2,053,370	1,988,928	2,143,762
Digital MOS							
Microprocessors	274,880	168,672	269,145	485,709	754,847	593,254	507,786
Memories	513,629	758,981	945,044	1,243,836	1,810,748	1,912,879	1,959,859
Other	283,039	270,020	322,498	398,357	622,442	828,054	1,091,567
Total	1,071,548	1,197,673	1,536,687	2,127,902	3,188,037	3,334,187	3,559,212
Total Digital	1,965,818	1,987,660	2,690,005	3,657,760	5,241,407	5,323,115	5,702,974
Analog	334,630	342,638	406,036	463,028	685,442	856,401	764,254
Total ICs	2,643,930	2,676,873	3,537,763	4,716,580	6,605,229	6,976,396	7,321,719

(1) Includes bipolar microprocessors for 1976 and 1977.

Source: U.S. Department of Commerce, Bureau of the Census, Current Industrial Reports: Selected Electronic and Associated Products, 1965 - 1971.

Table 4

U.S. Production of Semiconductors for Defense Requirements, 1955–68[a]

Year	*Total semiconductor production (millions of dollars)*	*Defense semiconductor production[b] (millions of dollars)*	*Defense as a percentage of total*
1955	40	15	*38*
1956	90	32	*36*
1957	151	54	*36*
1958	210	81	*39*
1959	396	180	*45*
1960	542	258	*48*
1961	565	222	*39*
1962	575	223	*39*
1963	610	211	*35*
1964	676	192	*28*
1965	884	247	*28*
1966	1,123	298	*27*
1967	1,107	303	*27*
1968	1,159	294	*25*

Sources: Data for discrete devices are from U.S. Department of Commerce, Business and Defense Services Administration (BDSA), *Electronic Components: Production and Related Data, 1952–1959* (1960); BDSA, "Consolidated Tabulation: Shipments of Selected Electronic Components" (annual reports; processed; title varied somewhat over the period).

a. The 1962–68 data include monolithic integrated circuits. Figures on the latter are as shown in Table 4-8 and come from the sources given there.

b. Defense production includes devices produced for Department of Defense (DOD), Atomic Energy Commission (AEC), Central Intelligence Agency (CIA), Federal Aviation Agency (FAA), and National Aeronautics and Space Administration (NASA) equipment.

Table 5

U.S. Integrated-Circuit Production and Prices, and the Importance of the Defense Market, 1962–68

Year	*Total production (millions of dollars)*	*Average price per integrated circuit (dollars)*	*Defense production as a percentage of total production*[a]
1962	4[b]	50.00[b]	*100*[b]
1963	16	31.60	*94*[b]
1964	41	18.50	*85*[b]
1965	79	8.33	*72*
1966	148	5.05	*53*
1967	228	3.32	*43*
1968	312	2.33	*37*

Sources: Total production and average price figures are from the *Electronic Industries Yearbook, 1969* (Washington: Electronic Industries Association, 1969), Table 55. Defense production as a percentage of total production is based on data for monolithic integrated circuits found in BDSA, "Consolidated Tabulation: Shipments of Selected Electronic Components."

a. Defense production includes devices produced for DOD, AEC, CIA, FAA, and NASA equipment.

b. Estimated.

Table 6

Value of U.S. transistors by usage, 1963 ($M)

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	Television	0.3
Surface systems	10.8	Other	11.5		
Strategic systems	8.8				
Other	6.7				
	119.2		92.3		40.8

Source: Edward Ney Dodson III, 'Component product flows in the electronics industry',[38] pp. 95–7.

Table 7

Integrated Circuits: Percentage Distribution of Sales of U.S. Producers, By Types of Markets 1974-1978

	1974	1975	1976	1977	1978
Computer	40.3	35.3	33.4	35.1	35.5
Consumer Product	16.6	16.3	10.1	9.6	10.5
Industrial	9.1	11.1	11.4	9.7	10.6
Communications	4.6	5.7	6.1	7.7	7.8
Automotive	1.0	0.7	0.6	0.8	1.1
Government	13.7	15.0	11.7	12.3	9.0
Distributor	13.9	14.4	21.9	20.0	25.0
Other	0.8	1.5	4.8	4.8	0.5

Source: U.S. International Trade Commission, Competitive Factors Influencing World Trade in Integrated Circuits, Washington, D.C., October, 1979, Table A-35, p. 102.

Table 8

AGGREGATE ELECTRONICS DATA 1987[a]
(Billion US$)

	IMPORTS	EXPORTS	PRODUCTION	MARKET	GDP	PROD/GDP
U.S.	53.5	35.6	184.8	202.6	4,497.2	4.11
U.K.	18.1	14.6	23.9	27.5	575.7	4.16
FRANCE	14.5	10.9	25.4	29.1	873.4	2.91
JAPAN	7.7	58.5	148.3	97.5	2376.4	6.24
BRAZIL	0.8	0.7	5.6	5.7	299.2	1.86
CHINA b/	1.7	0.1	5.4	7.2	274.6	1.86
INDIA	0.6	0.1	3.1	3.5	220.8	1.38
KOREA	4.4	9.8	13.3	7.9	121.3	10.98
SINGAPORE	6.6	10.1	7.5	4.0	19.9	37.87
TAIWAN	3.9	9.1	11.0	5.8	94.3	11.66
HONG KONG	7.5	9.2	5.3	3.6	36.5	14.53

NOTES: a/ Electronics includes electronic data processing, office equipment, control instrumentation, medical and industrial, communications and military, telecommunications, consumer electronics, and components. See Table 4 for breakdowns by country and type of product.

b/ Data for China is for 1983.

SOURCES: Import, export, production, and market data for all economies except China are from Yearbook of World Electronics Data, VOLS I & II, 1989. Oxford: Elsevier Advanced Technology, 1989 For China, data on electronics are from World Bank 1989, China Electronics Sector Report. GDP are from World Bank. World Development Report 1989, except for Taiwan Province which are taken from ROC Council for Economic Planning and Development, Taiwan Statistical Data Book, 1988.

PERCENTAGE BREAKDOWN OF ELECTRONICS PRODUCTION 1987
(Million US$)

	EDP	Office Equip.	Control Instru-mentation	Medical & Industrial	Commun. & Military	Telecommu-nications	Consumer Electronics	Com-ponent
U.S.	26.9	3.2	11.3	3.7	23.9	8.8	2.7	19.6
U.K.	30.8	2.4	14.1	3.6	16.1	11.0	5.9	16.3
FRANCE	23.3	1.4	8.0	2.4	24.9	18.5	4.4	17.2
JAPAN	26.7	3.3	3.6	2.8	5.3	7.7	18.9	31.7
BRAZIL	26.2	2.4	1.2	1.3	5.5	10.4	29.1	24.0
CHINA	NA	NA	NA	NA	NA	NA	NA	NA
INDIA	7.6	1.6	7.8	2.1	12.6	12.3	38.8	17.3
KOREA	11.0	1.5	1.2	0.6	1.8	8.1	35.3	40.5
SINGAPORE	37.6	2.5	2.3	0.5	1.2	2.0	17.1	37.0
TAIWAN	25.6	2.6	0.7	0.8	4.3	8.0	24.3	33.6
HONG KONG	16.1	4.8	1.4	1.5	9.2	6.6	38.8	21.7

SOURCE: Yearbook of World Electronics Data, VOLS I & II, 1989. Oxford: Elsevier Advanced Technology, 1989

Table 9

INDICATORS OF INVESTMENTS IN HUMAN CAPITAL IN SELECTED NICs AND JAPAN

	S. Korea	Taiwan	H. Kong	Singapore	Brazil	Mexico	India	Indonesia	Japan
Percent Age Group Enrolled in:									
Primary Education									
(1965)	101	97	103	105	108	92	74	72	100
(1985)	96	100	105	115	104	115	92	118	102
Secondary Education									
(1965)	35	38	29	45	16	17	27	12	82
(1985)	94	91	69	71	35	55	35	39	96
Tertiary Education									
(1965)	6	7	5	10	2	4	5	1	13
(1985)	32	13	13	12	11	16	9	7	30
No. of Tertiary Students per 100,000 population									
(latest year)	3606	2080	1410	1406	1140	1508	776 a/	600	2006
No. of Tertiary Students in CSE b/ ('000)	585	207	36	22	535	563	1443	235	707
(Year)	(1987)	(1984)	(1984)	(1983)	(1983)	(1986)	(1980)	(1985)	(1986)
AS % of Population:									
Total	1.39	1.06	0.67	0.89	0.40	0.70	0.21	0.14	0.58
Urban	2.02	1.36	0.72	0.89	0.58	1.02	0.97	0.53	0.77
No. of Students in SME c/ ('000)	320.6	151.7	27.5	16.2	323.3	336.9	1269.9	137.3	486.9
As % of Population:									
Total	0.76	0.78	0.51	0.73	0.24	0.42	0.19	0.09	0.40
Urban	1.10	1.00	0.55	0.73	0.34	0.59	0.86	0.33	0.53
No. of Students in Engineering Only ('000)	227.6	128.7	21.1	15.4	164.6	281.8	397.0	109.5	418.9
As % of Population:									
Total	0.54	0.68	0.41	0.61	0.13	0.35	0.06	0.07	0.34
Urban	0.78	0.85	0.42	0.61	0.17	0.50	0.27	0.27	0.45
No. of Students Enrolled In Vocational									
Training ('000)	814.5	404.6	31.7	9.4	1481.0	853.6	397.7	1061.3	1415.4
(Year)	(1986)	(1984)	(1984)	(1984)	(1985)	(1986)	(1981)	(1986)	(1986)
As % of Population of Working Age	3.06	3.24	0.86	0.54	1.83	2.0	0.1	1.14	1.71

Source: S. Lall "Explaining Industrial Success in Developing Countries," in S. Lall V.N. Balasubramanyam (eds.) Current Issues in Development Economies, London, Macmillan (forthcoming). Original data from World Development Report, 1988; UNESCO, Statistical Yearbook 1988, Paris, 1989; and Government of Republic of China, Statistical Yearbook of Republic of China 1988, Taiwan. Government of Republic of China, Ministry of Education, Educational Statistics of Republic of China, 1984.

a/ 1980.

b/ General science and engineering fields: natural science; mathematics and computer science; medicine; engineering; architecture; trade, craft; transport and communication; agriculture, forestry, fishery.

c/ Natural science, mathematics and computer science, engineering.

Table 10

World Electronic System Production
($ billion)

1984-1988 (est.)

Year	1984	1985	1986	1987	1988 (est.)
Geographic Segment					
U.S.	150	161	167	177	195
Japan	45	49	69	83	110
Europe	49	54	72	85	100
ROW	31	41	52	65	85

Source: William J. McClean, Status 1989: A Report on the Integrated Circuit Industry, Scottsdale, Arizona: Integrated Circuit Engineering Inc., 1989, p. 1-5.

Table 11. Annual World Merchant Semiconductor Industry Sales and Capital Investments: 1979, 1982, 1984, and 1988

	Sales	Capital Investment	% Annual Investment to Sales
1979[1]	$9,545	$1,566	16.4%
1982[2]	12,635	2,429	19.2%
1984[3]	27,000	6,390	23.7%
1988[4]	50,600	8,070	15.9%

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[1] Capital expenditure estimates from William J. McClean (ed.), Status 1985: A Report on the Integrated Circuit Industry, (Scottsdale, Arizona: Integrated Circuit Engineering Inc., 1985), Tables 2-10 and 2-11, pp. 46-47. These tables provide an estimate for semiconductor-related capital expenditures of the top ten firms and unspecified "others" in the U.S. and Japan. U.S. and Japanese semiconductor shipments for 1979 are taken from William I. Strauss (ed.), Status 1981: A Report on the Integrated Circuit Industry, (Scottsdale, Arizona: Integrated Circuit Engineering Inc., 1981), Table 1-1, p. 2. It is not reported whether the "others" category of capital expenditure (25% of the total) includes captives, (U.S. firms who produce solely for their own use). In 1979, the value of captive production ($2.01 billion) is excluded, but capital expenditure of "others" (25% of the total) are included. This treatment follows the treatment of sales and capital expenditures in McClean, 1985, Figure 2-2, p. 46.

[2] Capital expenditure figures from McClean, ibid. Sales from William I. Strauss, Status 1984: A Report on the Integrated Circuit Industry, (Scottsdale, Arizona: Integrated Circuit Engineering, Inc., 1984), Table 1-2, p. 4. The same issues as described in the previous footnote apply to the 1982 statistics. Note that "others" are included (again 25% of capital investment), and captive production is excluded ($3,160 million). As a result, the capital investments for 1982 are directly comparable with those reported for 1979.

[3] In 1985, Integrated Circuit Engineering, Inc. began estimating capital expenditures in Europe and the Rest of the World (ROW) in addition to the U.S. and Japan. ROW includes China, but excludes the Soviet Union. European semiconductor market world market share of output and capital expenditures are 10% and 8% respectively. ROW output and capital expenditure shares are 2% and 8% respectively. William J. McClean, Status 1985: A Report on the Integrated Circuit Industry, (Scottsdale, Arizona: Integrated Circuit Engineering, Inc., 1985), Figure 2-2, p. 46. The same issues apply as in previous footnotes. Included 1985 capital expenditures by "others" in the U.S. is $660 million (24%) and excluded captive output is $5,030 million, making the capital expenditures directly comparable to 1982.

[4] William J. McClean, Status 1989: A Report on the Integrated Circuit Industry, (Scottsdale, Arizona: Integrated Circuit Engineering Inc., 1989), Figure 2-39, p. 2-43. The 1988 value of captive producers output ($5,090 million) is excluded and the value of "other" producers capital expenditure ($480 million or 20%) is included, making the capital expenditure comparable to 1984. The significance of increases in the average sales price of ICs in 1988 is examined in the text.