12 February 1982, Volume 215, Number 4534 SCIENCE

The Revolution in Computers and Electronics

Philip H. Abelson

Effects of the computer and electronics revolution are all around us. They are so commonplace that we often do not notice them. Many of the individual effects are small. But taken together with large-scale changes that are in store, the summation is impressive. We are in the early phases of shifts in the economy and in social patterns comparable in magnitude to those of the industrial revolution. Some of the changes have already gone far. For example, the development of computational power, if viewed logarithmically, is probably already beyond its midpoint, although in absolute terms it still has far to go. Other aspects of the revolution are only in their beginning phases. Examples are robotics and the office of the future. This issue of *Science* is designed to provide an overview of the progress of the revolution as well as indications of developments that can be foreseen.

Readers of *Science* who examine this issue will bring to the task a diversity of backgrounds. Some will be experts, who will consider the material easy reading. Others who have some background in use of computers will find the articles informative. Those who have had little contact with computers will find part of the material difficult, but if they work diligently at comprehending the total content they will be rewarded. They will learn much about the revolutionary potential of computers. They will also obtain a behind-the-scenes glimpse of how American business and industry function.

The author is the editor of *Science*.

Cost and Performance Trends

For decades the dynamic engine of the computer revolution has been a steady increase in the number of circuits that can be placed on silicon chips and concomitant decreases in the costs of logic and memory. These decreases have led to related economies in the costs of computers. In this issue Branscomb states that "the price of small, general-purpose computers of comparable power . . . has been dropping at an annual compound rate of about 25 percent per year." At a time of serious inflation, decreases in dollar costs are particularly welcome. They are at least in part responsible for an annual increase in available computer power of about 40 percent. Accompanying the miniaturization that comes from crowding more circuits on a chip has been an enhancement in speed of computation and a great improvement in reliability. Reliability per circuit is now 10,000 times better than it was 25 years ago.

Another major trend is a move toward making computers more "friendly," that is, more easily used by those not versed in computer science. This development was largely motivated by a desire to expand the markets. It was made feasible by the decrease in costs of circuits on chips. Part of the computational capacity associated with the chips can be directed toward improving the human-machine interface. The friendliness is manifested in various ways, such as a series of simple instructions by the computer to the user. Perhaps the most striking help lately has come from substantial advances in computer graphics. The axiom that one picture is worth more than 10,000 words applies when complex information is presented in color on the screen of a cathode-ray tube. The article by Whitted describes recent developments in graphics, and his figures illustrate something of what can be done.

The number of circuits that can be placed on a silicon chip has been increasing exponentially for about 20 years. We know that exponential increases cannot go on indefinitely. But as Birnbaum points out in this issue, improvements will continue. Limitations will be circumvented. For example, the currently employed optical lithographic technique, which could be a limitation on processing the wafers, will be supplanted by electron beam– and x-ray–based techniques. After an analysis of trends in hardware, Birnbaum states that "advances in logic, memory, and storage are confidently predicted by technologists to continue at the present rate for the next decade." If these predictions are borne out, costs per circuit will be miniscule.

Software

Birnbaum is not so pleased with progress in programming for software. He points out that progress has been relatively slow. Evolution of the products of software has not matched changes in hardware. He states, "In the early days of computing, the ratio of hardware costs to software costs was about four to one; today it is probably closer to one to four or more." Bacon in his article writes, "The declining hardware costs allow new applications to become economical, but almost certainly new applications require new and more complex software. Many fear that the availability of the latter may be the gating factor in the growth of the computer industry."

A major reason for the comparatively poor showing of software is that its logical complexity typically far exceeds that of hardware. Bacon states that "in a large system it is not unusual to find the software responsible for more than 10^{12} bits of information. By any measure, the design and management of large soft-

0036-8075/82/0212-0751$01.00/0

ware systems are among the most complex tasks ever undertaken." A very large effort is now being devoted to programming and to the development of improved means of producing software. In any event the software bottleneck will be broken—either at small cost by ingenuity or at large expense by the employment of a large army of computer scientists.

Information Processing and Distribution

In the days before computers, information was collected and processed in analog form. Information was obtained in the laboratory by use of such analog devices as thermometers, thermocouples, voltmeters, and ammeters. The telephone system was completely an analog machine. Industrial processes were monitored and controlled by analog devices. In the last decade great changes have occurred in the way information is obtained, processed, and distributed.

Computers function and they store information by using the binary digits 0 and 1. The machines are so effective in their processing of information that would-be users have made the necessary efforts to convert their inputs into digital form. Once information is in digital form it can be transferred from one computer to another, it can be displayed on a cathode-ray tube, or it can furnish direction to a printer for hard copy.

The amount of information that can be transferred per unit time is dependent on the sending and receiving devices and on the communications link between them. When two mini- or maxicomputers are involved, the bottleneck tends to be the communications link. Minicomputers can process on the order of 10^7 bits per second. A conventional telephone line to the home can carry about 1200 bits per second. The Bell System, described in this issue by Mayo, has some 130 million miles of trunk cables that can carry individual bit streams of 1.5 million bits per second. It also provides special lines for higher data rates. The Bell System has installed computer-controlled switching and has moved to change the way signals are carried in telephone lines from analog to digital. It is also beginning to install glass fiber transmission lines that will be able to transmit data at rates up to 10^9 bits per second. The telephone system has an admirable record of reliability and continued orderly evaluation. It serves 175 million telephones and can promptly complete any of 6×10^{15} possible connections. For most of its customers the present conventional bit rate will be adequate, but this is not true for major business customers.

To transfer massive amounts of data among the branches of a major company requires very large bit rates. Edelson and Cooper in this issue state that "A large nationwide retail chain creates about 10^9 bits of sales information per day. Much of this must be exchanged among many locations, including company headquarters for management, inventory, and procurement control." Increasingly in business, audio and video teleconferencing is being emphasized to save time and avoid travel. Color video encoders operating at rates of 1.5 to 6.3 megabits per second are being introduced to improve the effectiveness and acceptability of teleconferencing.

Communications

For communications among large business users satellite transmission is highly competitive with terrestrial linkages. During the past 15 years there has been an exponential increase in the volume of communications and in the bit rate that can be achieved. A number of companies have entered the field. A recent entrant is Satellite Business Systems. It operates an all-digital system and employs the 14/12-gigahertz frequency band. Earth stations have 5.5- or 7.7-meter antennas combined with receiving and transmitting equipment in a small fiberglass shelter, often located on a customer's roof. Each such terminal has a throughput capability of 12 million bits per second. With time, the transmitting power of satellites will increase and the size and costs of earth stations will decrease. The recent settlement of the antitrust suit involving the Bell System will permit it to compete strenuously with Satellite Business Systems and others for the lucrative business communications market and ultimately for an expanded use of computer networks in the home.

About 75 percent of the U.S. work force is now engaged in the service sector. Two-thirds of the work force is concerned with information handling. Exchange of information is crucial to economic exchanges. To date, the medium by which information is exchanged and stored has been predominantly the 8½ by 11 inch sheet of paper. The impact of electronics and computers on office systems has been limited. However, revolutionary changes in office systems seem inevitable. A number of companies have been working to develop their version of the "office of the future." One of the leaders in this effort has been Xerox Corporation. In this issue, Spinrad describes the Xerox version. Instead of typing on paper, the system uses electronics to create, display, print, communicate, and file electronic documents. It exploits the sharply lowered costs of electronics and takes a form in which each element of the system has its own computational, storage, and communications capability. Each professional person has a terminal or "electronic desk." The elements of the system are linked by a wide-bandwidth communications channel, providing easy interaction. These local networks are, in turn, interconnected with distant systems. Spinrad's description of the system and its benefits is particularly easy reading. He writes on the basis of several years of living with such a system at the Xerox Palo Alto Research Center. One of the benefits he cites is the use of electronic mail. An electronic message is sent from one electronic desk to another, where it is stored until the recipient wishes to examine it. Such a system avoids unwanted interruptions by the telephone and the long delays of the postal service. Adoption of electronic systems in offices is likely to come only gradually. It will occur first in large corporations that are already heavy users of digital data and digital communications.

Process Control and Manufacturing

Electronics and computers already have a substantial role in the processing industries; they are destined to find greatly increased applications in design and manufacturing. In large chemical and petrochemical complexes use of large computers has been prevalent for a decade or more. There is now a trend toward use of distributed microprocessors. In addition, these very cheap microcomputers are becoming ubiquitous in small plants and in a wider array of industrial processes. Morrison points out that advances in electronics and computers have enabled industries to achieve better control of their processes with resultant improvements in quality, productivity, energy efficiency, and compliance with government regulations.

With microprocessors already cheap and becoming more so, their use in process control will continue to increase. The principal bottlenecks are in the sensors that yield process information, the devices that convert analog information into digital data, and the actuators that convert computer decisions into modifications of the processes. Software is an additional limiting factor in the rate of expansion of use of computers in the process industries. However, the advantage accruing from improved process control are such that this potential will be exploited in the years ahead.

An even greater opportunity for improvement lies in computer-aided design (CAD), computer-aided manufacture (CAM), and robotics, although here, too, progress will depend on the development of needed software. The United States has made progress in CAD and CAM, but its status in robotics is comparatively poor. In the latter area the Japanese are world leaders. Hudson cites the economic barrier as an explanation. He points out that when it costs \$100,000 to \$150,000 to build a robot to replace a man whose salary per year is \$25,000, there is insufficient economic incentive to build the robot. However, in hazardous jobs the robot would be employed. Prospects for broader application of robotics are changing. Many innovative firms are beginning to design and make them. Hudson speculates that "in a short time the cost of a typical robotic system will be paid back in 1 or 2 years. In the next decade the cost of a robot is likely to be down to \$10,000 to \$20,000, while skilled labor costs might easily be \$25 or \$30 an hour." The ultimate extent of the use of robots will be dependent on their flexibility. They will be widely adopted if the necessary software is developed to facilitate reprogramming them to address different jobs. For many tasks robots have already proved to be more dependable and accurate than humans. They will probably replace a large number of blue-collar workers.

For a long time robots will be only a minor though substantial part of the total manufacturing process. Computer-aided design and computer-aided manufacturing will have larger roles. These two functions can be combined to achieve the lowest possible manufacturing costs. Hudson points out that with CAD an engineer can define a part shape, analyze stresses, check mechanical actions, and produce engineering drawings from a graphics terminal. Manufacturing people can use this CAD geometrics and numerically coded information to create numerical control tapes that allow direct control of shop machines. Full exploitation of the potentials of CAD and CAM will require establishment of computer networks to tie together design, manufacture, materials management, and the monitoring of costs.

Societal Impact

The electronics and computer revolution is affecting many other areas of human activity, some of which are also treated in this issue. An important area that is not included is that of military applications—a topic that is not readily portrayed. Another topic that is not treated comprehensively is the future societal impact of the revolution. I sought the counsel of a number of experts whose responsibility it is to be future-oriented in such matters. They were all hesitant about making specific predictions. The consensus was that the impact will be very great.

The following are some of my own perceptions:

1) The revolution will continue throughout this century. Technological progress in this area will likely move toward (i) ever denser packing of solid-state devices, approaching 1 million circuits per chip, (ii) widespread use in telecommunications of both satellites and fiber optics, (iii) merging of data-processing and telecommunications technologies and systems, and (iv) large stand-alone machines and systems giving way to multinode networks and distributed processing.

2) Applications of computers will increasingly permeate a wide spectrum of human activities. Costs will continue to decrease relative to those of other goods and services.

3) There will be a change in the nature of the employment of a large fraction of the work force. Many routine tasks will be automated. Highly intelligent and educated people will find themselves in even greater demand. There will be more unemployment of those less well endowed or adequately trained.

4) In the management sector there will be more decentralization of office facilities. Electronic communication with video terminals will lessen the need for personal encounters and for much of the travel that now takes place.

5) A proliferation of sources of information, means of communication, and entertainment of many kinds will have profound effects on home life. The home will become a more attractive place to live in and to use as a base for many kinds of intellectual and other activities.

6) The revolution will affect those aspects of the economy that compete for the consumer's disposable income. Many consumers will find that they obtain more satisfaction from money spent on electronic products than, for example, on automobiles.

7) While bringing many benefits to society, the revolution will also bring problems, tension, and disbenefits. Changes in employment carry with them trauma for those displaced. To the ancient tensions between rich and poor will be added tensions between those with high intellectual capacity and the less gifted, and between the well educated and the untrained. Problems will develop with fixation on entertainment and possible misdirection of computer systems for antisocial purposes.