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The Electronics Revolution

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Earlier in the century, this country experienced a long era of sustained growth in many aspects. There was a steady increase in level of education, life expectancy, and standard of living. Growth of all kinds was welcomed, including industrial expansion and population increase. A feeling of progress, of achievement, of well-being was everywhere. As a corollary, a striving for excellence and the search for understanding were widely admired.

Today the mood of this country has turned pessimistic and negative. Those who are so inclined can find much evidence to support these views. Growth in the use of energy in the form of oil was suddenly curtailed in 1974. Growth in consumption of the kind seen in the 1950's and 1960's will not occur again. That part of the standard of living which is based on large-scale consumption of energy is not likely to improve during this century.

However, those who prefer optimism have reason for hope. Human ingenuity in solving problems is great. And native intelligence has been amplified enormously by the use of knowledge accumulated through research. An important product of research and a basis for hoping for a bright new future is the vitality of the electronics revolution. This revolution has been in progress for about 60 years. Lately its tempo has increased greatly. Until recently its importance was overshadowed by changes due to the large-scale expansion in the use of energy. But it promises to be more important, of more enduring consequence, than the earlier industrial revolution.

Some of the great changes brought about by the electronics revolution have gone comparatively unnoticed; at the start they were evolutionary rather than sudden and drastic. The telephone, which we take for granted, was invented 100 years ago. Nearly every decade since then the quality and scope of service have steadily improved, and the cost (measured in constant dollars) is now a tiny fraction of what it was 50 years ago.

Numerous applications of electronics gradually affected individuals and almost every component and activity of society. Radio was a marvelous toy and a source of wonderment when it was introduced 50 years ago. Now Americans listen to commercial radio an average of nearly 4 hours daily, and radio is accepted as practically a natural phenomenon. Television, which created a stir 25 years ago, is likewise commonplace.

During the last few years the impact of electronics on society has increased greatly. Examples are the rapid growth in popularity of citizens band radio, the worldwide use of the telephone, and the current astonishingly low prices at which hand-held calculators and electronic watches are being sold. Less evident to the individual but in total more important to society are other applications of electronics that affect nearly every sector of our economy.

This revolution, which is destined to have great long-term consequences, is quite different in nature from the industrial revolution. The industrial revolution was based on a profligate use of energy (mainly fossil fuels). Much of its technology was crude, with only a modest scientific or theoretical base. In large measure what the industrial revolution did was to make available and to employ large amounts of mechanical energy.

In contrast, the electronics revolution represents one of the greatest intellectual achievements of mankind. Its development has been the product of the most advanced science, technology, and management. In many applications electronics requires little energy. Indeed, one of the factors that guarantees enduring impact for the electronics revolution is that it is sparing of energy and materials.

With electronics one can control the disposition of large amounts of energy and force, but much in the way the brain is used in directing the action of muscles. In some aspects, electronics can be more subtle, more nimble, more dependable than the brain. In other applications, electronics serves as a great extender of human capabilities by rapidly carrying out routine but complex calculations, thus freeing the mind to make intuitive judgments and find shortcuts to new insights.

The industrial revolution, dependent on energy and materials, will be slowed and limited by the paucity of these necessary ingredients. The electronics revolution, fueled by intellectual achievements, is destined for long-continued growth as its knowledge base inevitably increases. Obviously, the current rapid rate of evolution of electronics cannot persist indefinitely, but significant change is likely to continue for a long time.

One of the factors contributing to this dynamism is that in laboratories devoted to extending the electronics revolution the use of powerful investigative tools based on electronics is speeding new developments. Moreover, the body of knowledge that is being accumulated in the natural sciences continues to grow, and its growth has been fostered by the new tools that electronics has provided. There are few laboratories devoted to studies on the frontiers of the natural sciences that are not dependent on one or many items of electronic-based equipment. Two examples indicate the extent of the impact. A human's speed of reaction is about one-fifth of a second. Measurements can now be made in times as short as 10^{-12} second. More important is the overall effect of electronic devices on quantitative determinations of many kinds. In some instances sensitivities have been increased by orders of magnitude while the times required for measurement have been diminished to a hundredth or less of those needed in earlier methods.

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One of the factors favoring the development of electronics has been a comparatively high degree of social acceptance. There have been sporadic attacks on various electronic devices such as computers and there is continuing concern about privacy, but the intensity of criticism has diminished. In comparison to the number of objections raised to chemical products, to the environmental concerns associated with nuclear and fossil fuel energy, or to fears of recombinant DNA, objections to electronics have been few.

The average citizen is fearful of air pollution, for example, and is frustrated by a feeling that there is little an individual can do about it. In contrast, if a television program is offensive, it can be summarily dispensed with. Items that have recently become broadly available, such as the hand-held computer, electronic watch, and citizens band radio, enhance the public's feeling of participating in the benefits of electronics while not bringing with them discernible side effects. In future, electronics will provide many new tools useful to the general public.

The first four articles of this issue were designed to provide an overview of the past, present, and future of electronics. This is a large task, worthy of a shelf of books. Three major themes are treated in various ways in some or all of the articles: the tempo of the revolution, its magnitude, and the changing driving forces that have spurred it.

Until 1940, developments in electronics took place at a comparatively moderate pace. As was true with many scientific and technological matters, the pace quickened during World War II and was further maintained during the Cold War. Two major developments occurred independently during the late 1940's and later fused to give enormous impetus to electronics. One was the construction of programmable electronic computers. The second was the invention of the transistor. Subsequent developments in solid-state physics led to the present-day silicon chip with its large-scale integrated circuits. One such circuit in 1977 can contain more active elements than the most complex electronic equipment of 25 years ago.

After about 1960, when solid-state devices were incorporated in computers, there was a rapid development in the capabilities of computers and a steady reduction in the costs of calculations. An important effect of integrated circuits has been a reduction in the size and power requirements of electronic equipment that has made possible, for example, a Viking lander. Other advantages include reproducibility, maintainability, and reliability. Especially helpful is a sharp decrease in the need for making interconnections.

Large Scale Integration

The tempo of change has been impressive. In 1959 a chip that was commercially available contained one component of a circuit. By 1964 the number of components per chip had risen to 10, by 1970 to about 1000, and by 1976 to about 32,000. The cost per chip advanced only modestly. Thus, the cost per function has dropped drastically. It is this great change in the cost-effectiveness ratio that has made possible inexpensive hand calculators and related microprocessors and minicomputers. One of the key individuals who has been pushing the development of large-scale integrated circuits is Robert Noyce. His article in this issue discusses the development of these devices with special emphasis on what is yet to come. He shows that further advances can be expected. Theoretical considerations show that physical limits have not been approached. He is so bold as to state that "if the present rate of increase of complexity were to continue, integrated circuits with 10^9 elements would be available in 20 years."

All of us have seen examples of the sudden termination of exponential growth, so perhaps Noyce's figure will never be attained. But substantial advances toward his goal are already in progress. He seems justified in the view that "the potential for developing inexpensive processing power is truly awesome." He projects that with low-cost processing many new tasks will be undertaken that are uneconomical today.

Another way of glimpsing the tempo and magnitude of the electronics revolution is to focus on what has been happening in computers. In the early 1950's, almost all computers were owned by or devoted to tasks of the federal government. Computers were procured for use in such applications as defense and nuclear reactor design. By the mid-1950's there were about 1000 large-scale computers, and the tendency was toward increasing computational power. By the mid-1960's, there were 30,000 computers, and the generally accepted view was that costs of computation decreased with size; that is, the larger the better. At the end of 1976 there were about 220,000 computers in the United States. Of these, 40 percent were medium or large computers; the remainder were minicomputers which are small and by definition cost less than \$50,000. At the same time, there were 750,000 of the microprocessors that form the heart of microcomputers. Ruth Davis estimates that by 1980 the number of minicomputers will reach 750,000, while the number of microprocessors will increase to more than 10 million.

As the number of computers in service grew, the uses and the organizations involved broadened. The Davis article summarizes the current distribution of ownership of conventional computers. The percentages in the major categories are: manufacturing industry, 31; miscellaneous business, 13.3; financial institutions, 13.4; wholesale and retail trade, 13.1; educational institutions, 5.7; state and local government, 5.7; and federal government, 3.4. There is further scattering of ownership throughout virtually every kind of organized activity. Thus it may seem that an enormous shift in the nature of the market for large computers has occurred. Beyond that is the larger market for minicomputers and the much larger mass demand for microprocessors.

Coincident with the expansion in the number of computers has been an increase in the number of computer professionals. During the past 20 years the total number of analysts, designers, programmers, and operators has increased from 100,000 to 2.5 million. The number of students having some degree of familiarity with computers is much greater. This reservoir of people familiar with applications of computers is certain to facilitate additional applications of electronics. The emergence of computer hobby shops is bringing additional enthusiasts and imagination into the field. One group that is likely to make substantial contributions is the working scientists in the natural sciences. Often their progress and ability to tackle problems are limited by their equipment. Having experienced the advantages of incorporation of microprocessors in measuring devices, they will be looking for novel kinds of electronic sensors that can be coupled with the current data processors.

Because many of the new major applications involve various kinds of computers, one might have the impression that the electronics revolution and computers are synonymous. It is easy to lose sight of the importance of the noncomputer aspects of electronics. Key to many applications are the transducers or sensors. For example, computers would have a limited role in process control if electronic devices for sensing temperature, pressure, and concentrations of components were not available.

The potential applications of electronic technologies are so numerous and so provocative as to give free rein to futurologists and science fiction writers. The domestic robot, the wired city, the global electronic village—none of these can be dismissed as being beyond the bounds of technical feasibility. But it is not necessary to look so far afield to see how pervasive the impact of electronics is, how many areas of human endeavor and how large a portion of the country's economic activity may be substantially altered. Indeed, it is probable that reality will outstrip fiction in the rate of introduction of new and often unexpected applications of electronics in coming years. Witness, for example, the incredible growth in popularity of citizens band radio. It is clear that the capability of some electronic devices, particularly microprocessor circuits and memory units on single silicon chips, is developing more rapidly than applications can be conceived of and introduced.

The markets for kitchen appliances, office equipment, and leisure games, to mention just a few, are ready to be revolutionized or at least substantially modified by the addition of logic and memory to yield "smart stoves" and similar products, the first of which are now available.

The driving force behind many of the commercial applications is the extremely low prices for sophisticated electronic circuits, which in turn derives from mass production. The key innovation allowing such large markets is the microprocessor, a general-purpose logical unit that can be programmed to perform an unlimited number of tasks, thus eliminating the necessity of designing new circuitry for each new application. Among other applications, microprocessors are making it possible to extend computer control to mechanical and electrical equipment of every description, from consumer appliances and automobile engines to milling machines and industrial boilers. In the past, automation of manufacturing and process control has moved slowly because of fear of dependence on a central computer and the cost of the controlling units. The first process control computers introduced in the late 1950's, for example, cost about $300,000; minicomputers reduced this to less than $100,000 by the late 1960's; now microprocessor controllers are available for $3000, cheap enough to automate control and data collection for even small process steps. What seems to be evolving is a linked, hierarchical arrangement in which microprocessors are used to control individual pieces of equipment; minicomputers collect and process management information from the microprocessors for an entire factory; and large central computers use the resulting data in compiling corporate financial reports.

But the impact will not be confined merely to consumer products or isolated devices. The application of electronics is already having a pervasive effect on the entire economy and on our way of life, one that promises to intensify in coming years. Consider only a few of the areas treated in this issue—medicine, education, national defense, banking and retail sales, postal and other communications, and the research process itself.

The practice of medicine, for example, has already begun to change in such areas as the handling of patient records, billing and other administrative chores, and computer-controlled examinations in response to conventional data-processing equipment. Even more fundamental extensions of the physician's skill are resulting from the application of compact integrated circuitry to diagnostic and monitoring equipment. The potential of medical electronics is indicated by the unprecedented demand for tomographic x-ray scanning equipment, which by computer processing and synthesis is able to distinguish different tissues with a sensitivity 50 times that of ordinary x-ray techniques; hundreds of these new diagnostic tools have been ordered. Another new and noninvasive diagnostic approach, the use of acoustic waves in such devices as ultrasound cameras, is also beginning to be widely applied; here the key role of electronics is to translate the acoustic information into visual and analytical data. Perhaps the most striking illustration of the unique power of electronic circuits in medicine is their potential use as prostheses to supplement or replace damaged neural tissue, a circumstance that is only possible because modern circuits now approach the size, power consumption, and logical capability of the natural tissue. The cardiac pacemaker is an early example of such a prosthesis, and, as R. L. White and J. D. Meindl point out, the development of far more complicated devices such as an implantable electronic ear for the deaf is well under way.

Potentially, electronics and electronic media could have an important impact on education, as almost anyone who has observed children watching Sesame Street could confirm. Despite a few such successes, however, there seems to be general agreement that television and computer-assisted instruction have not yet lived up to that potential. But educational innovators have not yet given up, and one new approach is proposed by J. F. Gibbons in this issue. There is another sense, however, in which electronics is certain to affect education for better or for worse, and that concerns the prospective flood of inexpensive electronic devices of which the hand-held calculator is only the first. Calculators have substantially altered the character of the traditional "problem sets" in science and engineering courses at the university level, they are becoming common in high school courses, and they are already creeping into use in primary schools. Some parents and educators are trying to stem this growing tide on the grounds that it will only add to the reasons "why Johnny can't add." Others see the trend as inevitable and point out that how computation is performed is irrelevant, what really counts is whether the students learn the underlying concepts, and in this respect the impact of the calculator is still uncertain. In any case, the ubiquity of the calculator seems to guarantee that electronic arithmetic will become the language of the real "new math," and these developments suggest the potential of the more elaborate calculator-based games and educational devices that are beginning to appear either alone or as attachments to the home television set.

It is difficult to imagine a modern military force without heavy dependence on electronics. Aircraft instrumentation, missile guidance systems, radar and other surveillance sensors, tactical computers—all depend on electronic components. But electronics plays more than a passive role in military systems; in recent years, advances in electronics have been perhaps the most important factor guiding the evolution of new weapons and new strategies. One example is the emergence of "smart bombs" and other unpiloted weapons, which can evaluate guidance information to track themselves to target or make use of preprogrammed instructions to maneuver evasively. Carried to its logical conclusion, this trend might eliminate the need for many manned aircraft and is at the core of the current debates over the B-1 bomber and the cruise missile. A second example is the NAVSTAR satellite system, for which prototypes are now being tested. These navigational satellites are designed to allow any military vehicle carrying an inexpensive receiver and computer to instantaneously determine its position anywhere in the world with an accuracy of better than 10 meters in horizontal and vertical coordinates; civilian aircraft and ships will also be able to use these satellites, but with somewhat less accuracy. This phenomenal accuracy is expected by many defense analysts to revolutionize navigation, weapons targeting, battlefield management, and other aspects of warfare; this is especially true for fixed targets, since the coordinates of any such target can be readily determined. The system also may supplant many of the commercial navigation systems now in use.

In 20 years, the role of computers in research has been transformed from what W. O. Baker and his colleagues describe as "a minor annex of mathematics research" to a major and often dominant role characterized by the proliferation of dedicated minicomputers and time-shared terminals in most research institutions. They assert that computers have transformed the research process from conceptualization to experimentation to publication. Baker should know, since his organization has been in the forefront of actually putting computers to work in research—Bell Laboratories now have an average of one dedicated minicomputer and five interactive terminals for every 15 professional staff members. Electronics has also transformed other instruments of scientific research, from the electron microscope to vidicon astronomical cameras, and the process is accelerating as more and more "smart instruments" are designed around microprocessors.

Nowhere is the potential impact of electronics greater than in the banking industry and the Postal Service, both of which face the prospect of converting from moving pieces of paper around to using electronic transfers for at least part of their business. These changes will certainly not come overnight and will raise a host of social problems; how does one protect against theft when most retail transactions are done electronically rather than by check, or guarantee privacy if much first-class mail travels by wire? But electronic transfers of money, of messages, and of documents are already established features of our society. The U.S. government, for example, makes some 5 million Social Security payments each month by sending banks magnetic tapes that the bank computers will use to credit depositors' accounts directly. Preauthorized, nonpaper payments are estimated to account for 10 percent of bank transactions in some areas of the country. Point-of-sale electronic terminals are now becoming common in retail stores, although their role is presently restricted to credit verification and inventory control, not direct transfer of funds from the customer's account to the store's. But with 26 billion checks a year passing through the banking system and the likelihood that the volume will double by 1985, there is ample incentive for banks to move toward electronic transfer and checkless banking. As F. E. Balderston and his colleagues point out, such a move will change the boundaries between the retail trade and the banking system, possibly resulting in more decentralized but far more complex financial networks.

Checkless banking, if and when it does occur, will intensify the economic pressures on the Postal Service, since nearly 40 percent of the mail consists of checks and other financial transactions. Diversion of this mail will reduce revenue but will not noticeably lower costs. But that is not the only threat. As complaints about lost or delayed mail increase, many large businesses are looking toward electronic mail systems. One prototype of such a system is the Department of Defense's ARPA computer network, which is routinely used by researchers all across the country to exchange messages and information. New optical scanning and electronic printing techniques are being developed by many companies that would allow users to transmit documents or whole pages of text. The Postal Service may be forced to embrace electronic mail or face the future as an obsolete, increasingly expensive system serving fewer and fewer people.

Computers and Communications

Postal communications are not the only form of communications facing new challenges. Not long ago radio and marine cable telephone circuits were the principal means for rapid intercontinental communications. Now an international satellite communications system is well established and carrying a growing volume of traffic. Domestic satellite systems are just getting under way in the United States, but they seem certain to expand the options for voice, television, and digital data communications. The transmission of digital information is the most rapidly growing area of electronic communications and reflects the increasing need for computers and other intelligent machines to "talk" with each other. Indeed, as D. Farber and P. Baran point out, computer and communications technologies have become so similar and intertwined that they are difficult to distinguish. More and more communications are transmitted in digital form, even within the telephone system. And more and more information in the communications systems is processed both before and after transmission; voice signals are compacted and compressed to put more calls on a channel, for example, or the output of the intelligent terminal on one end of the phone line becomes the input for a computer or a display device on the other end. Distributed processing—essentially networks of small and medium-sized computers connected by communications links—is clearly going to be one of the major forms in which computers are used.

These developments clearly pose a major problem for those, such as government regulators, who must decide where communications—a regulated activity—ends and where the unregulated computer market begins. Elsewhere in this issue M. R. Irwin and S. C. Johnson summarize the public policy issues involved in this intensifying conflict, and point out that among the principal contenders are some of the giants of American industry, AT&T and IBM. It promises to be a multibillion-dollar fight and one of the thorniest technological policy problems the government must face in the coming decade.

The evolution of computers to the point where communications is a major part of their activity is also reflected in other changes. The traditional use of computers as calculating engines for numerical work is rapidly being replaced by a new principal role, that of managing, storing, retrieving, and distributing information. A search for new computer architectures that better reflect this new role is under way and includes experiments with such things as augmented sets of instructions for the computer's own control program, specialized subcomputers or processors to manage databases, and multiprocessor machines. The generation of computer programs—all too often a bottleneck to effective use of computers, as H. D. Mills points out—is increasingly being put on a firm mathematical basis. The way information is stored in computer systems is changing too, as researchers look for more efficient search routines, new methods of combining memory devices, and new computer languages adapted for information processing. S. E. Madnick, describing this evolution, believes that what is emerging is the goal of an information utility that can serve many users for many purposes. Prototype experiments with information utilities are actually under way in Britain, where the British Broadcasting Corporation is testing a small decoder attached to television sets that can, on demand, deliver current information on a variety of subjects; the British Post Office, which runs the telephone network, is also experimenting with a telephone-based information utility that would combine the functions of a daily newspaper with the resources of a library.

We are increasingly an information-based society. Economically, for example, information industries ranging from broadcast television to book publishing to computer services contribute a large part of the U.S. gross national product and employ nearly half of the work force. The information sector of the economy is also among the more rapidly growing. Moreover, information is a resource that greatly enhances individual capabilities and opportunities and is not depleted by use. H. A. Simon describes the development of the ability to process and manipulate information on a large scale as having a significance, on the scale of human evolution, equivalent to the development of written language or the invention of the printed book. In any case, it is clear that the information revolution will accelerate as more persons acquire their own computers and as these computers are able to make use of larger and larger information resources.

The conventional economic wisdom is that the expanding opportunities in information-related activities will more than offset jobs lost to more productive electronic equipment. Recent experience in the electronic manufacturing industries would seem to bear this out, although substantial layoffs in some companies have been avoided only by a commitment to large retraining programs. In the coming decade automated electronic equipment is likely to make inroads into the service sectors of the economy as well. The nature of secretarial and other office support jobs may change, for example, as may that of mail clerks and bank tellers. Whether any of these changes will result in displacing large numbers of people from these traditionally labor-intensive occupations is not clear, but the process of change is certain to be uncomfortable for the individual whose job is involved and maybe for society as a whole. Consider the impact of converting the Postal Service, one of the largest employers of unskilled and semiskilled labor in the country, to an electronic mail system.

Despite such problems the electronics revolution is not likely to slow down anytime soon, if only because the research base is broad and vigorous and is already producing a host of new ideas and new concepts that are certain to be translated into new products and services in coming years (Fig. 1). One trend that can be identified is the incorporation of magnetic, acoustical, and optical phenomena into electronic devices, giving rise to a host of new effects that can be put to use. Examples include magnetic bubbles in memory devices, surface acoustic-wave filters in signal processing equipment, and optical fibers in communications. Particularly fascinating in this regard is the push toward optical communications.

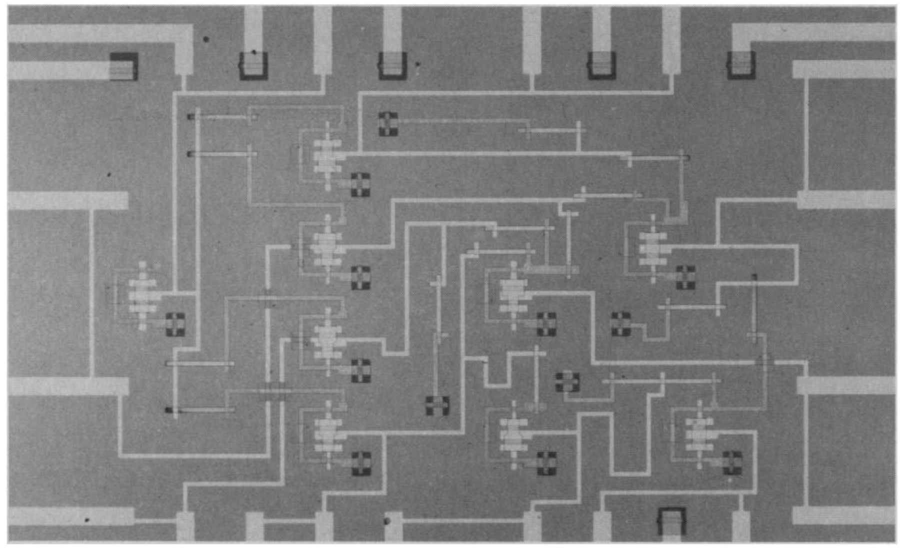

Fig. 1. Superconducting electronic circuits based on Josephson junctions are one or two orders of magnitude faster than conventional transistor circuits and consume a thousand times less power. This technology, which has yet to be incorporated in computers, may initiate a new era of extremely rapid processing equipment. The circuit shown here contains 18 Josephson junctions, operates at 4°K, and has an add time of less than 1 nanosecond. [Source: J. A. Giordmaine, Bell Laboratories]

The concept of transmitting information on a light wave dates back at least to Alexander Graham Bell, who in the 1870's demonstrated a wireless telephone based on light that could transmit sound for more than a kilometer. A hundred years later, optical communications is on the verge of becoming a reality. The principal advantage of communicating with light waves is their high frequency, compared with radio waves, which gives them a superior capacity to transmit information. A single optical fiber, for example, can carry hundreds of times as many bits of information per second as a copper wire. The Bell system is already experimenting with an optical link for interstation connections in areas with a high volume of calls, and others are looking at applications ranging from computers to military vehicles. As large-scale production of fibers and other components gets under way, cost reductions as dramatic as those in electronic calculators are expected.

In its modern configuration, optical communications relies on such components as lasers or light-emitting diodes for light sources and glass fibers for the transmission medium. It is, in fact, the dramatic improvement in these components that has brought the technology to the verge of utility. S. E. Miller reports, for example, that optical fibers have been produced with losses less than 1 decibel per kilometer—less than the loss in light passing through a single windowpane. But, just as solid-state technology progressed from individual devices to integrated circuits, integrated optical circuits incorporating lasers, amplifiers, and detectors on a single chip are already being developed. Many semiconductor materials, it turns out, are optically as well as electrically active, thus permitting the intimate interplay of both kinds of circuits. This activity is leading to an era in which the electron, long the workhorse of the electronics revolution, will be supplemented by the even greater potential of the photon.

The range of phenomena and the indications of still-to-be-exploited potential to be found in electronics research are convincing evidence that we have not yet seen the limits of what is possible. Still less are most of us and most of our institutions prepared to decide what we should do with our new capabilities or even how to cope with the speed at which electronics technology is changing the ground rules under which we operate. In business the price of being unprepared is often high, as many white goods manufacturers found out when one of their competitors introduced an electronically controlled microwave oven that has rapidly become the best-selling product in its field. For governments and individuals alike the stakes are arguably lower at present, but the continuing electronics revolution promises to be so pervasive as to compel the attention of even the most unobservant.