Electronics: Past, Present, and Future

We are so engulfed by electronics that we can scarcely gauge the impact of the art on society.

John R. Pierce

What *is* electronics? Once we associated electronics with vacuum tubes, but vacuum tubes are almost obsolete. Perhaps electronics is semiconductor devices. But then, what of magnetic cores and bubbles and liquid crystals? I think that electronics has really come to mean all electrical devices for communication, information processing, and control. This would include pre-vacuum-tube devices such as the electric telegraph, which replaced such light-wave communication as semaphore telegraphs, signal flags, and heliographs. It would include the telephone.

According to this definition, electronics was born nearly 150 years ago with the first electric telegraphs. One hundred years ago we had transoceanic telegraphy and the first crude telephony. Seventy-five years ago the telephone system had had a substantial impact on life but the continent had not yet been spanned. Fifty years ago we had transcontinental telephony, a good start on automatic switching, a crude start at transoceanic wireless telephony, and the beginnings of radio broadcast. Twenty-five years ago television had begun, we were on the verge of transoceanic telephony by submarine cable, and we had the first large and effective computers. Fifteen years ago we had the beginning of satellite communication and computers were out of the laboratory and into industry. Ten years ago computers were shrinking in size and growing in speed. Five years ago we were on the eve of what few expected—a pocket calculator more powerful than the first computer. And today? Today we are so immersed in, engulfed and almost buffeted by electronics that we can scarcely know the nature, extent, or impact of that art.

The author is professor of engineering at California Institute of Technology, Pasadena 91125.

Except for the computer, the things that I have mentioned show the impact of electronics on one field—communication. Largely, but not entirely (as x-rays remind us), electronics in other fields grew out of the electronics of communication. Today, communication, expanding as it still does, is only a part of electronics.

I think it is important to give some account of the widespread and astonishingly various triumphs of electronics. We frequently read of the triumphs of the computer in chess, or in recognizing patterns, or in transcribing speech, or in reducing profoundly the bandwidth required to transmit television, or in proving theorems, or in controlling traffic, or in providing information instantly and cheaply.

Electronics is, indeed, wonderful. But how wonderful?

I have made my own short list of things which I believe illustrates the wonders of electronics. It is certainly incomplete. It may be in error. The list includes three sorts of things: Those that would be impossible without the speed and accuracy of electronics (Table 1), those that would be exceedingly difficult or imperfect without electronics (Table 2), and those that are greatly aided or improved by electronics (Table 3).

Some of the entries may seem rather surprising. Surely, effective nuclear energy would have been impossible without the part electronics has played in discovery, design, and control. Archeology and electronics—what of carbon dating? In a recent report it was said that the four-color theorem has finally been proved. The computer played a crucial part. Physicists and others use computers to manipulate polynomials so complex that a trustworthy answer is completely beyond pen and paper.

In connection with medicine, biology, and chemistry we can recall nuclear resonance, spectroscopy, and measurements involving radioactive isotopes. Production of complex sounds is included because computers have been used to produce highly organized sounds of musical intent, sounds which, whatever their merit, could have been created in no other way.

In industry, numerically controlled machine tools are used in shops, large and small, here and abroad. Electronics has become an essential part of automation and process control. Planning and accounting, from the point of sale of a product to the annual report, have changed greatly as a result of electronics, as has banking.

It seems appropriate to ask whether, by considering the multifarious aspects of electronics and the world in which electronics plays a part, we can draw any general conclusions. So far I have tried to indicate the deep penetration and broad influence that electronics has had in our technology and our lives. In doing this it is difficult to distinguish fact from fiction and lasting impact from clever trickery.

There is quite another aspect of electronics and our experience with it. This is the insight that electronics and its use have afforded us on how science works in society. Electronics provides us a broad range of interactions of science with society that is at once heartening and illuminating.

One matter on which electronics casts light is the possibility of improving productivity in the service sector. It is a commonplace that increased productivity makes goods cheaper before inflation, while services do not become more productive and rise in cost in any terms. Electronics has provided services in which both output and labor can be measured quantitatively.

In telephony, the measure of output or use is the number of telephone calls per year and the measure of labor is the total number of employees. Over the past 50 years, the number of calls per employee has risen at a rate of about 2.5 percent a year, as shown in Fig. 1. This has been attained through automation of telephone switching and automation or partial automation of many testing, maintenance, operator, and billing functions.

In a day when opera, concerts, and the stage suffer from a constant audience size and ever-rising salaries, electronics has preserved the economic viability of music, drama, and entertainment. With the aid of electronic amplification, a small rock group can be heard "live" by tens of thousands. Records bring one

Table 1. Things that would be impossible without electronics.

Telegraphy
Telephony
Radio
Talking pictures
Public address systems
Television
Data communication
Radar
All automatic service and vending (except slot) machines
Management of airports and air traffic
Controlling moment by moment the total power used in industry
Radar and radio astronomy
A good deal of work in physics, chemistry, biology, psychology, statistics, mathematics, archeology, seismology, optical astronomy
Some medical diagnosis and treatment
Nuclear energy and nuclear weapons
Ballistic and guided missiles
Production of highly organized complex sounds
A machine to play chess

Table 2. Things that would be very difficult without electronics.

Calculators
Automation and process control
Guidance and navigation
Phonographs
Numerically controlled tools and processes
Collision avoidance
Large-scale testing
Seismography
Analysis of complex structures
Complex machining and fabrication
Much medical testing and treatment

Table 3. Things that are substantially improved by electronics.

Surveying
Banking
Retail sales
Typing, editing, publishing
Operation of automobile engines
Repressive government

performance to millions. Through television, a performance can reach a first audience of tens of millions, and reruns go on forever.

Electronics shows that productivity can increase in the service sector.

A demonstrated increase of productivity in the service sector is something that anyone can understand and applaud. A demonstration that science, industry, and the public interest can exist symbiotically is something that scientists should particularly applaud, because this demonstration helps to further their own interests, spiritual and temporal. Electronics has clearly inspired and supported scientists.

Solid-state physics was a sleepy subject before the invention of the transistor; it has become a major field of university research. All sorts of discoveries of great intrinsic and practical importance have followed: the elucidation of the band structures of various materials; the discovery and understanding of surface states; the devising, understanding, and exploitation of new compounds; and, most recently, the discovery of new states or phases in semiconductors illuminated by laser light—first a condensed phase of electrons and holes, and now a new metallic phase which is so strongly conducting that it can be used to switch a signal in 10^{-12} second.

Ranging a little further afield, there has been a similar growth of understanding in magnetics, in superconducting phenomena, including the exploration and use of the Josephson effect, and in the understanding of the nature of materials, including superstrength crystals which have no dislocations and spinodal copper alloys which derive their strength through a sophisticated control of dislocations.

Particularly worthy of mention is the production of transparent silica-based fibers a hundred or more times as transparent as the best glass. An attenuation of around 4 decibels per kilometer at 0.8 micrometer was attained by Corning in 1972; around 2 db/km at 0.85 μm by Bell Laboratories in 1974, and about 0.4 db/km at 1.2 μm by Nippon Telephone and Telegraph in 1976. Such fibers, used for communication by light waves, promise to be the most revolutionary advance in this field since the transistor and integrated circuits.

We should note that the very invention and production of integrated circuits has led to a new examination of materials, epitaxial growth, diffusion, the use of ion beams for both analysis and implantation, and to fundamental studies of the limitations of size, energy, and speed in the operation of semiconducting devices.

We should also note that the exploitation of electronics led Shannon to formulate in 1948 a penetrating theory of information which has had considerable consequences for mathematics as well as for communication.

Advances in electronics have produced social phenomena which all who respect both science and society desire—a body of scientific work which is shared among many institutions, and shared quite freely, which is of great scientific merit in itself, which has a clear value to and a beneficent influence on man's society, and which is of direct use to individual men. Who would want to give up his pocket calculator, let alone his telephone or TV?

Why has this interrelation among science as discovery, industry as provider, and government as a supporter of research in universities and elsewhere and as an initial market for such products as computers and integrated circuits been so agreeable and productive in electronics? Partly, I think, it has been a matter of selection and concentration.

The original thinker and experimenter can do only so much by himself and with limited equipment. Sometimes, fields of work have been pursued by many because of other people's new ideas and because the field has high prestige. Quantum mechanics and high-energy physics have progressed through deep insights which inspired workers and, of late, through massive government support.

Sometimes fields have attracted able minds into association and cooperative endeavors through government support toward goals quite other than giving every man something for which he will pay directly after taxes. The atom bomb and

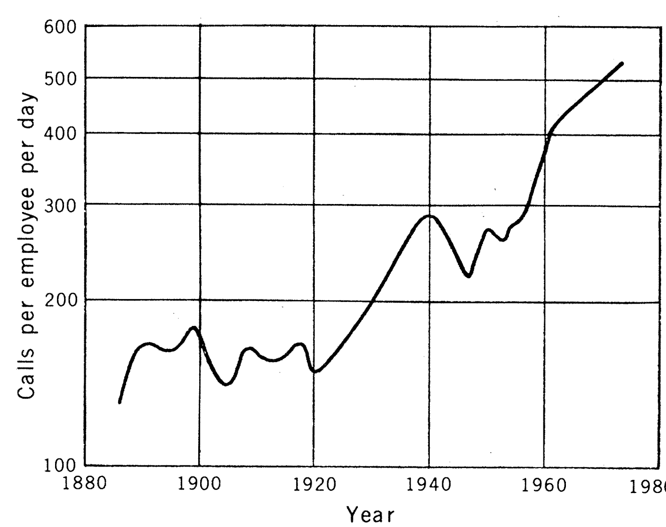

Fig. 1. Electronics can increase productivity in the service sector. The number of calls per employee at Bell Laboratories has increased at a rate of about 2.5 percent per year since 1920.

the space program are examples of successful cooperative scientific endeavors toward selected goals, goals much narrower than those of electronics.

Electronics attracted ingenious men to a reasonably defined area of work, it offered both scientific and commercial success, and, through this success, it provided support for the scientific work it had engendered. A good deal of wise support has come from the federal government, and taxes derived from electronics have flowed to the government to cover the support of electronics and other expenses. Further, our balance of trade has been saved from complete disaster only through the export of agricultural and high-technology products, and electronics has played a considerable part in providing high-technology exports.

Thus, electronics has created within our society a productive association among scientists and industries which has been profitable to both, and to consumers as well. In so doing it has answered the question, What sort of industry is better, large or small? The answer is both, and a little more.

Without small industries, many things would not have happened as quickly as they did. This includes transistor radios, hearing aids, and really good oscilloscopes. There are all sorts of other examples. Small companies move fast. They have to be quick and successful with a particular product in order to survive.

Successful small companies do more than supply the user with an attractive product at an early date. Very successful small electronics companies become larger and more diversified companies. Beckman Instruments, Varian, Techtronics, and Hewlett-Packard are a few examples among many. These firms supply a host of users with a variety of complex and sophisticated electronic devices on which science and progress have come to depend.

Important as they are, small and medium-sized companies draw the science on which they thrive, and sometimes the invention, from outside sources. They devise, perfect, and market rather than discover. The sort of inspired research of doubtful outcome which brings revolutionary advances is done elsewhere. Sometimes it is done in universities, but much is not. Academic activity seems not to span all socially important aspects of nature, or perhaps not to pursue them deeply enough. Much original discovery and the invention based on it has come from large industrial laboratories.

Industrial laboratories can carry out long-range work only if they are attached to large, stable industries which support them through thick and thin. Valuable discoveries are made on the average, not regularly at the end of each fiscal year. A small or even a medium-sized laboratory cannot afford even a productive long-range program of discovery. Enduring as government laboratories have been in pursuing many worthwhile endeavors, by and large the process of significant discovery has eluded them.

Thus, tangentially, the success of electronics has answered the question, should business be large or small? Success depends on both kinds. Small business has been quick to improve and exploit. It was no accident that the first successful microprocessor did not come from a giant in the computer industry. But large business has provided much of the ground from which discovery has sprung.

Electronics has interacted with all areas of society, including government in its regulatory as well as its supportive function. In this encounter, the stifling effects of regulation, even in an area as scientifically powerful and socially useful as electronics, have been made painfully apparent.

A high quality of telephony with moving vehicles is technologically possible at a price which would probably be attractive to a large number of users. What we have is a pittance of poor service and citizen's band radio. The latter is wonderful as a sport and influential on our language. We quickly recognize the true double-talk in which each statement is repeated as a consequence of trying to make ourselves understood over CB. Neither present mobile telephone service nor CB is an extension of what we should ask of telephony.

Our lack of a mobile service which is a compatible extension of telephony is entirely a consequence of government action, or inaction, in assigning adequate frequencies to someone who will provide adequate service.

The first successful active communication satellite (Telstar) was launched in 1962 and it carried live TV across the ocean. The first commercial satellite transmission was carried by Intelsat 1 (an outgrowth of the Syncom of 1963) in 1965. While international satellite traffic has increased rapidly in the 11 years since then, the first American domestic satellite was not launched until 1975. While six American domestic satellites are now in orbit, their use is limited, partly because of regulation of use, and partly because regulation has prevented the commercial use of the higher frequencies that are more suitable for domestic purposes.

Thus, government regulation has retarded the use of satellites for domestic communication. We may note in passing that government support of propagation measurements at higher frequencies was late and niggardly. For years the only measurements available were those made by industry, using the sun's microwave radiation and the microwave temperature of the sky as tools. Even detailed knowledge of the pattern of rainfall was obtained by industry rather than through government studies.

We may also note in passing that successful as satellites for overseas communication are, their vulnerability poses a threat to us which most do not appreciate, and the way in which our government decreed that satellite service be provided makes it seemingly impossible to do anything about this vulnerability.

Many have hailed cable TV and pay TV via cable as the best hope for mass communications in the future. They see many channels and new sources of revenue as an economical, commercially viable way for providing programs to segments of the public as well as to the whole TV audience assembled. Surely, cable TV and pay TV can give us local as well as regional and national news and advertising, and programs aimed at groups with special interests as well as programs aimed at the least common denominator. Or can they? Not as long as the regulators procrastinate and make inordinate demands for more complicated and higher quality service.

Not all important aspects of electronics involve all of society. Many problems, and particularly problems of a systems nature, arise from the very nature and power of electronics itself.

To me, the fact that I can pick up a telephone, dial a person in a distant city, talk, terminate the call and find it itemized with the number called on my telephone bill, all without human intervention, is more amazing than that a computer can be programmed to play a fairly good game of chess. The direct-dial, long-distance, automatically billed call is wonderful because of the complexity of the total system involved, which among other things, seeks an alternate route if the primary route is not available, and which functions even when some routes are destroyed. It is particularly wonderful because all sorts of different equipment of many vintages somehow operate together to give a standard service, and because this service is so reliable, working because of and in the face of continual maintenance.

Further, if we were to look inside the system, we would find a surprising amount of automated planning, testing, and maintenance.

Making a computer play chess is something that a single clever man can understand and do. Making a huge, complex system like the telephone network is something that no single man can do, nor can one man understand the telephone network in complete detail. The whole network operates because various pieces have been made to operate reliably in a prescribed manner, and a way has been found to connect together pieces whose functions, as seen from outside the black box, are known and orderly.

The sort of large, multiprocessor system that the telephone network is leads us to problems of complexity in digital systems such as computers. I can remember the days (about a decade and a half ago) when it was axiomatic that the best computer was the biggest computer. Grosch's law (now repealed, I believe) told us that the cost of computation decreased inalterably as the size of the computer was increased.

Computerniks met the challenge of complex systems head on. Operating systems and languages became capable and complex almost without limit. Computer manuals grew from slim volumes to 5-foot shelves of books. The computer was capable (between crashes) of doing anything for everyone, and everyone was urged to put his problem on one big machine.

When even the most primitive small transistorized computers came along, battered users fled the large systems and put their problems on their machines. Small computers equipped, adapted, and programmed to carry out a particular range of functions very well are now commonplace in laboratories, industries, businesses, and military systems. And, a good deal of computing that would once have been done on the computer is now done on hand calculators.

However, a small computer will not do everything. Sometimes the owner of a small computer will want to use the facilities of a large central computer to plot data, or to draw pictures, or to print out elegant text, or to compile programs. He may wish to use a central file system in editing programs or text. He may want to use a central computer to transfer data to some other computer.

Thus, a small computer may become part of a computing system. Like a local telephone office, one computer can do some things by itself. In order to do other things it must call on other parts of the system.

The parts of the system it calls on may not be computers. They may be plotters and printers. Other components may be smart instruments which take data or even run complete tests. Others may be efficient special processors. In the commercial area, point-of-sale and other terminals must communicate with host computers.

The problems of digital electronics are great. They involve more than the search for algorithms which will enable a computer to play chess, or retrieve information, or speak, or listen and type out. They involve the efficient organization of various limited or special purpose digital equipment into a system which will accomplish some overall result in a useful and effective manner. In many systems, such as those used for credit card verification or electronic transfer of funds, equipment in various geographical locations is of different manufacture. The inside of one piece of equipment is unknown to another piece of equipment or to its designer. Only the overall function provided and protocols of communication are common among various installations.

Data communication systems themselves must somehow conform to the requirements of the equipment they interconnect. Two extreme solutions are to provide translation among all possible protocols and to buy equipment from one manufacturer only. An intermediate solution will have to be found.

Whatever aspect of electronics we consider, we find it difficult to distinguish among dreams of the future, misconceptions of the present, and actual accomplishment. Electronics seems too extensive to evaluate.

Yet is is clear that electronics is a necessary ingredient, not only of the communication, out of which it grew, and computation which is a chief present manifestation, but of transportation, nuclear energy, and a great deal of various commercial activity and in scientific research of all sorts.

When we consider electronics in detail, we find that progress has been greatest and quickest in providing ever faster and cheaper memory and logic. The speed of electronics assures that electronics must surpass human capability for many tasks.

Despite problems of complexity, computer scientists have produced algorithms which solve very difficult problems, once those problems have been well posed. Thus, computers far exceed human capabilities, not only in numerical analysis, but in guidance and control; in the manipulation of polynomials; in keeping books and in making out income taxes (once the accountant has made certain crucial decisions).

Indeed, computer users have been ingenious in finding problem areas in which computers excel man by far. Computerniks also have ingeniously found a number of problems at which computers are inferior to man, including understanding speech, recognizing complex patterns (people, for instance), and playing chess.

However much progress we have made, there are still many unsolved problems in electronics. One of these is how to assemble digital equipment of many sorts from many manufacturers into large systems which will perform complicated tasks economically and very reliably.

Another problem is how to produce small, cheap, reliable interfaces to link cheap, fast logic and memory to tasks in the world around us. Such interfaces include displays, plotters, printers, keyboards, communication gear, sensors of all sorts and natures, simple and complicated, and all sorts of activators.

Surely electronics will progress as rapidly and as profitably and as complexly in the future as in the past. We will always think that we know where it will be in the future. We will continue to have misconceptions concerning the time state of electronics at any particular time.