Chapter 9

Technology and Industry

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Importance of Information Technology

Information technology and the industries that advance and use its products are becoming increasingly important to America's economic strength. Information technology is a core technology, contributing broadly to the Nation's trade balance, employment, and national security. The information sector already accounts for between 18 and 25 percent of the gross national products of seven of the member nations of the Organization for Economic Cooperation and Development (OECD) and between 27 and 41 percent of employment in these countries.[1 2]

An important characteristic of this technology is the rapidity with which research results are translated into "advanced" products and from there to the mainstream consumer marketplace. This rapid transfer has been particularly evident in semiconductor research leading to cheaper and more powerful microprocessors.

Given the accelerated movement from the research laboratories to a worldwide marketplace, it is natural that the attention of the trading nations has focused on information technology research and development (R&D). Two basic building blocks of information technology are:

- the microelectronic chip-the large scale integrated circuit that permits the storage, rapid retrieval and manipulation of vast amounts of information, and
- software-the sets of instruction that direct the computer in its tasks.[3]

As noted in chapter 2, there is no consensus on what composes the "information technology industry." Because of the varying definitions and the differing statistical analyses arising from them, it is impossible to pin down the size of the industry. A relatively conservative estimate, discussed later in this chapter, places the annual sales of the U.S. industry at over two hundred billion annually and growing. From another perspective: over one-half million jobs depend on computer industry exports.[4]

Findings

In examining the composition of information technology, the characteristics of the U.S. industry, and where the technology is heading, several trends become apparent:

1. The U. S. information technology industry is large and growing rapidly; there is a world market for its products and services as the developed countries increasingly move into the information age.
2. The technology is pervasive, making possible major productivity improvements in other fields, creating new industries, and enlarging the range of services available to the public. The technology diffuses through most facets of life, including business, engineering and science, and government functions.
3. With each level of technological advance in basic information technology, the level of complexity and cost increases for R&D, as does the demand for additional technical training for R&D personnel.

[1] *Information Activities, Electronics and Telecommunications Technologies: Impacts on Employment, Growth and Trade* (OECD, Paris, 1981), pp. 22 and 24.
[2] M. R. Rubin, *Information Economics and Policy in the United States,* Libraries Unlimited, Littleton, CO, 1983, pp. 32-44.
[3] Software may also refer to the stored information.

[4] Robert G, Atkins, *The Computer Industry and International Trade: A Summary of the U.S. Role,* Information Processes Group, Institute for Computer Sciences and Technology, National Bureau of Standards, December 1983, p. IX-1. Draft of a report under joint development by ICST and the International Trade Administration, as of February 1985.

4. Domestic and foreign competition for world markets is both intensive and escalating. The stakes for the United States are great in terms of corporate sales and competitive ness in world markets, and employment.
5. There will be continued rapid advances in the capabilities of the industry's underlying basic building blocks, microelectronics and software.

Composition of Information Technology

Individual information technologies have grown explosively in technical sophistication and, at the same time, diminished in cost. That rare combination has propelled the new technologies into the mass marketplace. As the two basic building blocks continue their advances, the parade of new information technology capabilities and applications will go on.

There is a recurrent pattern in which one technological advance makes possible still other advances, often in a "bootstrap" fashion. For example, sophisticated computer-aided design (CAD) equipment is a tool used in development of state-of-the-art random access memories and microprocessors; development of the next generation of super-computers depends on use of today's most advanced computers; "expert" systems— still in their technological infancy-are already employed in configuring complex computer systems and custom-designing integrated circuits.

Functions

For purposes of this report, the term "information technology" has been used to refer to the cluster of technologies that provide the following automated capabilities:

1. Data Collection. Examples of automated data collection systems range from large-scale satellite remote-sensing systems such as weather satellites to medical applications such as CAT-scans and electrocardiograms.
2. Data Input. Input devices include the familiar keyboard, optical character readers, video cameras, and so on. They are the means by which data are inserted and stored, communicated, or processed.
3. Information Storage. The storage media associated with the information industry are the electronic-based devices which store data in a form which can be read by a computer. They include film, magnetic tape, floppy and hard disks, semiconductor memories, and so on. The ability to store increasingly vast amounts of data has been essential to the information technology revolution.
4. Information Processing. Information processing is the primary function of a computer. The information stored by a computer can be numeric (used for computations), symbolic (rules of logic used for applications such as "expert" systems), or image (pictorial representations used in applications such as remote mapping). The stored information–in whatever form—is manipulated, or processed, in response to specific instructions (usually encoded in the software). The increasing speed of information processing has been another essential factor in the information technology revolution.
5. Communications. Electronic communications utilizes a variety of media-the air waves (for broadcast radio and television), coaxial cable, paired copper wire (used, among other things, for traditional telephony), digital radio, optical fibers, and communications satellites. Communications systems play a major role in broadening the use of other facets of information technology and make possible distributed computing, remote delivery of services, and electronic navigation systems, among many other applications.
6. Information Presentation. Once the information has been sent, it must be "pre-

sented" if it is to be useful. This can be accomplished through a variety of output devices. The most common display technology is the cathode ray tube or video display terminal. Hard-copy output devices include the most commonly used impact printers as well as those using non-impact technologies such as ink-jet and xerography. There are also audio systems that permit the computer to "speak"-exemplified by the automobiles that admonish you to fasten your seat belts.

Table 50 shows some of the technologies and application areas that depend on these functions.

Examples of System Applications

A few examples of the many information technology applications are provided below. They have been chosen to illustrate the diversity of applications, and in most cases reflect capabilities that have only become feasible on a significant scale in recent years. The examples include: cellular mobile radio commu-

table 50.—Functions, Applications, and Technologies"

Function	Typical application area[a]	Representative information technology
Data collection	Weather prediction	Radar, infra-red object detection equipment, radiometers
	Medical diagnosis	CAT-scanners, ultrasonic cameras
Data input	Word processing	Keyboards, touch-screens
	Factory automation	Voice recognizes (particularly for quality control)
	Mail sorting	Optical character readers
Storage	Archives	Magnetic bubble devices, magnetic tape
	Accounting systems	Floppy disks
	Scientific computation	Wafer-scale semiconductors (still in research phase), very-high-speed magnetic cores
	Ecological mapping	Charge-coupled semiconductor devices, video disks
	Libraries	Hard disks
Information processing	Social Security payments	General purpose "mainframe" computers, COBOL programs
	Traffic control	Minicomputers
	Distributed inventory control	Multi-user super-micros, application software packages
	Medical diagnoses	"Expert" systems
	Engineering design	Spreadsheet application packages, microcomputers
	Scientific computation	Supercomputers: multiple instruction-multiple data (MI MD) processors, vector processors, data driven processors, FORTRAN programs
	Ecological mapping	Array processors, associative processors
	Factory automation	Robotics, **artificial intelligence**
Communications	Office systems	Local **area networks, private branch exchanges** (PBX), editor applications packages
	Teleconferencing	Communications satellites, fiber optics
	Rescue vehicle dispatch	Cellular mobile radios
	International financial transactions	Transport protocols, data encryption, Integrated Services Digital Networks (ISDN)
Data output and presentation	Word processing	Personal computers, printers (impact, ink jet, xerographic)
	Management information	Cathode ray tubes, computer graphics
	Pedestrian traffic control	Voice synthesizers

[a]This list is not exhaustive; any given technology may also be used for some of the other applications mentioned.

SOURCE: Office of Technology Assessment.

nications, direct broadcast satellites, robotics, computer simulation, a biomedical application in heart pacemakers, and financial services.

Cellular Mobile Radio Communications

For decades, use of mobile telephone service has been limited by over-crowding of the electromagnetic spectrum; major cities have had only some few hundred subscribers because of spectrum constraints. Demand for additional mobile voice service has been growing at a 12 percent rate annually for the past 20 years. A new technology-cellular mobile radio communications—holds promise for vastly increasing the number of potential subscribers (to more than 100,000 in particular geographic areas),' while providing service of improved quality compared to that available previously. What is most significant about the cellular concept is that it permits conservation of the electromagnetic spectrum —a limited natural resource.

The older technology provided service from a single antenna to the area served. The cellular concept is based on dividing the service area into a number of geometric shapes, or cells, each served with its own antenna. The cell antennas are interconnected with leased telephone lines. When a vehicle leaves a cell, that cell passes control to the next cell, and so on. The number of subscribers is much greater with the cellular concept because the transmission frequencies can be reused repeatedly in nonadjacent cells. Thus the impact of increasing demands on the spectrum is minimized.

According to some estimates, cellular radio will be a $4 billion U.S. industry by 1990 and could reach $6 billion by the mid-1990s. Cellular mobile telephones recently cost about $3,000 but prices are likely to fall rapidly because of competition among vendors.

Other countries are also finding considerable demand for mobile radio services. In Japan, mobile telephone services are now available in Tokyo. In Spain, some 20,000 subscribers are anticipated by 1990. The Netherlands reached approximately 50,000 inhabitants by 1984. Saudi Arabia introduced cellular mobile radio communications in 1981 in three cities; by 1982, there were 19,000 subscribers, and the Saudis have now extended coverage to 32 cities.

Direct Broadcast Satellites

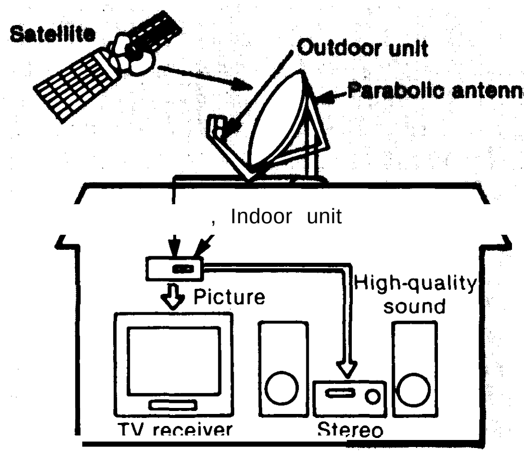
The use of direct broadcast satellites (DBS) has recently become feasible. With DBS, over-the-air signals (e.g., TV, radio) can be received directly by small rooftop antennas (see fig. 52). These new, commercial, geostationary systems may have widespread use in the United States and in other countries, primarily providing entertainment, but also with potential for education, advertising and other business uses. As of early 1985, nine applications had

Photo credit: Motorola

Mobile cellular radiotelephone

[5]**Operation of cellular mobile radio systems in dozens of U.S. cities has been approved by the Federal Communications Commission.**

Figure 52.—Direct Broadcasting Satellite System



been approved by the Federal Communications Commission (FCC) for subscription services to the public, some of which may become operational.

DBS services will compete with other media such as multiple distribution systems, STV (subscription TV), and cable TV (CATV) for serving television viewers. DBS services may prove especially valuable for providing service to sparsely populated geographical areas that are not economical to reach by other means, as well as to densely populated cities where new cable installations are prohibitively expensive.

Among the technical improvements that make DBS systems feasible are higher power and more efficient on-board power amplifiers; solar power generation equipment; more accurate satellite station-keeping control; improved ground receiver sensitivity; the use of higher frequencies; and better transmitter downlink beam control. Higher power and higher frequencies also make practical the use of small (about 1 meter or less) rooftop antennas. Some of the early U.S. experimental satellite communications systems, along with parallel advances in solid-state electronics and new materials processing techniques, have contributed significantly to the improvements in components and subsystems available today.

DBS systems had their genesis when NASA's ATS-6 satellite was launched in 1974—a system having a multiplicity of payloads, two of which included TV broadcast capabilities. A number of countries have DBS systems in place or in planning stages. Included among these are: Canada's medium-powered ANIK C-2, which is serving Canadian audiences as well as providing five channels of television entertainment to the Northeastern United States; Japan's modified BS-2 satellite, launched in early 1984; and France's TDF-1 and West Germany's TV-SAT, which are expected to be operational in 1986.

Robotics

Robots are mechanical manipulators which can be programmed to move workplaces or tools along various paths. They are one of the four tools employed in computer-aided manufacturing (i.e., robots, numerically controlled machine tools, flexible manufacturing systems, and automated materials handling systems).[6]

Robotics emerged as a distinct discipline when the century-old industrial engineering automation technologies converged with the more recent disciplines of computer science and artificial intelligence. The convergence produced the growing field of robotics, which has had wide factory applications in areas that include (but are not limited to) materials handling, machine loading/unloading, spray painting, welding, machining, and assembling. The robots are most often used in performing particularly hazardous and monotonous jobs while offering enough flexibility to be easily adapted to changes in product models.

Neither today's robots, nor those likely to be available in the next decade, look like humans nor do they have more than a fraction of the dexterity, flexibility, or intelligence of humans. A simple "pick and place" machine

[6]See *Computerized Manufacturing Automation: Employment, Education, and the Workplace* (Washington, DC: U.S. Congress, Office of Technology Assessment, OTA-CIT-235, April 1984.

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with two or three degrees of freedom may cost roughly between $5,000 and $30,000, while more complex programmable models, often equipped with microcomputers, begin at about $25,000 and may exceed $90,000.

Human workers, robots, and nonprogrammable automation devices each have certain characteristics which offer advantages for the manufacturing process. Table 51 compares some of the salient characteristics.

Table 51.—Characteristics of Human Workers, Robots, and Nonprogrammable Automation Devices[a]

Characteristic	Human Worker	Robot	Non programmable Automation Device
Flexibility	1	2	3
Consistency	3	2	1
Endurance	3	1-2	1-2
Ability to tolerate hostile environments	3	1-2	1-2
cost	n/a	2	1
Speed	2-3	2-3	1
Intelligence/ programmability	1	2	3
Sensing	1	2	3
Judgment	1	2	3
Ability to adapt to change	1	2	3
Dexterity	1	2	3

[a]Numerical ranking indicates relative advantage, With "l" Indicating the greatest advantage.

SOURCE: *Computerized Manufacturing Automation: Employment, Education, and the Workplace,* (Washington, DC: U.S. Congress, Office of Technology Assessment, 1964). This table was derived from the foregoing report

At the end of 1983 Japan had about 43,000 operating robot installations-by far the largest number in any country. The United States, where the original patents for robots were obtained, had about 9,400 installations (v. about 13,000 in early 1985 and 6,300 in 1982), followed by West Germany (4,800), and France (3,600). Some projections indicate that by 1990 there will bean installed base of nearly 90,000 robots in the United States. *

As reported by OTA[6a], significant robotics research is being conducted in over a dozen universities, about three dozen industrial firms and independent laboratories, and in Federal Government labs at the National Bureau of Standards (NBS), NASA, and DOD. The report further noted that the research was intensively addressing several problem areas: improved positioning and accuracy for the robot's arms; increased grace, dexterity, and speed; sensors, including vision, touch, and force; model-based control systems; software; mobility; voice recognition; artificial intelligence; and interface standards. The interface area is critical to widespread use of automated manufacturing. NBS has created an Automated Manufacturing Research facility in part to perform research on the interfaces between different computerized devices in a factory.

Computer Simulation

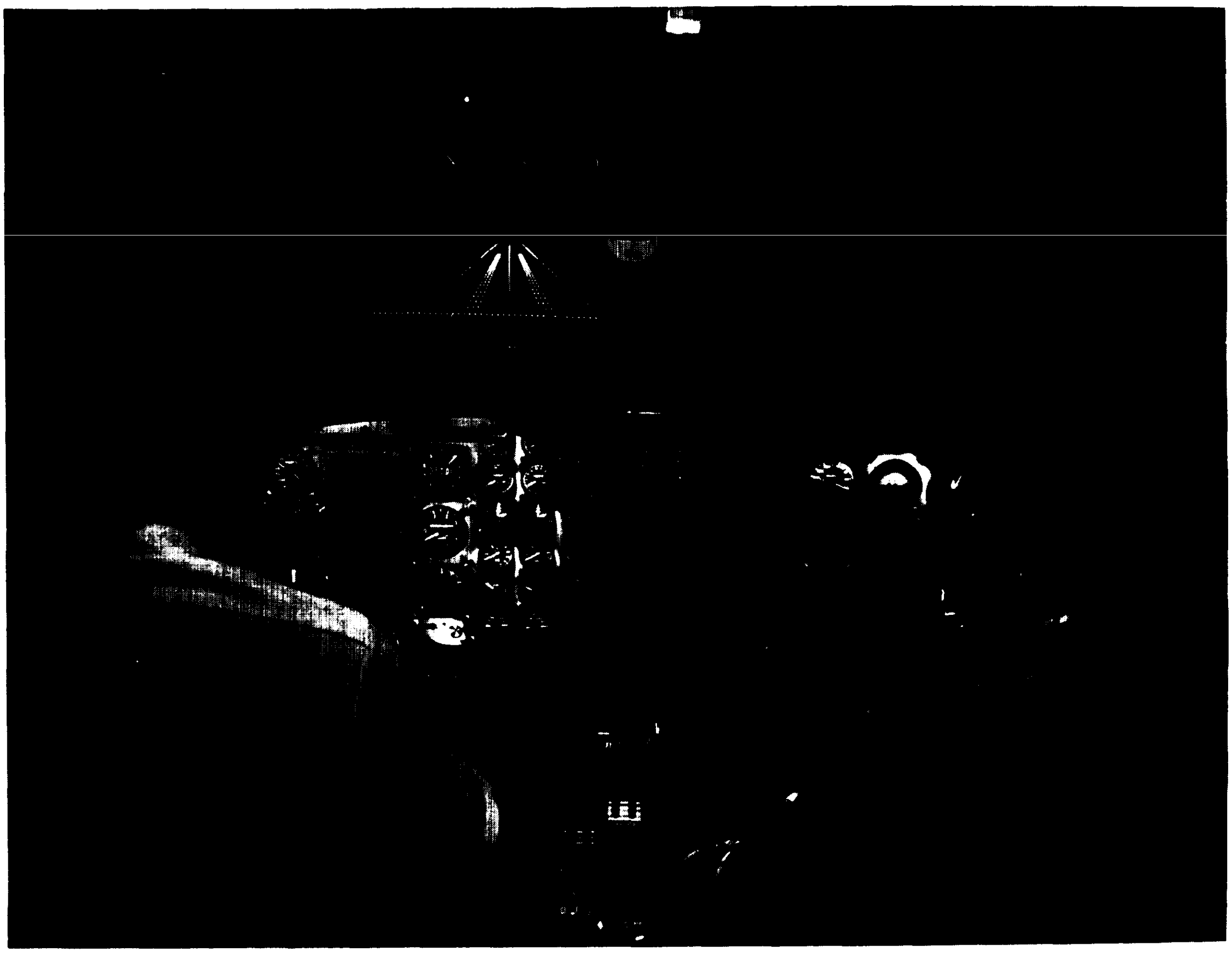
"Computer simulation" is a process that employs a computerized model of certain significant features of some physical or logical system which is undergoing dynamic change. We therefore find computers used in applications such as economic modeling and war games where "what if" scenarios can be played out to test suggested social policies or military strategies. As relatively inexpensive computer memories grow in size and integrated circuits grow in speed, increasingly complex operations are being modeled. Software advances have also played a large part in the growing use of computer simulations.

*Worldwide Robotics Survey and Directory, 1984, to be published, Robotics Industries Association, Dearborn, MI. This data is based on the RIA's definition for robots which excludes the simpler, nonreprogrammable machines.

[6a]*Computerized Manufacturing Automation: Employment, Education and the Workplace,* op. cit.

When combined with other information technologies, some startling simulations are possible. In flight simulators, for example, computer-generated imagery techniques are used to create background, images, sounds, and sensations, and to position discrete elements in a scene—elements which have been obtained from video images of real trees, buildings, clouds, aircraft, and other characteristics of the environment to be simulated. The flight simulator is placed in the dynamically changing recreated environment and the pilot then "flies through" in the simulator, which duplicates the performance of the actual airplane. Realistic simulations are made possible by the rapid calculation and implementation of flight characteristics related to the known aerodynamic and engine properties of the craft, air speed, altitude, attitude, and lift. Some systems use 10,000 variables associated with a single-engine jet fighter. In order to achieve visual accuracy, simulator systems calculate the aircraft's position between 25 and 60 times per second.

The Federal Aviation Administration permits 100 percent simulation training for experienced pilots who are upgrading their flight certifications to more advanced aircraft. Simu-



lated dogfight training at Williams Air Force Base is so realistic that some F-4 pilots have become airsick.[7]

Computer simulation is proving effective for improving the quality of training in a variety of jobs—e.g., operating a locomotive, controlling a supertanker, operating a space shuttle—while reducing the cost, time, and risk associated with conventional training.

Heart Pacemakers

Microelectronics and software systems are finding a variety of applications in medical diagnoses and treatment. The heart pacemakers now being used by more than 500,000 patients in the United States are illustrative of the widespread use of these technologies for medical purposes.

The heart muscle contracts in response to electrical impulses generated by apart of the heart itself. The contractions force the blood through the arteries to all parts of the body; but if there is something wrong with the electrical impulses, blood flow is impaired and the heart muscle becomes injured.

[7]"The Technology of Illusion," *Forbes,* **Feb. 27, 1984, pp. 158-162.**

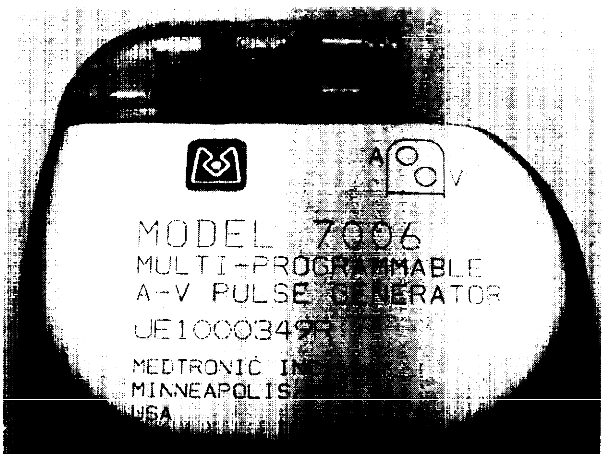


Photo credit: Medtronlc, Inc.

Heart Pacemaker

Pacemakers are medical devices that can be surgically implanted under a patient's skin with electrode leads fed through the veins into the heart. The two main components of a pacemaker are the pulse generator and the leads. Pulse generators contain a power source and the electrical circuitry for sensing, pulsing, and programming. Some new pacemakers are also capable of telemetry functions, which transmit certain critical measurements of performance of the pacemaker and the patient's condition. Programming changes and telemetry functions require external microprocessors that communicate with the implanted devices in order to monitor performance and to modify the pacemaker's operation.

The first implantable pacemaker was developed in 1958, and the first implantation in a human was performed in 1959. Early pacemakers sent electrical impulses to the heart at fixed intervals. By 1970, the technology for "demand" pacemakers was developed. These pacemakers sense when the heart is not working properly and, when necessary, send out electrical impulses to trigger the contraction of the cardiac muscle. Programmable pacemakers-which are continually being updated with advanced technology— can be reprogrammed without additional surgery, in response to changes in the patient's physiology. This capability reduces the risks of additional surgery for cardiac patients and decreases the costs of their care.[8]

The latest generation of pacemakers is designed to be flexible, enabling updating of the software and external keyboard to accommodate newer technology. The flexibility extends to enabling pacemaker parameter settings to be customized for each patient's special needs, and to the use of the same technology for other medical applications, such as drug dispensers and pain controllers.[9]

[8]**Special Committee on Aging, U. S. Senate,** *Fraud, Waste, and Abuse in the Medicare Pacemaker Industry,* **(Washington, DC: U.S. Government printing Office, 98-116. September 1982).**

[9]**Richard M. Powell, "A New Programmer for Implanted Pulse Generators," pp. 678-687, technical paper presented at the 15th Hawaii International Conference on Systems Sciences, January 1982.**

Financial Services

The financial service industry would not provide the level of service it does without information technologies.[10] The numbers of checks (over 37 billion annually), credit card drafts (over 3.5 billion annually), and securities trades (over 30 billion shares traded annually) are simply too much for any manual system to handle. In the 1960s, for example, before the financial service industry was substantially automated, there were days when the New York Stock Exchange suspended operations because the broker/dealers were unable to handle the workload.

Both users and providers of financial services have made use of virtually every category of information technology. Banks and other financial service providers have been longtime users of computers. However, an increasing number of retailers-large and small-are installing the hardware and using the telecommunications networks to verify checks and to authorize and complete credit transactions.

Applications software packages for financial services can process market data and generate information used for portfolio management. They can also generate and analyze loan information, and process bank card applications. The spread of remote terminals interconnected with central computers is becoming ubiquitous, and expanding the number of services available to the public.

The video-related technologies-videotex (a two-way information service) and teletext (a one-way information service)—are not yet widely used in the delivery of financial services, but experiments are under way and it is likely that they ultimately will gain acceptance. One videotex system, currently being marketed in Florida, uses an AT&T terminal attached to a television set to link the financial service provider with the customer.

[10] For detailed discussion, see *Effects of Information Technology on Financial Service Systems,* (Washington, DC: U.S. Congress, Office of Technology Assessment, OTA-CIT-202, September 1984).

There are also several card technologies. The embossed plastic card with its strip of magnetic tape provides the primary means for accessing credit and debit services that are delivered through both paper-based and electronic systems. Laser cards-not yet used by the financial service industry–can store digital data signifying the bearer's fingerprints. Electron cards combine three encoding technologies-the banking industry's magnetic tape, the retail industry's optical character recognition, and the UPC bar code.

Document and currency readers have had some acceptance, particularly for the reading of checks encoded with magnetic ink. Systems that process credit and debit card transactions already truncate the paper flow at the earliest practical time. The data are recorded on magnetic media and transferred electronically for processing by the card issuer.

Together, these technologies have resulted in a financial service industry that is offering an increasing number of services such as automated redemption of money market funds. At the same time these services are being provided in an increasing number of ways, including the use of automated teller machines and telephone bill payers.

With all this, there is the possibility of redistribution of functions among traditional suppliers as well as potential new entrants. Whereas in the past the payment system has been reserved largely to banks, because they had access to facilities for clearing and settlement, movement of funds electronically makes it possible to avoid the traditional payment system and to settle directly between trading partners. Alternative means of distributing information could diminish the role of brokers for such products as securities, real estate, and insurance. Cash-oriented businesses, such as gas stations and supermarkets, already use onsite automated teller machines to relieve the requirement to cash checks while minimizing the amount of currency that is held at each store location.

Characteristics of the U.S. Information Technology Industry

The information technology industry is a composite of several industries both in manufacturing and services. There is no single, generally accepted definition of the industry. The definitions in use by the Information Industry Association, for example, are too broad for the purposes of this report, while definitions used by the Computer and Business Equipment Manufacturer's Association and by the Association of Data Processing Service Organizations are too restricted.

Despite the ambiguities, this section attempts to characterize the industry in terms of size and structure, growth, employment, investment in R&D, and other areas of special concern. The part of the information technology industry portrayed here includes primarily manufacturers of: electronics; information processing equipment, including computers, office equipment, and peripherals and services; semiconductors; and telecommunications equipment.

Table 52 is a summary of the key indicators for the composite 30 industry categories covered by *Business Week*[11] for the period 1978 to 1982, compared with aggregated data for part of the information technology industry.[12] A point of contrast worth noting is that information technology firms' business performance during the period outpaced the composite industry average significantly as measured by the following criteria:

- growth in sales revenues: 40 percent for the composite industry groups vs. 66 percent for the information technology sector.
- growth in profits: 6.4 percent for the composite vs. 36.4 percent for the information technology sector.
- profits/sales ratios ranging between 4.2 to 5.7 percent for the composite vs. 7.9 to 9.7 percent for the information technology sector.
- growth in the number of employees: a decrease of 7.8 percent for the composite vs. an increase of 11.8 percent for the information technology industry.
- growth in R&D expenditures: 81 percent for the composite vs. 111 percent for the information technology sector. The information technology sector's R&D expenditures per employee were higher than the composite by about 20 percent annually for the period, and both groups increased their R&D investments in spite of a recession.[13]
- investments in R&D as a percentage of sales: averaging 2.1 for the composite vs. 4.2 for the information technology sector; and, as a percentage of profits, 42 vs. 48, respectively.

The above statistics are incomplete because firms whose primary business is *not* information technology do not appear as part of the industry—despite the fact that their information technology activities may be significant. Among the firms not represented are General Electric, Rockwell International, and Westinghouse.

The above data for the information technology manufacturing industry, when combined with related sectors such as the software and computer services, and telephone and telegraph services sectors of the economy, had total revenues of $229 billion for 1982, up from $180 billion in 1980, for a 27 percent increase. Figure 53 illustrates the increasing portion of

[11] *Business Week*, R&D Scoreboard, June 20, 1983, pp. 122-153. See also *Business Week*, July 9, 1984, pp. 64-77, which shows a continuation of the trends through 1983.

[12] Data shown by *Business Week* for national composite industry R&D expenditures correlates closely with NSF data in *Science Resources Studies* "Highlights," June 11, 1982.

[13] Of the four sectors-industry, Federal Government, colleges and universities, and other nonprofit organizations-only industry increased its funding for R&D in constant 1972 dollars during the 1978-82 period. *Probable Levels of R&D Expenditures in 1984: Forecast and Analysis*, Battelle, December 1983.

Table 52.—Comparison of the U.S. Information Technology Industry with Composite Industry Performance, 1978-82

	1978	1979	1980	1981	1982	Percent change	
Sales (millions of dollars)	1,085,291	1,277,764	1,421,551	1,586,510	1,520,313	40	Composite
	131,872	149,783	174,449	193,921	218,862	66	Infotech
Profits (millions of dollars)	59,578	72,505	73,493	81,757	63,365	6.4	Composite
	12,780	13,821	15,474	16,056	17,436	36.4	Infotech
Profits/sales (percent)	5.5	5.7	5.2	5.1	4.2		Composite
	9.7	9.2	8.9	8.3	7.9		Infotech
Employees (thousands)	15,133	15,542	15,498	15,045	13,959	– 7.8	Composite
	2,952	3,099	3,226	3,252	3,301	11.8	Infotech
R&D (millions of dollars)	20,610	24,674	28,984	33,285	37,179	81	Composite
	4,961	5,885	7,221	8,531	10,473	111	Infotech
R&D $/sales (percent)	1.9	1.9	2.0	2.1	2.5		Composite
	3.8	3.9	4.1	4.4	4.8		Infotech
R&D $/profits (percent)	34.6	34.0	39.4	40.7	59.0		Composite
	38.8	42.6	46.7	53.1	80.1		Infotech
R&D $/employee	1,362	1,588	1,870	2,212	2,667		Composite
	1,680	1,899	2,238	2,623	3,173		Infotech
R&D expenditures per employee Infotech/Composite (percent)	123	120	121	119	120		

Business Week "Scoreboard" Numbers Notes:

A This is a sample of R&D spending in information technology by U.S. corporations, It is based on total R&D expenditures for those companies that are publicly held, have annual revenues over $35 million, and R&D expenses of $1 million or 1 percent of revenue. Only that spending by companies whose primary business is Information technology (electronics, computers, office equipment, computer services and peripherals, semiconductors, and telecommunications) is included.

B Sales, R&D spending, and R&D spending per employee figures have been adjusted to reflect the numbers from Western Electric and other AT&T subsidiaries that are not included in the "Scoreboard" numbers, This adjustment involves:

1 addition of revenues received from Western Electric to the total operating revenues figures in the AT&T Annual Reports for the years covered,

2 use of the total AT&T spending figures for R&D which include spending by Western Electric and other AT&T subsidiaries as provided in *Business Week* for the years 1980-82 and as estimated from a chart in the 1983 AT&T Annual Report *for* the years 1978 and 1979.

3 use of total AT&T employment figures provided in *Forbes* each May for the years 1978-82.

C Employment numbers for all sectors have been calculated from the R&D spending per employee and the R&D spending figures provided in *Business Week* and may reflect rounding errors,

SOURCE. Data obtained, or calculated from Business *Week,* Scoreboard, June 30, 1983; the U.S. Commerce Department; *Forbes,* May 1979 through 1983; 10K forms filed by AT&T and Western Electric Corp

total sales due to services, which are approaching 50 percent of total industry revenues.

Employment

Employment in information technology manufacturing increased significantly between 1972 and 1982 in most segments of the industry (table 53), experiencing employment growth ranging between 9 and 142 percent. Only the consumer products (radio and TV sets) showed a decline (28 percent). Total employment in information technology manufacturing grew by 51 percent, in spite of economic recessions.

Employment in information technology services is about equal to that of the manufacturing segment, with some 1.6 million employees. The employment level in computing services closely matches that of computer manufacturing, both growing by about 140 percent between 1972 and 1982.

International Trade

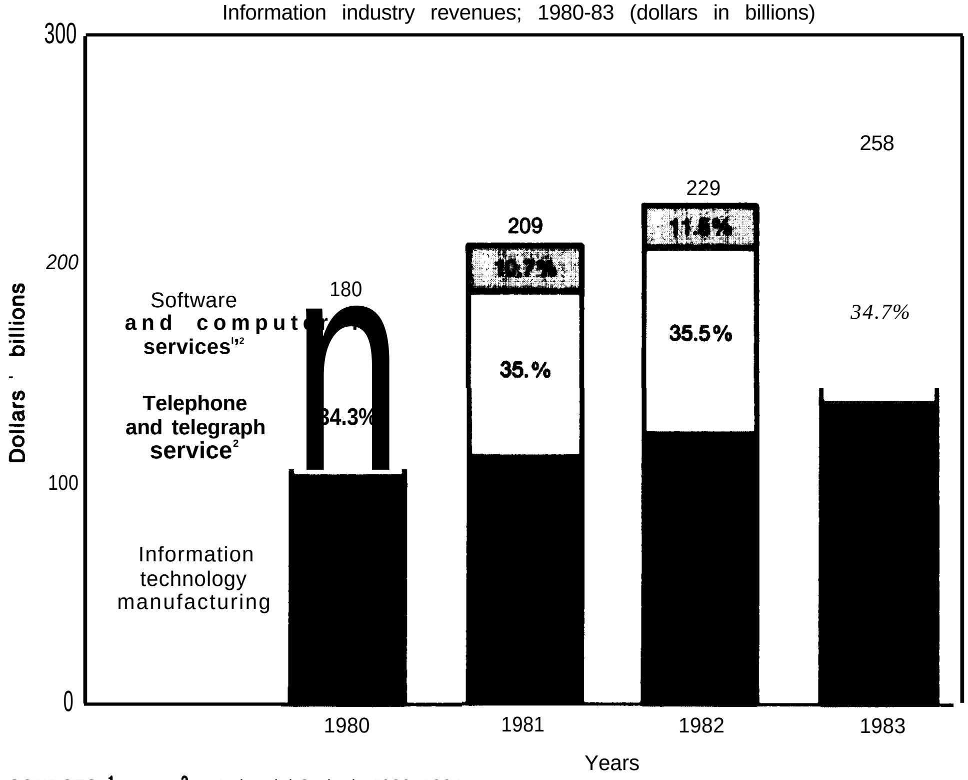
Technology-intensive products have important implications for the balance of trade. Studies on U.S. trade and the influence of technology have generally concluded that technology serves as an important determinant of comparative advantage in manufactured goods trade.[14] [15]

[14] C. Michael Aho and Howard F. Rosen, "Trends in Technology-Intensive Trade: With Special Reference to U.S. Competitiveness, " Office of Foreign Economic Research, Bureau of International Labor Affairs, U.S. Department of Labor, p. 11.

[15] T. C, Lowinger, "Human Capital and Technological Determinants of U.S. Industries Revealed Comparative Advantage, " *Quarterly Review of Economics and Business (1974),* winter 1977, pp. 91-102, as reported in Aho and Rosen, pp. 11, 12.

Figure 53.—The Changing Structure and Growth of the U.S. Information Technology Industry

Information industry revenues; 1980-83 (dollars in billions)



SOURCES: [1]ADAPSO; [2]U.S. Industrial Outlook, 1983, 1984.

Table 53.—Employment Levels in the U.S. Information Technology Industries Employees (in thousands)

	1972	1982	Percent change 1972-1982
Manufacturing[a]			
Computers	145	351	+ 142
Office equipment	34	51	+50
Radio and television receiving sets	87	63	–28
Telephone and telegraph equipment	134	146	+ 9
Radio and television communications equipment	319	454	+42
Electronic components	336	528	+57
Totals, manufacturing	1,055	1,593	
Services			
Telephone and telegraph	949	1,131	+11
Computing[b]	149	360	+ 141
Radio and television broadcast	68	81	+19
Cable television	40	52	+30
Totals, services	1,206	1,624	

[a]Estimates provided by the U.S. Department of Commerce, Bureau of Industrial Economics.
[b]Figures are for 1974 and 1983. Source: U.S. *Industrial Outlook, 1984.*
[c]Figures are for 1979 and 1983. Source: Federal Communication Commission in telephone interview with OTA staff, May 1984.
[d]Figures are for 1981 and 1982. Ibid. (FCC).

The U.S. merchandise trade balance has been negative in recent years: deficits of $42.7 billion in 1982; $69.4 billion in 1983; and over $100 billion in 1984. In 1980, advanced technology products showed a positive trade balance of $31 billion, compared with a deficit of more than $50 billion for all manufactured goods."

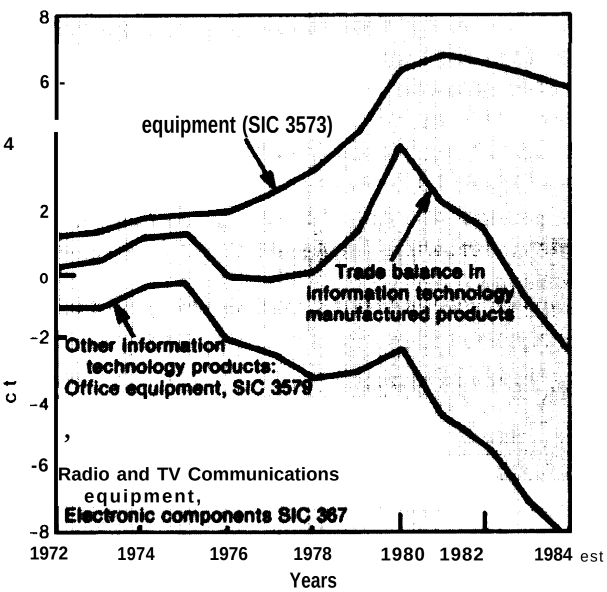
Information technology manufactured products[17] usually made positive contributions to the U.S. balance of trade between 1972 and 1982 (fig. 54), led by sales of computer equipment. However, 1983 and 1984 saw trade deficits of $0.8 and 2.3 billion according to Department of Commerce estimates.[18] The deficits would have been much greater without about $6 billion in exports of computer equipment in each of those years (see fig. 55).

"*International Competitiveness in Advanced Technology: Decisions for America,* National Research Council (Washington, DC: National Academy Press, 1983, pp. 23-24.

[17]The products include: computer equipment, SIC 3573; office equipment, SIC 3579; radio and TV sets, SIC 3651; telephone and telegraph equipment, SIC 3661; radio and TV communications equipment, SIC 3662; and electronic components, SIC 367.

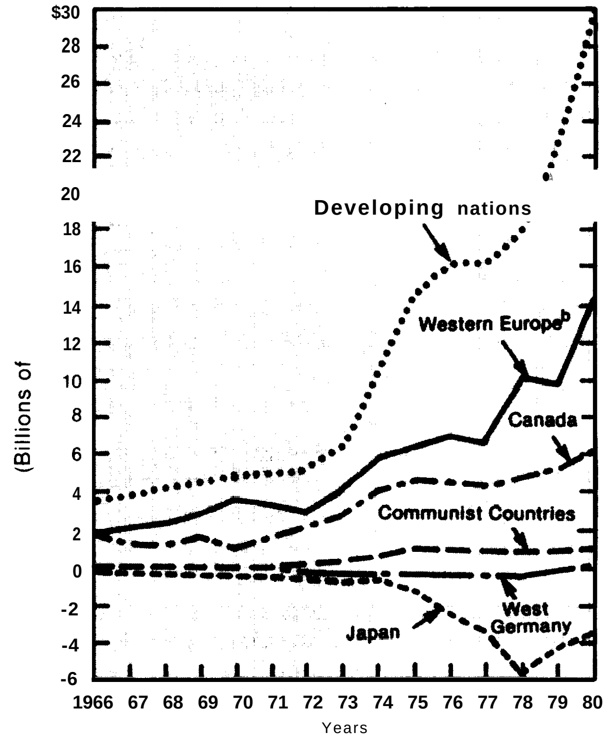
[18]*U.S. Industrial Outlook, 1978* through 1984.

Figure 54.—Balance of Trade, Information Technology Manufacturing Industry (dollars in billions)



SOURCE: U.S. Industrial Outlook for years 1978 through 1984.

Figure 55.—U.S. Trade Balance[a] With Selected Nations for R&D Intensive Manufactured Products



[a]Exports less imports.
[b]Includes West Germany,

SOURCE: *Science Indicators— 1982,* National Science Board, National Science Foundation, 1983.

Although the United States holds the major market share of the industrialized countries' exports of high-technology products, that share has declined from 30 percent in 1962 to 22 percent in 1978, and has increased only marginally since. In absolute terms, the U.S. positive trade balance in high-technology products increased over eightfold from 1962 to 1980. During that same period West Germany, and especially Japan, starting from smaller bases, have had impressive gains in their surpluses of exports over imports—a ninefold increase for West Germany and two-hundredfold increase for Japan.[19]

[19]U.S. Department of Commerce, International Trade Administration, as reported in "An Assessment of U.S. Competitiveness in High-Technology Industries, " prepared for the Working Group on High Technology Industries of the Cabinet Council on Commerce and Trade, final draft, May 19,1982.

Industry Structure

Information technology companies in the United States are heterogeneous in dollar value of sales, breadth of product lines, number of employees, and degree of vertical integration. Competing for those markets are thousands of firms ranging in size from the vertically integrated multinational companies such as IBM, ITT, and the still-large, post-divestiture AT&T to the more typical, smaller companies that produce a narrow cluster of products with a large technology content. While the majority of sales dollars are concentrated in the large companies, the vast majority of companies are relatively small.

The diversity in the sizes of the businesses that populate the information technology field is important for reasons that include the benefits of competition; the impetus to innovation due to firms' willingness to take risks and to try new directions; and the tendency to fill niche market demand for specialized products. The U.S. telecommunications, electronics, and software industries provide three illustrations of the contrasts in the breadth of that diversity.

The *telecommunications services* industry is simultaneously both a mature industry dating back to the 19th century and a growing industry marked by limited competition in some markets and diversity in others. While local public telecommunications services are largely dominated by regulated monopolies, long-distance services are now offered in a competitive market. New services, such as paging, cellular mobile radio services, bypass services and direct broadcast satellite services, are not dominated by the established carriers, but are being offered by a variety of firms.

The *telecommunications equipment* providers are exceptionally diverse and competitive. There are hundreds of firms in this field, ranging from a few U.S. and foreign multinational companies manufacturing a full range of equipment to dozens of medium size, and many hundreds of small companies concentrating on a more limited range of products—e.g., speech compression products, multiplexers, modems, data terminals and local area networks.

The *electronics* industry is even more diverse. The thousands of electronic systems and equipment providers, as well as consulting firms, range in size from those with billions of dollars in annual sales to small, start-up ventures such as the Apple Computer's garage operation of a few years ago. For those segments of the industry undergoing rapid technological change, diversity is often accelerated by spin-offs from rapidly growing companies, and other new entries into the field.

The U.S. *microcomputer software* industry is an example of rapid change, growth, and diversity. Future Computing, Inc. estimates that the U.S. market for home computer software grew by 168 percent from 1982 to 1983, and projects an 85 percent growth from 1983 to 1984, with the growth rate declining to 26 percent by 1988 in a projected $5 billion annual market by then (table 54). Software unit sales for office use are projected to enjoy comparable growth. Table 55 indicates growth rates of 87 percent between 1982 and 1983, and 58 percent from 1983 to 1984, gradually tapering off to 24 percent in 1988 in a $6.7 billion annual market.[20] Like the electronics industry, software firms number in the thou-

[20] Future computing, ~r,,n~ communication, March 1984.

Table 54.—U.S. Home Computer Software Sales[a]

	1981	1982	1983	1984	1985	1986	1987	1988
Software units (millions)	1.1	6.9	19.0	37.0	58.0	82.0	112.0	144.0
Percent growth (units)		486	168	85	52	42	32	26
Revenue (millions of dollars)	48	282	757	1,400	2,100	3,000	4,000	5,000

[a]Data for 1984-88 are estimates by Future Computing.

SOURCE: Future Computing, Richardson, TX, by OTA staff telephone interview, March 1984.

Table 55.—U.S. Office Computer Software Sales[a]

	1981	1982	1983	1984	1985	1986	1987	1988
Software units (millions)	3.2	6.1	11.0	17.0	25.0	35.0	46.0	59.0
Percent growth (units)		111	87	58	44	36	30	24
Revenue (millions of dollars)	343	724	1,351	2,100	3,100	4,200	5,400	6,700

aData for 1984-88 are estimates by Future Computing

SOURCE Future Computing, Richardson, TX, by OTA staff telephone interview, March 1984

sands. Although no hard data are available, it is the impression of industry analysts that the rapid pace of startups in the software industry seen in recent years now appears to be slackening.

An important trend in industry structure is toward concentration in the software and data services industries, where larger firms have acquired hundreds of smaller ones. Among these larger firms are Automatic Data Processing, Electronic Data Systems, and General Electric.

Larger firms are also integrating their product lines-some moving into subsystems and components, and others, such as semiconductor manufacturers, moving into subsystem and computer manufacturing. AT&T, Texas Instruments, Intel, and Northern Telecommunications Corp. are examples of companies recently expanding into computers and related products.

There is also an active trend toward affiliations between information producers and distributors. Among these are publishers of newspapers, books, and magazines and broadcast, cable TV, and interactive computer network companies.

Geographic diversification is taking place at a rapid pace as foreign-primarily European—companies acquire U.S. firms. Among the European firms are: Olivetti, CAP Gemini, Racal Electronics, Schlumberger, Thomson-CSF, and Agfa-Gevaert.

A number of U.S. firms are expanding their markets by establishing joint ventures or by acquiring foreign outlets—e.g., IBM, AT&T, and Datapoint.

Small Entrepreneurial Firms

Small businesses play a central role in U.S. industry in general, accounting for:

- thirty-eight percent of the Nation's gross national product;
- two-thirds of all new jobs;
- two-and-a-half times as many innovations per employee as large firms;[21] and
- a tendency to produce more "leapfrog' creations compared to large companies and to introduce new products more quickly than large firms.[22]

The contributions of small businesses to the information technology industry are significant. Small businesses with less than 500 employees account for 33 percent of sales in electronic components and 34 percent of the Nation's employment in this sector. In the computer services sector, small businesses account for 69 percent of the industry's sales and 67 percent of its employees. These firms also make contributions in sectors where large companies dominate, such as in office computing equipment, consumer electronics, and communications equipment (table 56).

Opportunities for innovation based on advances in information technology have been numerous. Consequently, hundreds of market niche applications have been created that

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"*Advocacy: A Voice for Small Businesses,* Office of Advocacy, U.S. Small Business Administration, 1984. p. 1.

[22]Stroemann, 1977. Karl A. Stroetmann "Innovation in Small and Medium Sized Firms." Working paper presented at Institut Fur Systemchnik und Innovations forschung, Karlsruhe, West Germany, August, 1977. See Vesper (Entrepreneurship).

Table 56.—Percentage of Total Industry Sales and Employment by Size of Small Businesses

	Companies with under 100 employees		Companies with under 500 employees	
	Sales	Employment	Sales	Employment
Office computing machines and computer auxiliary equipment	2.6	2.6	6.0	6.3
Consumer electronics	5.4	5.9	9.3	10.1
Communications equipment	4.7	5.2	9.9	10.8
Electronic components	18.3	17.2	32.7	33.7
Computer services	51.2	47.7	68.6	67.1

SOURCE: Small Business Administration, 19S4.

small firms are quick to fill-niches too narrow or specialized to attract large firms.[23] The development of the computer in the 1940s and the subsequent invention of the transistor led to an explosion of new applications and to opportunities for then small companies whose names are now familiar in the information technology industry: IBM, Fairchild, Intel, Texas Instruments, DEC, Data General, Wang, and Computervision. One market research company's listing of the fastest-growing niche markets shows that about 90 percent of the top 50 entries are in information technology,[24] and many of these technologies are relatively new.

As the successful firms in this industry grow, they tend to generate spin-off companies that often specialize initially in a narrow range of innovative products or processes. Fairchild is such a company, having begun with only eight employees and now accounting for over 80 spin-off enterprises.[25]

Venture capital funding is extremely important to the small entrepreneurial firms. Investments through organized venture capital investment businesses in 1983 amounted to $2.8 billion, up 55 percent from $1.8 billion in 1982.[26] It is improbable that this growth rate will be sustained for very long.[27]

The supply of U.S. venture capital financing has grown at least eightfold since the mid-1970s, helping to fund the more than 5,500 U.S. small startup and expanding firms. These firms tend to operate in innovative market niches where the risks are high and the potential payoffs much higher.

Information technology firms supported by venture capital funds numbered in excess of 1,000 in 1983, and received about $2.1 billion from organized venture capital investment businesses. These funds were used for both startups and expansion of existing companies. The distribution of funds is shown in table 57.

These firms account for a significant number of advances in the information technology field. Among the now-well known information technology firms started or aided by venture capital are: Intel, Apple Computer, Visicalc, DEC, and Data General. R&D limited partnerships also contribute to this process (see ch. 2).

The existence of so many entrepreneurial firms, the current abundance of venture capital to fund their growth, and the strengthening university-industry R&D relationships serve as a powerful source of strength for innovation in the United States. For example,

[23] In a July 1981 study, the General Accounting Office found that in concentrated industries, such as the information technology industry, small businesses are likely to perform specialized innovative functions and develop products or processes to be used or marketed by other, usually larger firms in that industry, For example, in the semiconductor industry there are many small companies that manufacture diffusion furnaces, ion implantation machines, epitaxial growth systems, and mask-making systems—all part of a necessary support structure for the semiconductor industry.

[24] 21st Century Research, Supergrowth Technology U. S. A., newsletter as published in EDP News Service, Inc., *Computer Age-EDP Weekly*, Feb. 28, 1983, p. 9.

[25] Carl H. Vesper, *Entrepreneurship and National Policy*, Heller Institute for Small Business Policy Papers, p. 27.

[26] Data provided by Venture Economics, Inc., from its database covering organized venture capital investment companies.

[27] "Scramble for Capital at Almost-Public Companies," *Fortune* June 25, 1984, p. 91.

Table 57.—Venture Capital Funding and Information Technology Firms, 1983

	Percentage of 1,000 venture capital firms	Distribution of available venture capital (percent)	Distribution of available venture capital (millions of dollars)
Computer hardware and systems	**28**	**39**	**819**
Software and services	12	7	309
Telecommunications and data communications	9	11	231
Other electronics	10	10	210
Total	59	61	1,569

[a]Includes semiconductor fabrication and test equipment, instrumentation, fiber Optics, laser-related devices, etc

SOURCE Venture Economics Inc, provided in telephone interwew with OTA staff, May 22, 1984

over 30 new computer chip firms have started operation since the late 1970s. The fastest-growing niche markets noted earlier are heavily populated with products that are new, or radically different from those of only a decade ago. Few of our major competitors now have a comparable combination of factors to spawn the next Silicon Valley. In fact, our West German,[28] French, and Japanese trading partners are now actively seeking ways to emulate the environment that fosters this type of entreprenuership.[29]

Small Businesses and Joint R&D

Congress has passed, and the President signed, legislation that would ease the restrictions of antitrust laws on joint R&D ventures.

[28]" The Technological Challenge: Tasks for Economic, Social, Educational, and European Policy in the Years Ahead, " speech by Hans-Dieter Genscher, (West German) Federal Minister for Foreign Affairs, Bonn-Bad Godesberg, Federal Republic of Germany, Dec. 13, 1983.

[29]"In This New Age of Entrepreneurs, We're Number One Again, " Joel Kotkin, *Washington Post,* Apr. 29, 1984, p. B1.

Small business may find both new opportunities and impediments. Although small businesses are currently permitted to undertake joint research activities among themselves, the new joint venture legislation may encourage increased opportunities in joint ventures between small and large firms.

This type of cooperation between large companies and small companies has already begun to occur. For example, Control Data Corp. has made its advanced computer design tools available to two small companies, Star Technologies, Inc. and ETA Systems, Inc. (the latter a CDC spin-off). IBM also has a marketing agreement with Floating Point Systems. If the joint venture legislation can stimulate transfers of marketing and technological resources of major U.S. companies to small information technology firms, small companies can realize definite benefits from the encouragement of these new types of arrangements. A potential impediment could occur if technology developed through R&D by large firms is not made available to small firms through licensing or other means.

Where the Technology is Heading

This section looks ahead to prospects for further advances in two building blocks of information technology-microelectronics and software. As discussed later, these technologies are being integrated and are providing important tools for coping with increasing complexity through the use of computer-aided design (CAD) and computer-aided engineering (CAE) systems, and are driving a wide range of applacations.

Advances in microelectronics and software are dependent on entirely different underpinnings-e.g., physics, chemistry, materials science and electrical engineering for the former, and computer and information science, psychology, and software engineering, among others, for the latter. Prospects for continuation of the explosive growth of information technology during the past two decades will be paced by advances in microelectronics and software.

Microelectronics[30]

The rate of technological improvement in semiconductors has been phenomenal during the past quarter century, and has sparked new applications and economic advances worldwide. This section reviews the growth of integrated circuit capabilities and seeks to provide insight into future progress, its dependencies and foreseeable limitations, and the likely timeframe of that progress.

Probable trends include:

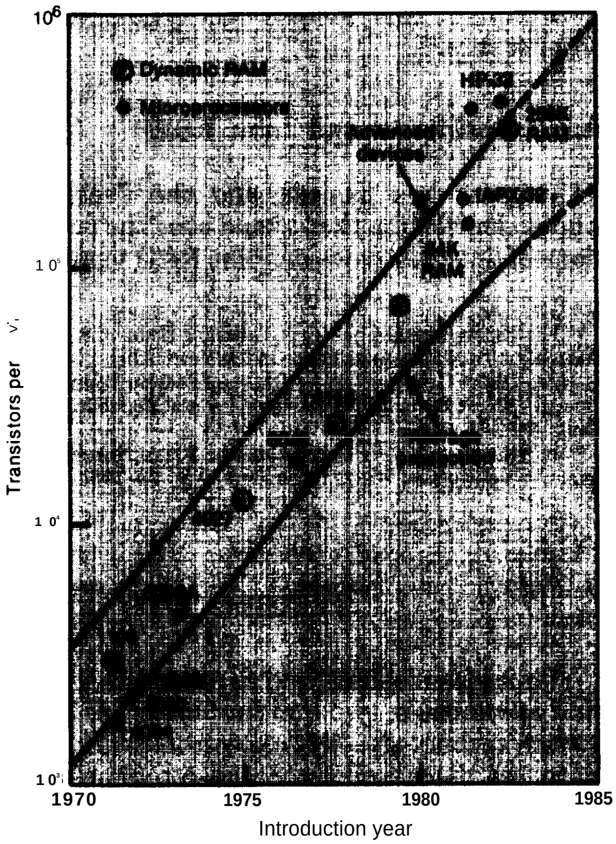
- Silicon is likely to remain the most important semiconductor material for the next decade and beyond, while gallium arsenide is likely to come into wide use in certain applications where its special properties provide specific advantages. The impact of other innovative materials is likely to be marginal until after the turn of the century, when biotechnology may begin to converge with information technology.
- Prices for the main output of microelectronics technology, logic and memory, can be expected to continue to decline on a per function basis, following the general pattern of the past two decades.
- Continued advances during the next two decades in large-scale integration of silicon and gallium arsenide will require the continued advance of other sciences and technologies, particularly physics, chemistry and materials science, and manufacturing and software engineering.
- The R&D costs for incremental advances in microelectronics technology are expected by industry experts to increase as the complexity of circuits increases and as the theoretical physical limits of microelectronics are approached.

Silicon Integrated Circuits

Transistor Size and **Density**

Between 1972 and 1981, the number of transistors that could be packed on a chip doubled each year (11,000 in 1972 and 600,000 in 1981) (see fig. 56). Today, integrated circuit technol-

Figure 56.—Historical Development of the Complexity of Integrated Circuits



SOURCE: Arthur D. Little, Inc. estimates.

[30] A significant amount of data in this section is taken from, or based on: 1) the Sixth Mountbatten Lecture, *Microelectronics* Progress Prospects, delivered by Ian M. Ross, President, AT&T Bell Laboratories, Nov. 10, 1983, London, England; and 2) J. D. Meindl, *Theoretical, Practical, and Analogical Limits to ULSI*, Technical Digest of the International Electron Devices Meeting, December 1983, pp. 8-13.

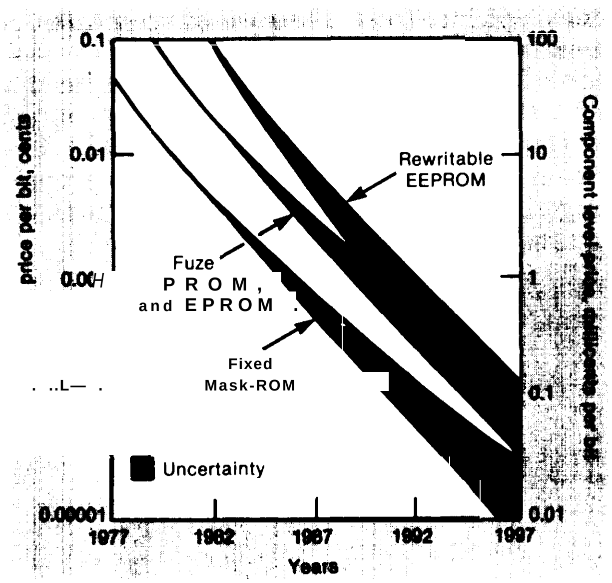
ogy is approaching the capability of packing a million components (mostly transistors) on a single silicon chip.[31]

Along with these improvements in density, costs per function have dropped dramatically until now some memory components are less than 0.01 cent per bit, and many microprocessors are under $10 per chip (see figs. 57 and 58). This is the result of a thousand-fold decrease in the cost of manufacturing compared with 20 years ago.

The substantial increases in transistor density have been made possible by reductions in integrated circuit feature size, which in turn have depended on advances in photolithography, the technique by which integrated circuits are manufactured. Minimum line widths have been reduced by a factor of two every 6 or 7 years. Using photolithography with visible light, line widths have been reduced from 25 microns in 1972, or l/1,000th of an inch, to about 1.5 microns currently, or less than 1/10,000th of an inch.

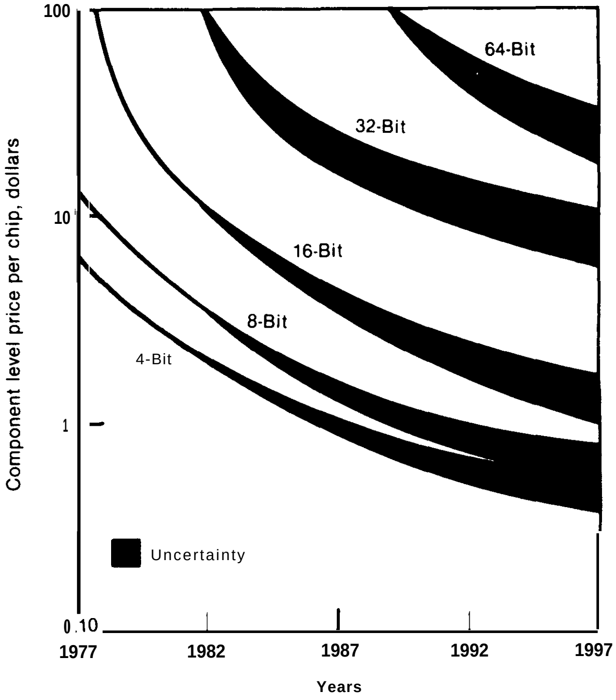
[31]While other technologies (gallium arsenide, iridium antimonide, cryogenic superconductors,photonic devices, and potentially biotechnology) with higher switching speeds, lower heat dissipation, or other qualities, will compete in certain special applications, current expert opinion is that silicon will have the major role for the next decade or more in meeting most needs for digital memory and logic.

Figure 57.—Read-Only Semiconductor Memory Component Prices (per bit) by Type



SOURCE: Arthur D. Little, Inc., estimates.

Figure 58.—Median Microprocessor Price v. Time (1,000 unit purchase)



SOURCE: Arthur D Little, Inc, estimates

Optical, or visible light, lithography, which currently remains the leading integrated circuit manufacturing method, is expected to reach the practical limits of its capacity for small feature sizes in the range of 1.0 to 0.5 microns (the wavelength range of visible light). At the same historical rate of progress, these limits will be reached in the 1990-94 period (see fig. 59.).

Most experts believe that advanced lithographic techniques using light of shorter wavelengths, in the X-ray range, and electron-beam (see fig. 60) and ion implantation machines that can directly draw lines and features on semiconductor substrates[32] will be needed in

[32]In current commercial lithographic techniques, the semiconductor substrate is coated with a light-sensitive emulsion, or *photoresist*, and a mask, much like a stencil, is used to expose a pattern in the substrate that is then etched away with a chemical, creating lines and features. Electron beams can be focused and directed to create patterns in the emulsion without a mask, and ion beams can implant materials on the substrate without the need for photoresist or etching.

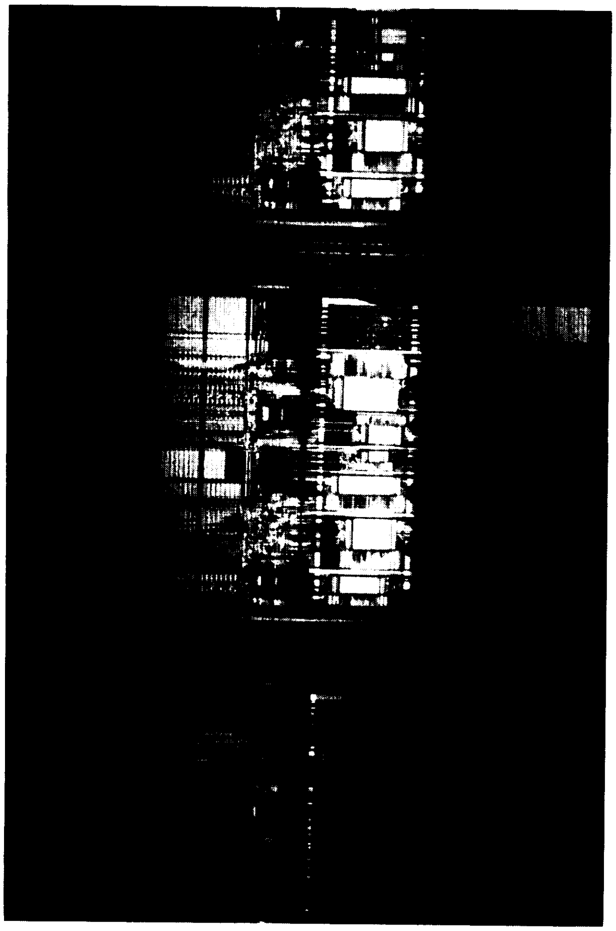


Photo credit: AT& T Bell Laboratories

Microprocessor WE 32100

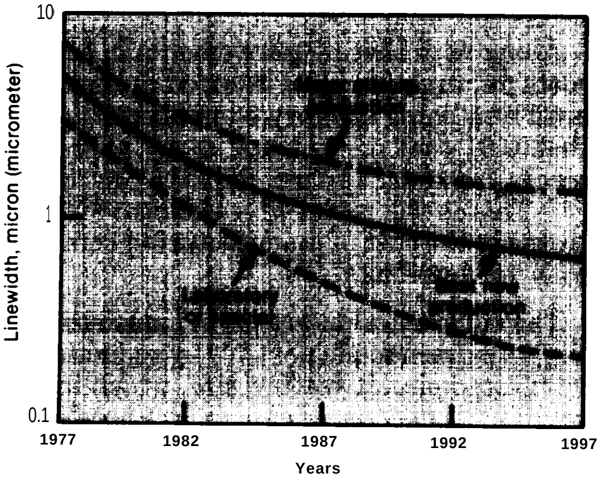
order to achieve further advances.[33] A number of such machines are in use for experimental purposes and for production of circuits to be used in-house at major companies such as IBM and AT&T.

Electron beam lithography and ion implantation[34] may become the ultimate semiconductor manufacturing techniques, with minimum line widths possible in the range of 0.1 to 0.01 micron. The latter widths are comparable to feature spacing on the order of 20 to 200

[33] Some engineers have begun to question the premise that more densely packed circuits are necessary. See "Solid State, " *IEEE* Spectrum, January 1984, p. 61.

[34] The Defense Department's Very High Speed Integrated Circuits (VHSIC) program supports research on electron-beam and ion-beam manufacturing techniques. Discussion of both of these can be found in *IEEE Spectrum*, January 1984, pp. 61-63.

Figure 59.—Minimum Linewidth for Semiconductor Microlithography



SOURCE: Arthur D. Little, Inc., estimates.

atoms. The major drawback of such systems is that they are much slower than mask lithography; they are now used only in producing custom chips of low production volume. Electron-beam and ion implantation technology are expected to be in use on commercial integrated circuit production lines by 1994[35] (see table 58).

Research is under way in the United States and Japan that is striving to achieve more densely packed circuit components by stacking chips into three dimensional structures. A number of problems need to be solved to realize 3-D circuits, among them is the difficulty of making connections with elements buried within layers of semiconductor material. Ion-beam equipment is seen as critical to producing the complex microscopic structures required for such 3-D chips.[36]

[35] *IEEE Spectrum*, January 1984, p. 63.

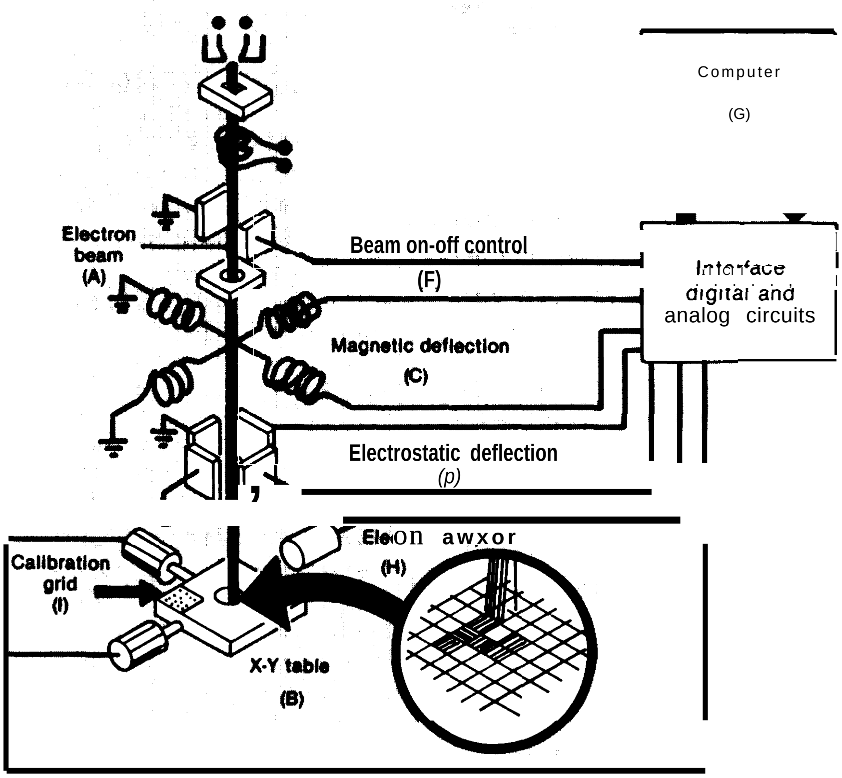
[36] "3-D Chips," *The Economist*, Feb. 12, 1983, p. 84.

Table 58.—ICs Made with Lithographic Techniques (percent)

Technique	1983	1985	1987
optical scanner	85	58	38
Optical stepper	15	40	52
Electron beam	0	1	8
X-ray	0	1	2
Ion beam	0	0	0

SOURCE: IEEE *Spectrum,* January 1984, p. 80,

Figure 60.—A Schematic of an Electron Beam Lithography System, and its Uses to Make LSI Logic Circuits



SOURCE Mosaic, *SSI/MSI/LSI/VLSI/ULSI*, vol 15, No. 1, p 15.

In devices with such subminiature dimensions, other limitations become significant, e.g., the dielectric strength, electronic isolation, and heat dissipation of the silicon material-some of which may represent more severe limitations than the theoretical limits imposed by the most advanced manufacturing techniques. Transistors with critical dimensions of 0.1 micron have been demonstrated to operate by Bell Telephone Laboratories. These dimensions would theoretically lead to some billion components on a square centimeter of silicon. A more realistic, practical limit for silicon may be 100 million components per square centimeter.[37]

Increasing the physical dimensions of the chip may also contribute to increasing the component count per chip. Chip sizes are determined by manufacturing control–the ability to minimize the number of impurities and defects in the semiconductor substrate material and in finished circuits. Today's typical chip size is about 1 square centimeter. There are development efforts under way toward wafer-scale integration[38] which could provide a factor of 100 increase in integrated circuit chip size, to 100 square centimeters or larger. This factor, coupled with component densities of 100 million transistors per square centimeter made possible with the advanced manufacturing techniques noted above, could result in component counts of 1 billion transistors per integrated circuit.[39]

"Ross, op. cit., p. 6.

[38]Chips are cut from 3 to 6-inch-diameter wafers which are currently manufactured with some 100 separate integrated circuits per wafer.

"Ross, op. cit., p. 7.

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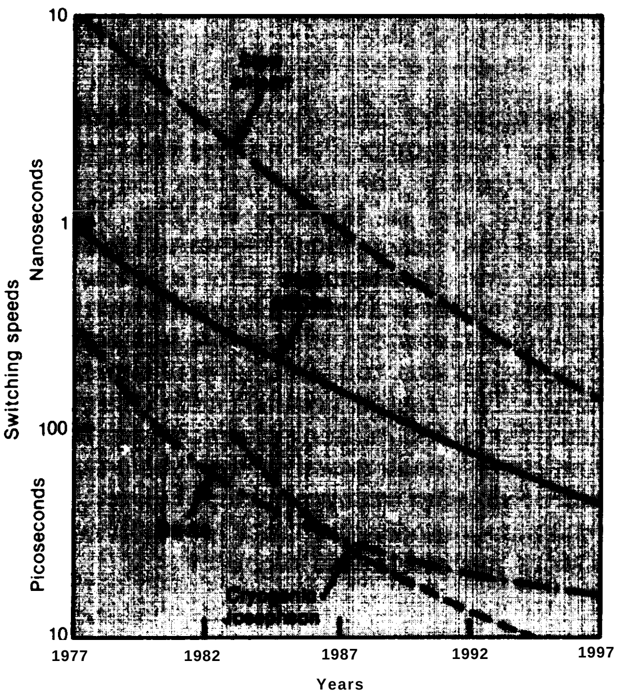
Integrated Circuit Speed and Reliability

Concurrent with, and largely the result of, decreasing circuit feature size and increasing density, circuit switching speeds have increased significantly. A little more than 20 years ago, switching delays were crossing the millionth of a second threshold; by 1977 the billionth of a second threshold had been passed; by 1990, delays of 1 trillionth of a second (a picosecond, or 10^{-12} second) may be possible (see fig. 61). Practical limits are foreseen, however, that would reduce actual maximum performance to one-tenth that speed, or 10 picoseconds.[40]

As well as reducing circuit delays, the continued shrinking in the size of individual components and the concentration of more functions in each succeeding generation of integrated circuits have reduced computer system chip counts and thus the time used up in computers when signals travel between chips.

[40] Ibid.

Figure 61.—Trends in Device Speed—Stage Delay per Gate Circuit for Different Technologies



SOURCE: Arthur D. Little, Inc., estimates.

Chip reliability has also improved. It is estimated to have increased by at least a factor of 100, while the scale of integration has increased by a factor of 1,000.[41]

Gallium Arsenide Integrated Circuits

Another compound, gallium arsenide (GaAs), should find an increasing number of applications as a semiconductor substrate because of its special characteristics. These include high frequency operation, low power consumption, radiation resistance and optoelectronic and photonic properties.

Analog Devices

Currently, GaAs is used mainly in discrete component (non-integrated) analog devices such as microwave and millimeter wave radar, telecommunications and electronic warfare transmitters. Electronic signals at these high frequencies (10 to 100 Gigahertz or billion cycles per second) can be generated at much lower power with GaAs than is possible with conventional transmitter technologies. Integrated circuit, or monolithic, microwave and millimeter wave GaAs circuits have recently become available. Integration promises improved performance and lower prices in military systems and private sector microwave communications (local loop bypass and other) applications. Cellular radio is expected to provide a large market for GaAs transmitters, receivers and amplifiers.

Another application that offers a large potential consumer market for analog GaAs integrated circuits is direct broadcast satellite service (DBS). The principal French laboratory of N.V. Philips Co., based in The Netherlands, recently announced development of a GaAs chip that includes all of the functions necessary for the reception of DBS signals.

Optoelectronic and Laser Devices

Gallium arsenide is provoking excitement in another telecommunications technology, fiber optics. It can be fashioned into tiny lasers to

[41] Ross, op. cit., p. 2.

function as light sources for fiber optic transmission, into optoelectronic photodetectors to receive optical signals and translate them into electrical signals, and into signal processing components for fiber optic system amplifiers and repeaters (see Fiber Optics Case Study). Recent work at Bell Labs has developed large-scale integrated (LSI) GaAs signal processing circuits that are scheduled for production.[42]

Heretofore, separate devices have been required for fiber optic light generation, reception and signal processing. Communication among these separate devices introduces delays in fiber optic transmission systems. Lasers have been particularly difficult to integrate with the other circuit components on single chips because of their complex structure and the large amount of heat that is generated by their operation.

Fujitsu, the Japanese electronics giant, has conducted GaAs R&D funded by that government as part of a $74 million, 7-year project among a number of Japanese companies. In 1983, it announced development of a process that integrates a laser light source and the signal processing transistors necessary for fiber optic transmission, all on a single GaAs chip that operates at room temperature. A similar integrated optoelectronic photoreceiver is in the works.

American researchers at Honeywell and Rockwell International have also announced the development of integrated GaAs optical transmitters.[43] The Rockwell device in particular is reported to be adaptable to well-known LSI circuit manufacturing techniques, promising low production costs.”

Digital Devices

Interest has begun to intensify in the use of GaAs as a replacement for silicon in digital logic and memory devices. High switching speeds and low power consumption make this semiconductor attractive in certain applications. For instance, Cray Research has announced its intention to develop and use GaAs chips in the Cray-3 supercomputer which is scheduled to be available in 1986 (see Advanced Computer Architecture Case Study). But commercial semiconductor firms have thus far been reluctant to move GaAs logic and memory into production. Only low levels of integration (fewer devices per chip than silicon) and low yields (few good chips in a batch) are currently attainable with GaAs. Although 42 U.S. companies conduct laboratory work on GaAs, only two firms have announced plans to sell digital GaAs chips.[45]

The Department of Defense is interested in digital GaAs because, as well as having speed and power consumption advantages, GaAs circuits are highly resistant to radiation effects, making them attractive for military and space applications. Since 1975, DOD, through DARPA, has funded a total of $6 million to $7 million in R&D of digital GaAs integrated circuits. DARPA has announced plans to spend an additional $25 million to set up pilot production lines for GaAs 64K RAM and 6,000 to 10,000 element gate array (programmable logic) chips. The contract has been awarded to a joint venture between Rockwell International, who will develop the gate array chip, and Honeywell, who will design the RAM chip. Each of the two companies will develop production capacity for both the logic and memory chips to provide second sources for each.[46]

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[42] *Electronics*, Oct. 6, 1983, p. 154.

“Honeywell announced an integrated optical transmitter in 1982, but it originally required special cooling. The Honeywell device has since been improved. See C. Cohen, “Optoelectronic chip integrates laser and pair of FETs, ” *Electronics*, June 30, 1983, pp. 89-90. See also *The Economist*, Feb. 5, 1983, pp. 82-83.

441. Wa_le r, “GaAs Optical IC Integrates Laser, Drive Transistors,' ” *Electronics*, Oct. 6, 1983, pp. 51-52.

“W. R. Iversen, “Pentagon Campaigns for GaAs Chips, ” *Electronics*, July 28, 1983, pp. 97-98.

[46] J. Robertson, “Say Rockwell, Honeywell Get $25M DARPA IC Pact, ” *Electronic News*, Feb. 30, 1984, p. 4.

The DARPA program has received mixed reviews from the industry. On one hand, Rockwell believes that the DARPA-funded facilities will help make digital GaAs profitable for the entire industry, since the technology is expected to be made available to other defense contractors,[47] but neither of the two companies that have announced plans to develop digital GaAs for the merchant semiconductor market. The companies-Gigabit Logic, which recently entered into a private R&D venture to develop GaAs RAM chips,[48] and Harris Microwave Semiconductors-submitted bids for the DARPA contract. Both cited the DARPA emphasis on low power for portable military systems at the expense of higher speed as the major factor in their decision to forego bidding on the contract.[49] This tradeoff is seen as forfeiting the major advantage of GaAs in commercial competition with silicon digital memory and logic devices.

Optical Logic

Another area of applied research in which gallium arsenide is playing a critical role is optical logic. The replacement of computer processors based on electronics with ones based on photonics, which would theoretically be capable of vastly higher speeds, has been considered a possibility for some time. Such optical computers might be capable of trillions of operations per second.[50] With the spread of fiber optic communications technology, optical processing is even more attractive. The large capacity of light-wave transmission demands higher processing speeds to fully exploit the available fiber optic bandwidth. Conversions between optical and electronic signals introduce delays into current fiber optic systems.

Only recently, with the use of GaAs and another new semiconductor material, iridium antimonide, has the technology been available to begin to develop optical devices that function like the logic elements that make up microprocessors. Hughes Aircraft Research Laboratories, which is performing R&D work on optical logic under contract from the National Security Agency, has announced the development of a prototype device that is expected to be capable, in about 3 years, of more than 10 times the speed of current electronic logic devices. The device is to be applied in data encryption systems.[51]

The major drawback seen with current approaches to optical computing is that the logic elements are much larger than comparable electronic ones. Barring fundamental theoretical and practical advances, especially in physics and in materials sciences, optical logic systems will probably not see widespread use before the end of the century.

The Convergence of Bio-technology and Information Technology

Advances in the biological sciences and breakthroughs in genetic engineeering have encouraged speculation and some preliminary research on the possibility of designing biocomputers. Devices constructed from biochemical molecules potentially offer greater logic and memory densities, and the possibility of totally novel information processing methods, including the emulation of brain functioning. The first interdisciplinary scientific conference on this subject, sponsored by the National Science Foundation and the University of California, Los Angeles, was held in October 1983.[62] The meeting brought together biologists, chemists, physicists, mathematicians, computer scientists and electrical engineers to discuss the prospects for this technology and to generate questions to guide research.

The field is just beginning to adopt theoretical concepts on how such biochemical-based machines might operate, and on the more dif-

[47] 1 bid., see also Iversen, op. cit., p. 97.

[48] Gigabit in **$6.1M GaAs static RAM R&D Venture,"** ***Electronic*** *News,* **Jan. 9, 1984, p. 66.**

[49] **Iversen,** op. cit., pp. 97-98.

[50] **E.** Abraham, C. T. Seaton, and S. D. Smith, "The Optical Computer," *Scientific American,* February 1983, pp. 85-88.

[51] **L. Waller,** "components for Optical **Logic Start to Click, "** Electronics, Dec. 29, 1982, pp. 31-32,

[52] **International** Conference on Chemically **Based Computing, Santa Monica, CA.**

ficult questions of how one might construct a bio-computer and make it work in concert with existing information systems. Lewis Mayfield, head of the Chemical and Process Engineering Division at NSF concluded, "The consensus of the Santa Monica Conference was that a great deal more work will be needed at the fundamental level before development can begin. So although we will accept grant proposals in this area, we have no plans to organize a program to promote it. "[53]

Software

Software and hardware are primary elements in information technology systems. The hardware provides the set of generic functions that information systems may perform (input, storage, processing, communications and output), and the software combines and organizes these functions to accomplish specific functions. The two elements are responsible for the burgeoning range of capabilities of information technology, and, increasingly, for advances in the technology itself.

Software is the part of information technology that is most readily modifiable. A major attraction of computer-based systems is that they are programmable-machine functions are fixed, but their sequence may be modified to achieve different ends at different times or to respond to changing conditions. The content of information systems maybe changed, expanded and contracted, within limits, to accommodate the changing needs of users. Software is the vehicle for providing the flexibility of information systems to the users of the technology; software aids users in communicating and managing large bodies of information and in coping with the complexity of large or specialized systems.

Traditionally, the term "software" narrowly referred to programs for large mainframe computers and was of concern only to computer professionals. But as computer power has spread to wider segments of society, the characteristics of software have been modified by the uses to which computer systems are put, and the meaning of software has broadened. Now, software is both the instructions that direct the operations of computer-based systems, and the information content, or data, that computer systems manipulate.

The focus of software production and use is changing from concerns of computer professionals to the concerns of a broad range of end *users* of information technology -i.e., those with no particular interest in the technology, but only its capabilities and results. Because of this and the increasing availability of computer and telecommunications capabilities, future limits on the utility of information technology will depend less on hardware capability and more on the difficulties of defining and accommodating the needs of users.[54]

Possible implications of an expanding number of users of information technology, and a shift in the focus of concern toward the needs of that expanding set of users include:

- The relative importance of software issues in the research and development of information technologies will likely increase.
- Small companies will continue to be important players in software development because of their ability to respond to the specialized needs of small segments of the user population.
- There will be movement toward standardization of software for common applications, such as in accounting, banking, insurance and government.
- There will be continuing pressure to introduce systematic engineering practices into the production of software to lower software development costs and to assure the reliability of software in critical applications. (See Software Engineering Case Study.)
- There will be a demand for higher level, *nonprocedural* computer languages for the development of new and unique appli-

"J. B. Tucker, "Pioneering Meeting Puts Biochips on the Map, " High Technology, February 1984, p. 43.

[54]An analogy can be drawn between computer users and auto mobile drivers: all want the benefits of the technology but most are indifferent to how it works.

cations; such languages will allow the user to focus on the characteristics of the tasks to be performed and not on how the hardware performs them.

- The search will intensify for powerful and simplifying concepts for the organization of information and knowledge in many fields.
- Computerization will require the users of information systems to more clearly define and organize their habits and operations related to information use.
- There will be more concern among users of information technology with the uses of information and the content of information systems, and less concern with how the technology works.

The production of software has become a major industry in the United States, with estimated expenditures of $40 billion in 1982[55] for software products and for in-house development of programs. Sales of software in the United States doubled between 1982 and 1983 from $5 billion to more than $10 billion, and are expected to increase to more than $24 billion in 1987 (see table 59).

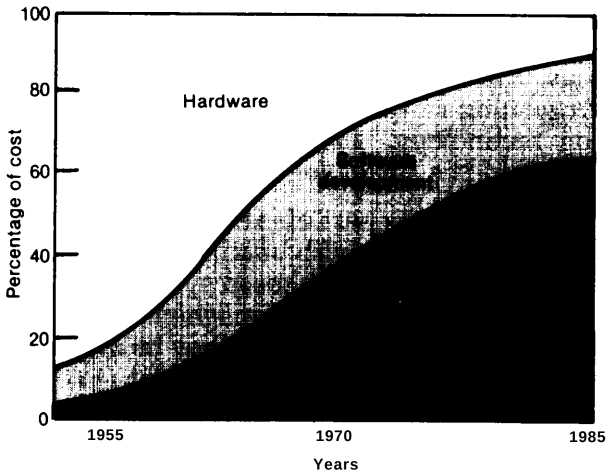
As information technology applications proliferate in the office, factory and home, and in the military, computer software is required to fulfill many new and complex functions. The growing demand for software is causing pressure to make software more useful, reliable and cost effective, and to make software development more productive. Not unexpectedly, software comprises higher and higher proportions of the cost of new information systems. Estimates of the relative cost of software in large systems range to above 80 percent (see fig. 62).

5%. Olsen, "Pathways of Choice," *Mosaic,* July/August 1983, p. 3.

The Changing Role of Software in Information Systems

Computer software is traditionally classified as two general types: applications *software* that is designed to apply computer power to

Figure 62.—The Relative Costs of Software and Hardware



SOURCE: Steve Olson, *Pathways of Choice,* **Mosaic, July/August 1963, p. 6.**

Table 59.—Software Sales by Use

	1982	1983	1984	1985
		(millions	of dollars)[a]	
Software, total	5,001	10,309	15,017	24,677
Application programs, total	1,997	3,448	5,455	11,100
Computer-aided design, manufacturing and engineering	776	1,126	1,636	3,200
Other applications	1,221	2,320	3,819	7,900
Systems software, total	3,004	6,861	9,562	13,577
Compilers, interpreters, and assemblers	541	610	700	932
Data-base management systems	1,100	1,430	1,888	3,500
Diagnostic and performance monitoring	493	645	710	
Operating system	870	4,176	6,264	8 , %

[a]All figures in current U.S. dollars.

SOURCE: *Electronics,* Jan. 12, 1964, p. 128, a specific task or tasks, such as computer-aided design of automobiles or inventory management in a retail store; and *systems software* that is used to manage the operations of information systems themselves, such as computer operating systems or database management systems.

Applications software has come to include a user interface that allows persons other than computer professionals to work with the computer system, while systems software is designed to help computer professionals write and execute programs, make efficient use of system components, diagnose and correct faults, and manage and audit system resources, contents and usage. This distinction, though useful, is beginning to break down with the advent of personal computers, in which operating systems are important tools to help users control the workings of their machines and perform such mundane tasks as copying files. However, the ends to which the software is applied still remain distinct-applications software solves user problems, systems software solves computer problems.

In general, systems software is an integral component of the hardware because its job is to control the hardware and to schedule and accommodate the development and execution of applications programs. The trend has been for the manufacturers of hardware or specialized software vendors to write systems programs, and for more of the systems programs to be embedded in hardware, or ROM (Read Only Memory), making the end user incapable of altering them. There is also a trend toward the standardization of operating systems to increase the *portability* of applications software, or the ability to use identical applications programs on different machines.

The expansion of the computer user population is being fueled by the expanding content of information systems, and is leading to an expanding definition of the term "software." Information systems are increasingly encompassing and integrating many collections of information formerly considered to be separate and segregated, such as the files of corporate divisions or government departments. The technology that has heretofore embodied such large information bases, for the most part paper and print, was not integrated; thus the information contained in those files has not been accessible to single individuals. Now, relatively cheap computer terminals and telephone links are making the enormous amounts of information being stored in digital electronic form (software) accessible by people in their homes and offices.[56] Through such services as videotex, newspapers, periodicals and even entire libraries may eventually be made available "on-line.

Integration of information management on such a large scale will require sophisticated control software to help people find the information that they want; advances in information science and contributions from such fields as artificial intelligence and psychology will be needed for this to occur. The integration of information management will also have profound effects on the way people view and handle information, and on how organizations conduct their business; the social sciences (sociology, political science, anthropology) will increasingly be looked to for understanding of the inevitable organizational and human conflicts that will flow from the changes in information access and use made possible by information technology.

The Software Bottleneck

Demand for computer applications is outstripping the ability of the traditional large data processing organizations (e.g., banks, insurance companies, government agencies) to supply the programs these organizations need in a timely and cost-effective manner. The lag

[56] The massive integration of information systems raises a number of public policy issues including questions of the government role in protecting *intellectual property,* privacy and other civil liberties assuring equity of access to information, and the effect of information technology on the processes of government itself. These and related issues are the subject of two OTA assessments now in progress, "Intellectual Property Rights in an Age of Electronics and Information" and "Federal Government Information Technology: Administrative Process and Civil Liberties. "

time between identification of an application and completion of the software in the average data processing department is 2½ years and is increasing, probably discouraging the proposal of many new applications.[57] There area number of factors that contribute to this "software bottleneck, " chief among them that approximately 50 percent of the data processing budgets are spent maintainingg old programs—making changes in existing codes because of errors in the design or coding of programs, or because applications requirements were inade quately specified.[58]

Another factor that slows the development of new programs is that software development, as it is practiced now, is *project-oriented*. Each new program is built up from scratch with little systematic reuse of parts of older programs, even though identical functions may be implemented. The knowledge and experience gained in one project are not systematically preserved and transferred to other projects. Innovations in programming techniques tend to be adopted piecemeal as project budgets allow. As a result of this project orientation and lack of standardization, large programs that must rely on the efforts of a number of programmers tend to be patchwork of pieces that reflect different programming styles, and are often nearly incomprehensible to people other than the original authors. These problems are exacerbated by a turnover rate among computer professionals estimated at 15 percent per year.[59]

[57] A recent survey of IBM **mainframe-based** data processing departments found that the average time lag for the initiation of applications programming projects is 2 years and this lag is growing by 3 months per year. Once under development, the average application requires 8 months **to** complete. At the same time, software representing 10 months of programming effort is discarded yearly by the average data-processing department because of obsolescence. A certain backlog of work is desirable to keep data-processing staff busy, but it is clear that many organizations are falling behind. *Application Development in Practice,* Tech Tran User Survey, Xephon Technology Transfer Ltd., 1983., p. 2.

[58] **W. Rauch-Hindin,** "Some Answers **to** the Software Problems of the 1980s, " ***Data Communications,*** May 1981, p. 58. See also the Case Study on Software Engineering.

[59] **This** figure reflects a recent decline in turnover attributable to the last recession and may well be on the rise. Also, it is believed by experts that the greatest turnover is among those professionals *writing code, so* that this figure understates the effect of turnover on program development productivity.

These difficulties combine to produce the present software development situation in which time is wasted in writing essentially identical parts, testing is laborious and expensive, and maintenance programmers spend most of their time trying to understand programs rather fixing them. The difficulties have grown out of the historical context in computing in which hardware resources were expensive, and the creative aspect of programming was devoted mostly to the efficient use of these resources through the clever compression of code. Now, with the precipitous decline in hardware costs, progr amming productivity rather than code efficiency is widely recognized as the limiting factor in the use of computing power.

The software development resources now in use appear to be inadequate and too fragmented to keep up with the demand for computing power. These resources include trained manpower and tools (software development tools include workstations, computer-aided-design, coding and testing programs, and documentation) to aid designers, programmers and managers in creating and maintaining cost-effective, reliable software.

Computer manufacturers and software developers, and government, university and industry experts are recognizing the problems associated with the software bottleneck and see the potential for sizable productivity gains by changing the nature of software development. For example, some avenues to alleviating the productivity problems of software development and maintenance lie in the use and reuse of standard function software modules, and the development of software to produce, test, and maintain other software. Research and development efforts in software engineering are seen as essential to this change (see Software Engineering Case Study).

Software and Complexity

Computer software is an important factor in making information technologies useful in a widening array of complex applications—from space vehicles to telecommunications networks to weapons systems. Software is used to produce *simulations* of complex systems and events, so that scientists and engineers can experiment and analyze without building expensive prototypes, and to control the *operations* of the most complex of man's creations, such as nuclear reactors and the space shuttle.

The need to manage a variety of increasingly complex systems is a major source of the pressure to improve software capability and reliability. For example, a large air traffic control program can consist of more than half a million instructions that must mesh perfectly and be essentially free of errors.[60] The efforts of hundreds of programmers over several years may be required to produce a software system of this size. The complexity of the software makes it virtually impossible to assure that no errors are present in a completed program.[61]

Software written for critical applications such as air traffic control, manned space vehicles, nuclear reactors, weapons systems, or electronic funds transfer, although impossible to guarantee as error-free when completed, must be constructed in such a way that at least the parts of programs and their *interconnections are* rigorously designed and adequately tested as they are built up. The complexity of software development is likely to increase dramatically with the advent of *massively parallel* computing systems and the construction of large *knowledge-based* systems.

[60]Olsen, op. cit., p. 3.

[61]Every two-choice branch point in a program (where decision is made on what procedure will follow depending on the conditions that are present) doubles the number of possible paths that the program can take, so that a program with 10 branch points will have 1,024 possible paths. A program for a large air traffic control system may have more than 39,000 branch points. If a computer could test a trillion paths per second (a capability far beyond today's most powerful supercomputers) it would require over $10^{11,731}$ years (that's the number one followed by 11,731 zeros) to test all possible paths in such a program. See P. E. Olsen, and R. W. Adrion, M. A. Dennis Branstad, and J. C. Chemiavsky, *ACM Computing Surveys*, June 1982, p. 184.

Conclusion

The microelectronic and software building blocks for information technology are likely to advance dramatically in coming decades. The path of progress for microelectronics is reasonably clear into the 1990s as practical and theoretical limits are approached for silicon and as other technologies come into use. For software, the path is less clear, but most likely will include far more standardization, reuse of software modules, and development of software tools to produce, test, and maintain other software. Most importantly, the *integration* of the concepts behind advances in these two building block technologies will shape future capabilities.

Information technology capabilities and their efficient utilization will depend upon the integration of ideas from a variety of disciplines. For example, the acceptance and efficient use of emerging computer and telecommunications resources in organizations require understanding of behavioral and social variables, as well as understanding of computer technology. Similarly, computer-aided-design requires both new software and new hardware for the display and manipulation of complex designs. The integration of hardware and software in new microelectronics and software design tools leads to further advances in information technology itself.

This integrative interaction constitutes a powerful technological engine which is fueling the advance of information technology in many applications—including computers for science, engineering and business, robotics and computer-integrated manufacturing, telecommunications, and artificial intelligence, among many others. These applications in turn will influence opportunities for economic growth and create alternatives for change in society, and thus will have major impacts on some of the policy issues that will become preeminent for legislators.