Semiconductor productivity gains linked to multiple innovations

High productivity gains, especially in the 1970's, stemmed mainly from rapid improvements in product design and manufacturing techniques and processes

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Output per employee hour in the semiconductor industry rose at an average annual rate of 13.1 percent between 1972 and 1986—a much higher rate than for all manufacturing, 2.4 percent.[1] Output increased 21 percent a year and employee hours, 6.9 percent. The long-term trend in productivity masks two distinct periods during which annual rates changed markedly. The rates moved as follows:

	Output per employee hour	*Output*	*Employee hours*
1972–86	13.1	21.0	6.9
1972–81	16.6	25.4	7.5
1981–86	4.1	9.5	5.2

Between 1972 and 1981, average annual output growth (25.4 percent) was more than three times higher than employee-hour growth. The major factor behind the strong output performance was the continual innovation in integrated circuits combined with the industry's adroitness in rapidly turning such innovations into low-cost, mass-produced devices. In an environment of rapidly evolving products and low unit prices, myriad new uses were found for semiconductor devices and most existing electronic products, such as computers and military hardware, were substantially upgraded.

These factors were also present during the first half of the 1980's, but gains in output per employee hour were less than one-quarter of those registered in the 1970's—4.1 as against 16.6 percent per year. During the 1981–86 period, output growth was dampened by increasing Japanese competition and a series of slowdowns in computer manufacturing (a major user of semiconductor devices). Increases in average employee hours also lessened during the early 1980's—from 7.5 percent a year in 1972–81 to 5.2 percent in 1981–86. The slowdown mainly reflected less robust output growth. While circuits became more intricate, they required more employee hours to design and produce; this tendency was partially offset by the increasing use of computers in both design and manufacturing processes and by more automated production techniques.

Output and demand. The semiconductor industry manufactures two major types of products—discrete devices, such as transistors and diodes, which perform only one electronic function; and integrated circuits (chips) which are arrays of discrete devices imprinted on small pieces of silicon. Increases in industry output since the late 1960's stem, to a large degree, from rapid growth in the production of integrated circuits. In 1966, integrated circuits accounted for about one-eighth of all semiconductor production, for over one-half in 1972, and for almost four-fifths in 1980. During the same period, their current dollar value leaped from just over $100 million to about $6.5 billion.

The earliest integrated circuits, developed in the late 1950's, contained fewer than 10 discrete devices. By the late 1960's, chip capacity had increased a hundredfold. Since then, chip capacity has doubled about every 2 years; in 1987, a chip the size of a postage stamp might hold up to 16 million separate elements.[2] While this increase in capac-

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ity would probably, by itself, have promoted strong output and demand growth, its effects were intensified by the industry's ability to supply large numbers of chips and by declining unit prices.

Prior to the late 1960's, the semiconductor industry focused on manufacturing customized integrated circuits for computer manufacturers and the military.[3] Limited production runs meant that development, overhead, and labor costs were spread over a small number of chips, and unit prices tended to be relatively high. In addition, chips designed for one purpose could not be readily adapted for another. With the introduction of the first high-capacity standardized memory chip in the late 1960's, emphasis was increasingly placed on both enlarging chip capacity and quickly attaining mass production status. Peak production (in terms of hundreds of millions of chips) typically occurred about 3 years after the first prototypes of a new chip generation were introduced. High production levels then tapered off as the next generation of chips entered the mass production stage.[4]

When a new generation of integrated circuits was introduced, individual unit prices were much higher than for the previous generation. As firms gained manufacturing experience, unit prices typically fell by 30 percent with each doubling of production.[5] Not only were unit prices eventually lower than the previous generation's, but, because the improved devices contained more elements, the cost per electronic function also declined. For example, the cost for a bit of memory (a single piece of information such as a letter or digit) dropped from just under 1 cent in 1973 to around one-thousandth of a cent in 1986.[6]

During the 1970's, the combination of declining unit prices, higher capacity devices, and standardized products led to explosive growth in demand for integrated circuits because of substantial upgrading of existing computer hardware and military equipment. Demand was further spurred by the development of new products, such as video games and watches, and the replacement of mechanical controls by solid state electronic devices in a wide variety of products ranging from refrigerators and thermostats to automobiles and industrial equipment. In 1968, 50 percent of total semiconductor output was used in military applications, computer manufacturing absorbed 30 percent, and consumer and industrial goods, 20 percent.[7] By 1979, military use accounted for only 10 percent of total semiconductor output; computers, 30 percent; and industrial and consumer goods, 60 percent.

While improved circuits were still being introduced and unit prices continued to decline during the first half of the 1980's, a slackening of growth in computer manufacturing and increased foreign competition retarded demand for and output of U.S. manufactured semiconductor devices. In the 1970's, for example, U.S. companies supplied about 60 percent of world demand for semiconductor devices; by 1985, their share had shrunk to 45 percent, while the market share held by Japanese firms had increased from 25 percent to 40 percent.[8]

Within these long-term trends, year-to-year movements in output and employee hours also reflected general business activity but were usually more volatile—as illustrated by the almost 30-percent output decline in 1975 and the 60-percent increase in 1976. (See table 1.) Such large year-to-year changes stem from a number of causes. When the demand for electronic equipment and products declines, manufacturers reduce their purchases of semiconductor devices to a much larger extent than they reduce production of finished electronic goods, resulting in inventory depletion.[9] As demand recovers, they often double or triple their orders for semiconductors to ensure delivery and rebuild inventories. Such rebounds occasionally coincide with the commercial introduction of a new chip generation—as in 1976, when 4K memory chips (containing 4,000 memory bits) first became available in large quantities and at low unit prices. When that happens, electronic goods manufacturers not only increase their orders for older generation chips but also place large orders for improved chips.[10]

Yield ratios. The basic building block of integrated circuits is a flat wafer (disc) of silicon on which large numbers of individual discrete devices, such as transistors, are imprinted. A key factor in increasing output per employee hour is the ability to increase the number of usable devices on a wafer. The same amounts of material and production worker labor used to produce a wafer yielding a small number of good chips are needed to produce a wafer yielding a larger number of good chips. As the yield of good chips improves—typically from an initial low of 5 percent or less to around 60–70 percent—unit prices decline because output dramatically increases.[11]

Table 1. Productivity and related indexes for the semiconductor industry, 1972–1986
[1977=100]

Year	Output per employee hour	Output	All employee hours	Employees
1972	46.3	36.4	78.7	78.1
1973	53.6	51.0	95.2	94.8
1974	64.1	63.5	99.0	100.5
1975	56.0	45.8	81.8	82.5
1976	82.5	72.4	87.8	88.0
1977	100.0	100.0	100.0	100.0
1978	120.5	139.0	115.4	114.5
1979	138.1	190.4	137.9	136.3
1980	149.4	226.1	151.3	151.5
1981	171.6	260.5	151.8	151.7
1982	197.9	301.2	152.2	153.0
1983	211.5	339.9	160.7	159.3
1984	229.2	432.5	188.7	185.6
1985	206.1	392.3	190.3	189.4
1986	218.4	399.4	182.9	181.4
	Average annual rates of change			
1972–81	16.6	25.4	7.5	7.5
1981–86	4.1	9.5	5.2	4.9

Achieving high yield ratios, however, is not an easy task and depends more on the refining of manufacturing processes than on the gaining of experience by production workers (let alone on differences in material inputs).[12] Attaining acceptable yield ratios using standard production processes requires coordinating and adjusting hundreds of separate manufacturing stages, some of which involve new machinery and techniques, because processes used in research and development are not directly transferable to regular production lines.[13] This effort initially requires large amounts of skilled engineering and technical employee hours, but as yield ratios improve, these requirements ease and production labor inputs per good chip also decline.[14]

Although this process is repeated for each new generation of integrated circuits, recent advances in computer-assisted and computer-integrated manufacturing techniques have lessened the time required to achieve acceptable yield ratios as well as the cost associated with small runs of customized chips.[15]

Employment and hours. Between 1972 and 1986, employment in the semiconductor industry more than doubled, from 115,000 to 268,000 workers. Overall, employment increased at an average annual rate of 6.8 percent during this period, compared with a 0.2-percent decline for all manufacturing industries combined. Average weekly hours of semiconductor production workers, however, were similar to those of their counterparts in all manufacturing—about 40 hours per week. Overtime hours for both groups also were almost identical, averaging about 3 hours per week.

Paralleling annual average rates of change in employee hours, semiconductor employment gains were also higher in the 1972–81 period (7.5 percent) than in the 1981–86 period (4.9 percent), although increasing circuit complexity necessitated more design work and more complex manufacturing techniques—just as circuit density doubles every 2 years, it has also been estimated that design costs increase almost as rapidly.[16] This trend was mitigated, however, by the increasing use of computer-aided design and computer-integrated manufacturing systems as well as the introduction of more highly automated production machinery and process.[17]

During the 1972–86 period, the rate of increase in the number of nonproduction workers (8.7 percent a year) was almost twice as large as the rate for production workers (4.6 percent). This disparity partially reflected the rapid pace of product innovation within the industry. Regardless of year-to-year fluctuations in demand and output, semiconductor firms maintain large research and development staffs of engineers and computer specialists designing the next generation of integrated circuits. Year-to-year changes in production worker employment more closely follow yearly changes in output. In 1985, for example, output declined by 9.3 percent and production worker employment fell by 8.1 percent. Nonproduction employment, however, increased by almost 10 percent.

Occupational structure

Considering the highly technical nature of semiconductor devices and the emphasis placed on rapid innovation, it is not surprising that the industry's work force mainly consists of engineers, computer programmers, and other technical workers. With the increasing complexity of chips and manfacturing processes, the proportion of employees classified as nonproduction workers has also increased—from around 40 percent in the 1960's to 50 percent in the 1970's and 60 percent in the early 1980's. Production workers accounted for only two-fifths of the total work force during the 1980's—a much lower proportion than for manufacturing, in which about two-thirds of all employees are production workers. Semiconductor assemblers, testers, and inspectors represent the largest production occupations. Predominantly consisting of women, these occupations make up about one-half of total production employment.[18]

Just as increasing product complexity has changed the broad occupational structure of the semiconductor industry, it has also affected the composition of the production work force. Each succeeding product generation has called for more sophisticated manufacturing techniques and equipment, which, while obviating the need for low-skilled manual production workers, has raised the demand for higher skilled technicians and machine operators.[19] This shift is also reflected in average production worker earnings. As more of the production work force consisted of relatively high-paid technicians and machine operators, average production worker earnings rose from 10 percent below the all-manufacturing average in 1972 to parity in 1985.

Industry structure

Although the number of semiconductor firms more than doubled between 1972 and 1985—from 325 to 766—the industry remained highly concentrated. Establishments employing 1,000 workers or more have continually accounted for about two-thirds of total employment and industry shipments, even through they represent only about 5 percent of the total number of establishments in the industry. The relatively low proportion of employment and shipments accounted for by smaller sized establishments, however, belies their importance. Traditionally, these firms have developed a disproportionate number of product improvements and manufacturing innovations.[20]

The industry relies mainly on outside suppliers to provide it with the basic materials used to produce semiconductors, such as silicon crystals, metals, chemicals, ceramics, and plastics. The highly specialized machinery used in manufacturing integrated circuits is mainly supplied by outside firms, which in many instances, have initiated innovations in materials or machinery which subsequently led to improvements in semiconductor products.[21] In recent years there has been increasing collaboration between semiconductor manufacturers and their customers as the industry shifted back towards producing semicustomized and customized chips.[22]

The early 1980's witnessed an increase in the number of firms specializing in specific areas of semiconductor production, such as designing integrated circuits or stages of the manufacturing process.[23] Given the large increase in the cost of an average semiconductor plant—from roughly $10 million in 1975 to $100 million in 1985—very few complete manufacturing facilities have been built in recent years.[24] Large semiconductor companies, however, typically construct complete facilities encompassing all stages of semiconductor manufacturing, from design to testing.

California accounts for about one-third of total semiconductor employment and shipments. Other major centers are located in Arizona, New York, Massachusetts, and Texas.

Capital expenditures. Between 1972 and 1985, semiconductor capital expenditures grew at an average annual rate of 22.5 percent or about 7 times faster than the rate for all manufacturing combined (3.3 percent per year). In most years, about four-fifths of total capital investment is spent for new machinery rather than for buildings. The torrid pace of capital expenditure mainly reflects the rapid obsolescence of production machinery—the average useful life of equipment in the industry is between 3 and 5 years. Each chip generation typically requires new production equipment or major upgrading of existing equipment to cope with the smaller element sizes of the improved circuits.[25]

Total capital expenditures of the semiconductor industry rose in constant dollar terms[26] from $453 million in 1972 to $2,832 million in 1985. Constant-dollar expenditures per worker have also been consistently higher than for all manufacturing. In 1985, for example, they ran 3½ times higher for semiconductor employees ($14,872) than for all manufacturing employees ($4,429).

Despite high levels of capital investments, the semiconductor industry is still one of the most highly labor intensive of any manufacturing industry, mainly attributable to the complexity of the batch production process employed by the industry and the production adjustments needed to produce new generations of chips.[27]

Semiconductor capital expenditures, of course, varied from year to year, mainly reflecting changing business conditions, product life cycles, and industry expectations. Between 1972 and 1985, more than half of the year-to-year changes fluctuated by 33 percent or more.

Research and development. The semiconductor industry is one of the most research and development oriented sectors in U.S. manufacturing. In 1977, for example, the industry spent 24.9 percent of sales on research and development, compared with 3.1 percent of sales for all manufacturing industries combined.[28] The relatively high output and productivity gains registered by the semiconductor industry reflect the success of these research and development efforts because product improvements have spurred demand, and manufacturing innovations largely stem from in-house research and development efforts.[29]

Manufacturing techniques and technologies

There are four major stages in semiconductor production—design, imprinting, assembling, and testing. Given the close-knit nature of the semiconductor manufacturing process, however, the separate contributions of improvements in each of these areas to overall industry productivity cannot be measured precisely.

In the design phase, engineers draw a series of integrated circuit blueprints. Because the ability to design products quickly both spurs the demand for new generations of semiconductors and makes semicustomized chips more economical,[30] the industry has continually increased its use of computer-assisted design and engineering systems. Productivity advances stemming from the use of these systems may be either constrained or hastened by changes in the manufacturing process. On the one hand, designs may have to be substantially modified because of manufacturing limitations while, on the other hand, advances in manufacturing techniques or materials may compel major changes in design parameters.[31]

After the design phase, devices are manufactured by imprinting silicon wafers with layers of circuitry. First, blueprints are reduced to the actual size of the device and turned into stencils. A stepping machine then duplicates a single stencil repeatedly until a master mask consisting of 400 to 600 identical chip stencils is created.[32] Next, a variation of photolithography is used to transfer these mask patterns onto silicon wafers. A wafer is first coated with a thin film of electrically conductive material and then with a layer of photosensitive material that hardens on contact with light. Shining light through the master stencil onto the wafer creates patterns in this top layer. Various solvents are then used to dissolve the soft parts, leaving a tracery of conductive material. This process is repeated again and again, eventually creating hundreds of identical chips on a single silicon wafer.

The basic manufacturing technique used to imprint wafers is batch processing. A group of silicon wafers is moved through a series of work stations. At each station, the wafers undergo specific imprinting processes before they are moved to the next station. With hundreds of processing stations involved, semiconductor manufacturing is one of the most complex production processes ever adapted to mass production.[33]

As chip complexity and density have increased over the years—with the size of electrical pathways shrinking to the tens of thousandths of a human hair's width—imprinting machinery has also become more complex. Today's equipment employs x-rays, lasers, and electronic beams in addition to the traditional photolithography techniques. Each generation of this equipment, however, presents unique production problems in that procedures developed for one generation are usually not applicable to its successor. Techniques, for example, used to adjust photolithography machinery to produce the maximum number of good chips are not useful in adjusting laser machinery.[34]

Besides adjusting machinery to achieve acceptable yield ratios—as mentioned, initial yields are as low as 5 percent or less—the imprinting process also involves adjusting various chemical reactions, such as solvents and reaction times, and maintaining or improving the manufacturing environment as a whole. To minimize the number of defective chips caused by dust particles, for example, imprinting is done in special "clean" rooms in which the air has been purified 100 times cleaner than hospital operating rooms or 10,000 times cleaner than typical office air.[35]

Imprinted wafers are usually air freighted to offshore plants for final assembly and testing work. In these plants, typically owned by the same company that designed and imprinted the chips, each good chip has small wires attached to its edges so it can carry electrical current. The wired chips are then encapsulated into plastic or ceramic cases and shipped back to the parent company for final testing and sale.[36] In recent years, the introduction of automated wiring and encapsulating machinery has made for a return of this assembly work to the United States as the amount of manual labor required has deceased.[37] In the 1970's, for example, a worker could wire about 120 chips per hour, compared to 5,120 per hour using the machinery of the 1980's.

Outlook

While semiconductor output and demand have recovered from the 1985 downturn—with output increasing 1.8 percent in 1986[38]—the long-term outlook for the industry hinges on a number of more fundamental factors than cyclical business movements. The continued development of improved generations of integrated circuits coupled with improvements in manufacturing techniques offers two (not mutually exclusive) paths to follow—the mass production of improved standardized products, such as 4 megabit or larger memory chips and concentration on producing customized chips for individual customers. To confront the challenge of mass production, a consortium of semiconductor companies is constructing a factory to test manufacturing techniques for the latest generations of semiconductor devices.[39] To economically produce customized devices, many companies, especially small startup firms, are focusing their efforts on developing computer-assisted and computer-integrated manufacturing and design processes.[40] For the industry overall, however, the key to continued productivity gains will still mainly lie with the industry's ability to turn laboratory innovations quickly into marketable products—especially considering the wide array of future semiconductor materials and devices currently on the drawing boards, such as superconducting compounds, holographic laser cubes, organic memory devices, silicon micromechanical devices, and three-dimensional quantum well devices.[41] □

FOOTNOTES

[1] The semiconductor industry is designated as SIC 3674 by the 1982 *Standard Industrial Classification Manual* of the Office of Management and Budget. This industry consists of establishments primarily engaged in manufacturing semiconductors and related solid state devices, such as semiconductor diodes and stacks, including rectifiers, integrated microcircuits (semiconductor networks), transistors, solar cells, and light sensing and emitting semiconductor (solid state) devices.

Average annual rates of change are based on the linear least squares of the logarithms of the index numbers. Extensions of the indexes will appear in the annual Bureau of Labor Statistics bulletin, *Productivity Measures for Selected Industries*.

[2] Andrew Pollack, "Japanese Chip Breakthrough," *The New York Times*, Feb. 5, 1987, p. D6; and Albert J. Blodgeet, Jr., "Microelectronic Packaging," *Scientific American*, July 1983, p. 84.

According to some projections, a billion element chip can be achieved, although limits imposed by fabrication processes may affect the time required to reach this level of density. See James D. Meindl, "Chips for Advanced Computing," *Scientific American*, October 1987, pp. 78–88.

[3] Robert W. Wilson, Peter K. Ashton, and Thomas P. Egan, *Innovation, Competition, and Government Policy in the Semiconductor Industry* (Lexington, MA, Lexington Books, 1980), pp. 86–89; and industry sources.

[4] U.S. Department of Commerce, *A Report on the U.S. Semiconductor Industry*, September 1979, pp. 45–48; and industry sources.

[5] W. J. Sanders, *Competitive Factors Influencing World Trade in Semiconductors*, Statement before the Subcommittee on Trade, Committee on Ways and Means, U.S. House of Representatives, Nov. 30, 1979, Serial 96–92, pp. 53–54; and industry sources.

While improvements in manufacturing techniques and processes are the major impetus behind declining unit prices, other factors, such as industry capacity and foreign competition, also play a role. In the early 1980's, for example, semiconductor manufacturers, both foreign and domestic, increased their manufacturing capacity in anticipation of 30- to 50-percent annual sales growth. When this growth did not materialize, the resulting surplus of chips triggered sharp unit price declines even though the preferred capacity utilization rate of domestic manufacturers fell from 83 percent in 1983 to 69 percent in 1985. See Stephan Koepp, "Feeling the Crunch from Foreign Chips," *The Wall Street Journal*, Oct. 27, 1986, pp. 72–73; Michael W. Miller, "Microchip Firms in U.S. Yielding a Major Market," *The Wall Street Journal*, June 5, 1985, p. 34; and, *Survey of Plant Capacity, 1985*, Current Industrial Reports, MQ-C(85)-1 (Bureau of the Census, November 1986), p. 8.

[6] Wilson and others, *Innovation, Competition, and Government Policy in the Semiconductor Industry*, p. 35.

[7] *Ibid*, p. 19; and U.S. Department of Commerce, *A Report on the U.S. Semiconductor Industry*, p. 8.

Although the military's consumption of semiconductor devices is lessening in proportion to that of other users, the Department of Defense still plays a significant role in the development of new technologies and products. Beginning in the early 1960's, when the Air Force funded the development of integrated circuits for the Minuteman missile guidance system, the military has continued to support the semiconductor industry directly through research and development contracts and indirectly through product purchases. In 1979, for example, the Defense Department funded a program to develop very high speed integrated circuits that involved nearly every major semiconductor manufacturer. By 1984, the program was beginning to yield results in the form of improved integrated circuits, manufacturing techniques, and processes. While national security considerations constrain the immediate commercial applications of these advances, they eventually do occur.

See *Aviation Week and Space Technology*, July 30, 1984, "New Circuits Expected to Exceed," pp. 46–51; "Honeywell Plans to Supply Samples

Early Next Year," pp. 52–60; "Hughes Chip Sets Supports Signal Processing Needs," pp. 61–63; "Texas Instruments Seeks Commonality," pp. 64–65; and John Paul Newport, Jr., "A Supercomputer on a Single Chip," *Fortune*, Sept. 29, 1986, pp. 128–29.

[8] Wilton Woods, "How Chipmakers Survive," *Fortune*, Apr. 13, 1987, pp. 89–92; and industry sources.

This breakdown of world market shares does not reflect the production of "captive" semiconductor establishments who manufacture semiconductors mainly for use in-house as contrasted to merchant firms who produce for the general market. In 1981, it was estimated that the combined production of the two largest "captive" producers—AT&T and IBM—amounted to about 25 percent of total semiconductor production as reported by the Department of Commerce. See Wilson and others, *Innovation*, p. 8.

[9] Douglas A. Webbink, *The Semiconductor Industry: A Survey of Structure, Conduct, and Performance*, Staff Report to the Federal Trade Commission, January 1977, pp. 117–19; and industry sources.

[10] U.S. Department of Commerce, *A Report on the U.S. Semiconductor Industry*, p. 43; and industry sources.

[11] Industry sources.

[12] Grunwald and Flamm, *The Global Factory* (Washington, The Brookings Institution, 1985), pp. 53–54; and industry sources.

[13] Industry sources.

[14] U.S. Department of Commerce, *A Report on the U.S. Semiconductor Industry*, pp. 17–18; Wilson and other others, *Innovation, Competition, and Government Policy in the Semiconductor Industry*, p. 33; and industry sources.

[15] Industry sources.

[16] "Toward the Silicon Foundry," *Scientific American*, February 1983, pp. 82–83; and industry sources.

[17] U.S. Department of Commerce, *A Report on the U.S. Semiconductor Industry*, pp. 23–26; "Automated Semiconductor Line Speeds Custom Chip Production," *Electronics*, Jan. 27, 1981, pp. 121–27; and industry sources.

The relatively recent introduction of automated production equipment and processes may seem a bit odd considering the high-tech nature of the industry. The tardiness reflects the past reluctance of the industry to invest in expensive automated assembly lines that would soon be made obsolete by continuing product improvements. During the 1960's, for example, there were many cases of firms' building highly automated facilities only to find them quickly outmoded, in some cases even before completion, because these facilities were not adaptable to producing later generations of semiconductor devices. See Grunwald and Flamm, *Global Factory*, pp. 69–70; and industry sources.

[18] Mark Sieling, *Industry Wage Survey: Semiconductors, September 1977*, Bulletin 2021 (Bureau of Labor Statistics, April 1979).

[19] John A. Alic and Martha C. Harris, "Employment lessons from the electronics industry," *Monthly Labor Review*, February 1986, pp. 32–34.

[20] Wilson and others, *Innovation, Competition, and Government Policy in the Semiconductor Industry*, pp. 13–18; U.S. Department of Commerce, *A Report on the U.S. Semiconductor Industry*, pp. 10–13; and industry sources.

[21] U.S. Department of Commerce, *A Report on the U.S. Semiconductor Industry*, p. 19.

[22] John W. Wilson, "U.S. Chipmakers Are Learning to Cope," *Business Week*, Jan. 12, 1987, p. 92; Thomas C. Hayes, "Texas Instruments vs. Japan," *The New York Times*, July 1, 1987, p. D1; and industry sources.

Within the semiconductor industry, there have been occasional attempts to manufacture finished electronic goods which incorporate integrated circuits (vertical integration). In the early 1970's, for example, about 50 large semiconductor firms started to produce personal calculators and watches. By the late 1970's, however, most had abandoned these efforts in the face of declining prices for these products—ironically brought on, in large part, by the declining unit prices of semiconductors devices themselves. (Between 1974 and 1975, average prices for electronic calculators fell from $30 apiece to $6—mainly reflecting lower unit prices for their semiconductor innards.) At the height of this movement by the industry into consumer electronic products (1974), secondary products accounted for about one-fifth of total industry shipments. By 1975, they amounted to only 10 percent.

Very few electronic goods manufacturers, however, have attempted to produce semiconductor devices in the face of relatively large investment requirements and the complex nature of the product. See Wilson and others, *Innovations, Competition, and Government Policy in the Semiconductor Industry*, pp. 25–36, 98–101; and industry sources.

[23] Otis Port, "For Chipmakers, National Boundaries Begin to Blur," *Business Week*, May 6, 1985, p. 110; Peter H. Singer, "The Semiconductor Revolution," *Semiconductor International*, February 1986, p. 86; and industry sources.

[24] Industry sources.

[25] Grunwald and Flamm, *Global Factory*, p. 52; and industry sources.

The swift replacement of semiconductor production machinery also results in a smaller total cumulative working capital investment than is found in most other manufacturing industries whose yearly capital expenditures mainly add to an already large base of relatively long-lived machinery. In 1985, for example, the semiconductor industry produced goods worth $5.82 for each new dollar of capital expenditures while the overall manufacturing sector produced goods worth $27.38.

It is worth noting that innovations in production equipment occasionally led innovations in integrated circuits. For example, polysilicon deposition made metal oxide silicon dynamic random-access memories feasible. See Wilson and others, *Innovation, Competition, and Government Policy in the Semiconductor Industry*, pp. 38–41.

[26] Adjustments for price changes were made by using the implicit deflator for nonresidental investment in structures and producers' durable equipment. See *Economic Report of the President*, January 1987, p. 236.

[27] Grunwald and Flamm, *Global Factory*, pp. 51–53; and industry sources.

In 1976, a million dollars' worth of semiconductor devices required 54 employee years of labor inputs to produce, in contrast to 9 employee years for a similar amount of motor vehicles and 23 employee years for computers.

[28] National Science Foundation, *Science Indicators* (U.S. Government Printing Office, 1979).

[29] Of course, not all inventions springing from the industry's research and development efforts result in successful products or manufacturing innovations. In fact, a large number of such inventions have not been commercially viable. See Wilson and others, *Innovations, Competition, and Government Policy in the Semiconductor Industry*, pp. 56–62; and industry sources.

[30] Robert Neff, "The River Boat Gamblers of the Chip Business," *Business Week*, Dec. 15, 1986, pp. 96–98; "New Service Cuts the Cost of Making Just A Few Chips," *Industry Week*, Sept. 29, 1986, p. 36; and industry sources.

While not matching the gains cited in these articles of between an eight- and tenfold improvement in the costs and time associated with transferring prototypes into devices capable of being mass produced, many semiconductor companies have experienced significant improvements attributable to computer-assisted design techniques.

[31] Industry sources.

[32] Everett M. Rogers and Judith K. Larsen, *Silicon Valley Fever—Growth of High Technology Culture* (New York, Basic Books, 1984), pp. 111–18.

[33] U.S. Department of Commerce, *A Report on the U.S. Semiconductor Industry*, p. 17; and industry sources.

[34] Industry sources.

[35] Rogers and Larsen, *Silicon Valley Fever—Growth of High Technology Culture*, p. 112.

[36] William F. Finan, *The International Transfer of Semiconductor Technology Through U.S.-Based Firms*, Working Paper 118 (Cambridge, MA, National Bureau of Economic Research, December 1975), pp. 18–19; and industry sources.

[37] Steven P. Galante, "U.S. Semiconductor Firms Automate, Cut Chip Production in Southeast Asia," *The Wall Street Journal*, Aug. 21, 1985, p. 28; and industry sources.

[38] Andrew Pollack, "More Chips Expected From Japan Demand Rises in America; Shortage Seen," *The New York Times*, June 22, 1987, p. D1; and David E. Sanger, "U.S. Chip Makers Recovering," *The New York Times*, May 26, 1987, p. D16.

[39] *Defense Semiconductor Dependency*, Report of Defense Science Board Task Force, as excerpted in *Manufacturing Productivity Frontiers*, April 1987, pp. 1–12.

[40] U.S. Department of Commerce, International Trade Administration, *U.S. Industrial Outlook 1987*, January 1987, pp. 32–1—32–6.

[41] Yasar S. Abu-Mostafa and Demetri Psaltis, "Optical Neural Computers," *Scientific American*, March 1987, pp. 88–95; Klaus Bechgaard and Denis Jerome, "Organic Superconductors," July 1982, pp. 72–84; James B. Angell, Stephen C. Terry, and Phillip W. Barth, "Silicon Micromechanical Devices," April 1983, pp. 44–55; and James D. Meindl, "Advanced Computing."

APPENDIX: Measurement techniques and limitations

Indexes of output per employee hour measure changes in the relationship between the output of an industry and employee hours expended on that output. An index of output per employee hour is derived by dividing an index of output by an index of industry employee hours.

The preferred output index for manufacturing industries would be obtained from data on quantities of the various goods produced by the industry, each weighted (multiplied) by the employee hours required to produce one unit of each good in some specified base period. Thus, those goods which require more labor time to produce are given more importance in the index.

In the absence of physical quantity data, the output indexes for the semiconductor industry were constructed using a deflated value technique. The value of shipments of the various product classes was adjusted for price changes by appropriate Producer Price Indexes to derive real output measures. These, in turn, were combined with employee hour weights to derive the overall output measure. These procedures result in a final output index that is conceptually close to the preferred output measure.

The indexes of output per employee hour relate total output to one input—labor time. The indexes do not measure the specific contributions of labor, capital, or any other single factor. Rather, they reflect the joint effect of factors such as changes in technology, capital investment, capacity utilization, plant design and layout, skill and effort of the work force, managerial ability, and labor-management relations.