Microelectronics and Computers in Medicine

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Summary. Microelectronics and computers are in use in virtually every aspect of modern medicine. Computers are used widely in medical research, where an important need is for better microelectronic sensors for data acquisition. In medical practice, data collection from patients as well as subsequent storage, retrieval, and manipulation of data are enhanced by the computer. In medical decision-making computers improve accuracy, increase cost efficiency, and advance understanding of the structure of medical knowledge and of the decision-making process itself. Powerful new noninvasive diagnostic instruments including x-ray tomographic scanners and ultrasonic imaging systems are based on computers. The efficiency and scope of clinical laboratory procedures and advanced analytical instruments are greatly increased by computerization, and careful application of computers has improved the interpretation of diagnostic tests, such as the electrocardiogram, and monitoring of critically ill patients. The powerful sensory, computational, memory, and display capabilities of microcomputer systems and their compact size offer new opportunities to relieve functional deficiencies associated with loss of limbs, paralysis, speech impediments, deafness, and blindness.

The number of transistors commonly fabricated in a single silicon chip, now less than 1 by 1 by 0.1 centimeter in dimensions, has increased from one in 1960 to approximately 100,000 in 1982. Moreover, chip cost has remained relatively constant and reliability has improved during this period. A comparable rate of progress is projected for the current decade. Single chips including 1,000,000,000 transistors appear to be feasible about the year 2000 (*1*). The principal vehicle that has conveyed the microchip to its myriad tasks has been the computer in all its manifold forms, ranging in size from that of a credit card to a household moving van and beyond. The impact on society of this growth in capability of microelectronics and computers has been accurately described as both profound and pervasive (*2*). Moreover, microelectronics and computers have now come into use in virtually every aspect of modern medicine. In fact, the computer system, with data acquisition and display added to its computational and memory power, now epitomizes the application of high technology to diagnosis and treatment of disease (*3–7*).

Medical Research

Computers have been adopted, adapted, and absorbed into virtually every aspect of medical research (*8–12*). The crux of the creative process, idea conception, has been affected in a fundamental fashion. The kinds of ideas that are conceived, what they deal with, and the terms in which they are considered have been profoundly affected by the computer. The usable level of complexity of ideas has shifted upward dramatically. Computer models of biological systems (such as DNA) that involve many elements, interrelated in specific but analytically opaque ways, can now be evaluated, manipulated, and explored in quest of confirmation, insight, and narrowing of uncertainties (*8*). Computer simulation of disease processes, physiological mechanisms, and pharmacological interactions, as well as computer analysis of data, has made many important contributions to medical research.

Indeed, the success of the computer in storing and manipulating biomedical research data has now shifted the emphasis, in many instances, to data acquisition. That is, the principal need in many modern biomedical research projects is the design of appropriate experiments and the application of novel microelectronic sensors to acquire the database for those keen insights which epitomize major advances.

A fundamental requirement in data acquisition is that the method or instrument used to perform a scientific measurement not disturb the essential state of the system under test. In the case of animal models of human disease, for example, this may dictate that during data collection the animal not be anesthetized or physically restrained. In addition, it may be necessary to obtain data for periods of more than 1 year of normal life for both healthy and diseased animals, including 24-hour monitoring periods to account for circadian rhythms. One promising means of solving such problems is totally implantable microelectronic sensors that include radio-frequency transmitters for telemetering data to recording stations remote from the research animal. Totally implantable sensors for measurement of blood flow and pressure, organ dimensions, strain, and bioelectric potentials such as the electroencephalogram, electrocardiogram, and electromyogram as well as temperature have been described (*9, 10*). Such sensors are closely akin to the artificial implantable cardiac pacemaker, a now common prosthetic device which is often vital to the life of a recipient. [In fact, special-purpose microcomputers on a single silicon chip have been designed for use in implantable cardiac pacemakers (*11*) and programmed insulin delivery systems (*12*).]

Innovative applications of microelectronics in new implantable telemetry systems offer a singular opportunity for advances in biomedical research for two reasons: (i) more than all other types of biomedical instruments, implants exploit fully the inherent technical advantages—complex functional capability, high reliability, low power drain, small size and weight—of microelectronics, and (ii) implants bring microelectronics into intimate association with biological systems. For these reasons implants allow otherwise impossible experiments to be conducted to improve the quality of health care through advances in research.

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Medical Data Collection, Storage, Retrieval, and Manipulation

Medical data are remarkably soft in character. They are described, collected, and interpreted with a degree of variability and inaccuracy that falls disturbingly short of typical engineering standards. In order to provide data to a physician, a patient must first perceive himself as ill. The patient-physician dialogue then entails two types of data. The first is expressed by the patient and includes past medical history, a description of current illness, and statements in response to examination. The second type is directly obtained data, which do not pass through the patient's intellectual and emotional filters. These data include some aspects of the physical examination and diagnostic tests that do not require patient responses for their measured values. A patient's description of his medical history or illness may be compromised by intellectual, informational, emotional, and language barriers. Electrocardiograms, x-rays, hematology laboratory tests, and similar directly obtained data are more objective (*13*).

Variability in medical history can be addressed by use of standardized questionnaires that present the same questions phrased in the same way. Computer-obtained histories appear to be generally valid when compared with physicians' interviews. Computer-based medical information systems provide a memory of previous events that is less error-prone than human memories and that enhances the completeness and retrievability of all information. These systems may also reduce data variability and inaccuracy in a more subtle way by forcing consideration of how data should be defined and in some instances quantified. The process of data collection cannot be separated from data interpretation in connection with a patient's description of his illness. Indeed, in deciding what expressed and directly obtained data to collect, a physician must select questions on the basis of tentative decisions about the probable diagnosis.

In addition to their use in data collection, computers greatly facilitate data storage, retrieval, and manipulation for medical record-keeping, report-writing, and patient or third-party billing. Important features of such a system include confidentiality, ready accessibility, unrestricted space for entries, as well as editing and backup capabilities. Once data are entered, they should be available to be manipulated for numerous research screening and accounting purposes. Graphic displays on a television screen have the advantages of clarity in showing trends, for example, in disease progression and treatment response.

Only when accurate data can be collected, stored, manipulated effectively, displayed in an appropriate context, and then communicated properly do they become information. Computers make these functions possible and thereby offer substantial potential improvements in the effectiveness of clinical practice, although successes in the field have been limited to date (*14–18*).

Medical Decision-Making

Decisions are central to the diagnosis and treatment of disease, and many attempts have been made to use computer assistance in medical decision-making. To provide optimal assistance, computers should be used to augment or amplify other decision-making tools—principally the judgment of an experienced clinician. Computers are used in clinical decision-making mainly to (i) improve diagnostic accuracy by using systematic approaches and explicit decision criteria, (ii) enhance diagnostic reliability by precluding unwarranted influences of nonidentical but similar cases, (iii) increase cost efficiency, (iv) advance understanding of the structure of medical knowledge, and (v) gain insight into clinical decision-making itself (*19*).

Three paradigms of clinical reasoning have been suggested (*20*). These may be described as decision-making, clinical judgment, and problem-solving. Decision-making is the process whereby the clinician selects one action from a number of alternatives. Frequently, these actions are either diagnostic or therapeutic. The decisions about what question to ask while collecting a medical history and what drug to prescribe are specific examples. In clinical medicine decisions must be made under conditions of uncertainty. Therefore, in seeking an optimal decision, the clinician strives to formulate an appropriate set of alternatives and a consistent set of selection rules. Bayes' theorem from probability theory has been used to assist clinical diagnosis with computers. The question addressed is the following: Given a conditional distribution of diseases along with their characteristic signs and symptoms and a particular clinical syndrome in a patient, what is the probable disease state of the patient?

Decision analysis and other more recent analytic approaches have led to more comprehensive techniques for decision-making by including in the process more complex value statements and selection mechanisms for specific actions. Decision analysis provides an approach to a decision problem under conditions of uncertainty. This approach requires that preferences for various consequences be numerically scaled according to the value of their utility, and similarly that judgments of uncertainties be numerically scaled according to their probability. In clinical practice, the analysis attempts to determine the optimal or best medical action for a patient.

Physicians often refer to their clinical reasoning process as judgment. Somewhat more narrowly, judgment is a term applied to the study of the degree to which information provided about a problem is used in making a decision. Multiple regression and discriminant function analysis are useful tools in the study of judgment. Within this particular paradigm, emphasis is placed on the way available information is used by the clinician and not on whether the chosen treatment is correct in some objective sense.

The problem-solving paradigm views the physician as an information processing system that operates with the limited capabilities of the human mind. Careful analysis of the approach to solving a problem yields insight into the task environment and the strategies at work. These insights are then incorporated in a computer program with the goal of reproducing the problem-solving approach of the physician, given the original task environment. Here the focus is on the programs to be used by the problem-solver in guiding sequences of behavior. A problem-solving theory should first predict the performance of a physician handling specified tasks, including what processes are used and what mechanisms perform them. Next, it should predict incidental events that accompany problem-solving and show how changes in surrounding conditions affect problem-solving. Finally, it should explain how problem-solving skills are developed and what the problem-solver has learned when he has them. Computer-based clinical decision aids now account for a large portion of clinical computing efforts, but the acceptance of these aids by the professional health care community has been limited to date (*21–24*).

Computed Tomography

The advent of computed tomography (CT) precipitated a revolution in the field of diagnostic radiology because of the markedly enhanced resolution and reduced ambiguity it affords compared with common projection systems of x-ray imaging. Computed tomographic scanning consists of two sequential processes. First, x-ray absorption data from different views within a single cross-sectional plane must be acquired. Second, these data must be used as input to a computer, which calculates and then displays an image. This image is derived, for example, from a fan beam of x-rays passed through the body from many different angles. The x-rays are partially absorbed or attenuated as they pass through various tissues, and the variations so produced are recorded by x-ray detectors. The electrical signal outputs from these detectors are amplified, converted from analog to digital form, and stored in the computer memory. From these stored data an image of a single slice of tissue is reconstructed by the computer through the solution of a series of complex equations. The brightness of each portion of an image is proportional to the degree to which the tissue absorbs x-rays. The image is displayed on a television monitor in shades of gray or colors and is photographed for permanent recording. The image data can be manipulated to provide quantitative attenuation measurements of all regions (*25*).

Computed tomography images a transverse plane through the body similar to a section that might be made by a knife cut through a cadaver. In contrast with conventional x-ray imaging, which projects all anatomy between the x-ray source and the film plate detector into a single image, CT imaging presents a new vision of anatomic detail during life. Conventional x-ray imaging reliably detects differences in density in the range of 5 to 10 percent. Computed tomography can detect differences as small as 0.5 percent and therefore resolve heretofore unobtainable detail. For example, CT readily discriminates between normal and infarcted myocardium. It is also noninvasive and applicable to outpatients. Because the information CT provides is both quantitative and immediately available for computer manipulation and storage, it opens vast new opportunities for the computer as a diagnostic tool (*26–31*).

Ultrasonic Imaging

In comparison to x-rays, ultrasound is a noninvasive diagnostic modality that has superior characteristics in some circumstances and inferior ones in others. Applications in which ultrasound usually provides advantages include (i) imaging moving targets, such as the heart or fetus, (ii) imaging the pregnant uterus, where minimal x-ray exposure is advisable, and (iii) imaging soft tissues, such as muscles and blood, with similar densities but different acoustic properties. Applications in which x-rays are often more useful include imaging the lungs or the brain, where air passages and the skull, respectively, severely attenuate ultrasound (*10*).

The basic principle of operation of most ultrasonic imaging systems is similar to that of sonar or radar. A train of short pulses of high-frequency ultrasound is emitted by a piezoelectric transducer contained in a hand-held probe in contact with the patient's skin. As a packet of ultrasonic energy propagates through the body, most of it is lost through absorption by tissue, but a small amount is reflected at boundaries between tissues of differing acoustic impedance. It is this reflected or scattered component, which returns to the transducer, that provides useful information. Arrays of microelectronic acoustic transducers and associated circuits are used in a computer-controlled time sequence for both electronic focusing and scanning in a sector pattern to produce a real-time cross-sectional image. High resolution is achieved at all ranges since "electronic zoom" is used dynamically to adjust the focus of each depth. In addition, a large sector angle of 70° to 90° provides a panoramic field of view (*32, 33*) displayed on a television screen.

Ultrasonic instruments under computer control are now widely used for noninvasive imaging of the heart, kidneys, spleen, pancreas, liver, abdomen, gallbladder, fetus, brain, and eye. Their performance, compared with that of early instruments, has been greatly enhanced by the use of computers and microelectronics. Specially designed ultrasonic systems can measure the flow velocity of moving structures, such as blood cells in blood vessels, by comparing the frequency of the transmitted sound with the Doppler-shifted frequency of the returning sound. The frequency shift is proportional to the velocity of flow. Circuitry for distinguishing positive from negative Doppler frequency shifts allows the differentiation of forward or backward flow. Cross-sectional imaging systems and Doppler systems have been combined to allow the diagnostician to improve the accuracy of positioning the ultrasonic beam for measurement of the Doppler frequency shift. In contrast to x-rays, ultrasonic radiation is nonionizing and, when applied at the low power levels sufficient for diagnosis, causes no harmful effects. Indeed, the absence of patient discomfort, apparent safety, ease of performance, and measurement accuracy make ultrasound nearly ideal for use in human patients (*32, 33*).

Clinical Laboratories and Analytical Instruments

In modern medicine the clinical laboratory occupies a position of great importance. Few hospitalized patients escape undergoing a host of laboratory studies. Both mechanical equipment and electronic equipment are used in modern clinical support laboratories in response to the demand for rapid execution of large numbers of tests. This equipment is interfaced with computers in order to reduce response time, minimize errors, and control costs. Since the tests performed provide numerical results, an excellent opportunity is presented for computer data processing (*34*).

During normal operation of a computer-managed clinical laboratory, patient files can be kept current on a minute-by-minute basis by transferring automatically from a central hospital computer system information regarding all discharges, admissions, and transfers. This eliminates the need for routine keyboard entry of census data into the laboratory computer system. In addition, it permits results of completed tests to be transferred automatically to the correct nursing station as patient transfers occur. As patient specimens with attached requisitions arrive at the laboratory, they are entered by keyboard into the computer, which assigns accession numbers. This process provides accurate specimen processing labels and initiates computer communication of pertinent test information. Selected test results can be printed promptly at key clinical locations. Simultaneously, the test results are stored in the computer memory for later retrieval from terminals located in patient care areas. Automatic billing for laboratory tests is facilitated by a central hospital computer system on receipt of test data from the clinical laboratory system. An itemized listing of all laboratory tests is included as an end result in the patient's computer-generated hospital statement.

Cost per procedure in computerized clinical laboratories tends to increase more slowly than costs for noncomputerized operations. In addition, the capacity to share the clinical laboratory is facilitated by the speed and improved communication of results. The clerical work load of laboratory technicians is markedly reduced and the capacity to expand the number of tests performed without expansion of staff or space is improved. These benefits are precisely the ones computers must offer in medicine if they are to be practicable (*35–38*). Many of the benefits cited for clinical laboratory computerization have been equally well demonstrated in other ancillary services such as radiology and pharmacy.

Although not yet in wide use, perhaps the most powerful analytical instrument used in the clinical laboratory is the gas chromatograph–mass spectrometer (GC-MS). The use of a minicomputer data acquisition and processing system for this analytical instrument greatly enhances its effectiveness in a clinical laboratory. Using the gas chromatograph as the input device to introduce separated sample constituents to the spectrometer greatly increases the qualitative information obtainable from the complex mixtures usually represented by biological samples. In fact, almost automatic identification of all components of the mixture is achieved. A key feature of the mass spectrometer, compared with most other analytical instruments, is its very high sensitivity. With built-in computers, on-line recording and processing of the output of a GC-MS has become common and much more information is obtained from tests than was previously thought possible. On-line recording of large amounts of original data makes it possible to obtain qualitative information on complex samples in very short periods of time with a single test as well as quantitative measurements with unprecedented accuracy. Thus the diagnostic value of the GC-MS in the clinical laboratory has been substantially enhanced (*39, 40*).

Adjuncts for Diagnostic Tests

Study and interpretation of the results of diagnostic tests may occupy a substantial fraction of the clinician's time in certain medical specialties such as cardiology. A large percentage of these tests may yield results within the normal range, and the data may be quite repetitive. A physician may be released from the burden of examining large numbers of test results by using the computer as a substitute. Frequently, a highly abnormal result detected by the computer is referred to the physician for additional review. Utilization of computers in interpreting results can increase the speed of entering results on the patient's records, improve follow-up by feeding back results to consulting physicians, and relieve some of the burden of interpretation by the physician [(*34*), p. 93].

Electrocardiography was one of the first areas in which computers were applied as adjuncts for diagnostic tests. Automated cardiac dysrhythmia analysis is now the most common application of computer processing and interpretation systems. Compared to most biological signals, the surface electrocardiogram (ECG) is rather well behaved, and its clinical interpretation has been studied extensively. Briefly, the result of a sequence of electrical depolarizations coupled to contractions of the muscular chambers of the heart produces the ECG. These depolarizations can be detected by using electrodes in contact with the skin and manifest themselves as a series of deflections in a time-varying electrical wave form. The shapes of the wave form vary with the precise depolarization sequences and locations of electrodes on the skin. The underlying rhythm of the heart is indicated by both the wave form timing and shape. Premature ventricular contractions are a particularly important form of dysrhythmia.

Automated computer analysis of abnormal cardiac rhythms is now well established for use in real-time ECG monitoring in both long-term ambulatory care and hospital intensive care units. However, many difficulties persist. Many facets of ECG signal acquisition have not been well standardized, with the result that signal characterization continues to be troublesome. Although advances have been made in other domains, the analysis algorithms rely largely on correlation techniques or time-domain feature extraction. The accuracy of these algorithms is improving, but none is free of weaknesses. Consequently, human interaction is necessary to compensate for deficiencies in computer analysis with most systems. Furthermore, the evaluation of system performance demands extensive effort, and to date such assessments have been hampered by the absence of standards and lack of a database that is widely accepted. Efforts to establish a firmer basis for system performance evaluation are continuing. Moreover, research in this field is being addressed to all of the foregoing issues because of the promising clinical utility of automating dysrhythmia analysis.

Automated cardiac dysrhythmia analysis presents a formidable challenge to computer technology. Serious pitfalls exist due to the vagaries of the signal itself as well as the many sources of artifacts. Nevertheless, a number of practical systems for both patient care and clinical research have evolved over the past two decades. Moreover, the extensive effort that has been expended in pursuit of the perfect dysrhythmia analyzer has underscored the need to fully comprehend ECG signal analysis. The need to develop explicit processing algorithms has forced a more searching examination of signal content. Electrocardiography and the patients it serves will benefit from these efforts (*41–44*). In addition to ECG analysis, computers have been applied to spirographic and blood gas analysis with rather broad success.

Monitors of Critically Ill Patients

Computer monitoring of critically ill patients has been explored intensively for more than a decade. During this period hospital intensive care units have proliferated. For maximum effectiveness, intensive care units require prompt and accurate information about the patient's condition. Although a patient may suffer ventricular fibrillation only once in several days, the occurrence of this event cannot be overlooked. Computers offer tireless observation for such infrequent events whose detection is vital. In addition, computers allow recall of data already collected in order to improve understanding of changes in a patient's condition. This is especially important when a medical team is following several patients with diverse problems [(*34*), p. 107].

A computer-based system for monitoring critically ill patients typically includes (i) sensors such as ECG electrodes for signal acquisition, (ii) electronic modules for signal amplification and preprocessing, (iii) a computer system with input and output interfaces, data manipulation and storage hardware, and a set of software programs, and (iv) television displays for wave forms, text, charts, and so on, and a keyboard. In a thoracic surgical unit, for instance, both bedside and central displays are often used for presentation of the ECG, arterial pressures, and respiratory wave forms. The fidelity of the ECG signal is dependent on careful preparation of the skin and placement of the electrode to ensure acceptable electrical impedance at the electrode-skin interface. Amplified and filtered ECG wave forms are transmitted to the computer for digitizing, analysis, and display. Frequently, pressures are obtained from indwelling intravascular and intracardiac fluid-filled catheters. The catheter fluid column transmits hemodynamic pressures to piezoelectric or piezoresistive transducers for conversion to electrical signals. Respiratory rate estimates are derived from thoracic impedance measurements, which require careful electrode placement. Many other clinical measurements are performed both automatically and manually, and the resulting data are stored in the computer monitoring system (*45*). One of the most interesting of these measurements currently being made in critical care is on-line mass spectrographic analysis of gas components from the patient's exhalations.

Computer automation of physiological measurements and attendant recordkeeping relieve nurses of time-consuming tasks, enabling them to devote more time to direct patient care. Some intensive care units have gone further and use computers to assist in clinical decision-making. A few systems even perform closed-loop feedback control of a limited number of physiological variables through infusion pumps which are controlled subject to rigidly structured algorithms. Overall, experience with computer monitoring of critically ill patients suggests that the additional associated costs may be recovered through enhanced personnel performance as well as more rapid stabilization of patients, who can then be transferred sooner from intensive care to less costly rooms. However, indisputable evidence that computer-based intensive care systems are cost effective is not yet available. Quantitating the economic value of the benefits is a major obstacle in establishing cost effectiveness. The applicability of computer monitors depends a great deal on the nature of the clinical environment. Critical care units in which patient management is highly structured offer the most promising opportunities for the future use of computers (*46–49*).

The Handicapped

The quality of life and job opportunities for many people are substantially diminished by loss of some natural function. Many suffer from afflictions such as loss of limbs, paralysis, speech impediments, deafness, and blindness. The compact size and powerful sensory, computational, memory, and display capabilities of microelectronics and computers offer opportunities to relieve these functional deficiencies. Computers especially have substantially increased the variety and quality of job opportunities available to handicapped and homebound individuals. The intellectual character of the work that they can now perform is more challenging. Both personal and economic rewards are greater. The handicapped person can now engage in computer science and engineering, data processing, accounting, and bookkeeping, fields of gainful professional employment in which there is considerable outside contact through computer terminal, telefacsimile, and telephone (*10, 50–53*).

Computers have been incorporated in prosthetic devices usable by individuals with motor dysfunctions so severe that they can neither produce intelligible speech nor use any part of the body to write effectively. The operation of these devices is dependent on the availability of biological signals that are under control of the user. For example, a neck movement could be interpreted by the device as a command to produce a particular phrase previously synthesized and stored in computer memory (*54, 55*).

Mobility is one of the most acute requirements of all handicapped persons, for without it their capabilities are severely limited. This necessitates the development of lightweight, maneuverable, and reliable electrically powered wheelchairs. Microprocessors in particular offer vast improvements in wheelchair control compared with current systems. Automatic speed limiting, programmed acceleration and deceleration, obstacle avoidance, battery monitoring, and component temperature monitoring are both needed and feasible in microprocessor-based controllers (*56*).

Microelectronics has been used to achieve a portable reading aid for the blind. The Optacon is a direct translation device that converts an optical image of a printed character on a page of an ordinary book, magazine, or newspaper to a vibrating tactile facsimile. By means of a simple optical system contained in a hand-held camera, an image of a printed character is focused on a microelectronic array of light sensors. Electrical output signals from the sensor array are processed in a simple computer system and then used to control a corresponding array of piezoelectric tactile stimulators or bimorphs. Tiny pins attached to the tips of the bimorphs protrude slightly through perforations in a rectangular plastic plate. A blind reader whose fingertip is resting over the perforations can then feel a tactile facsimile or vibrating image of the original printed character (*10*).

Because the signals that travel the human nervous system are electrical in character, it should in principle be possible to replace defective nervous tissue with an electronic substitute. The most striking possibilities for neural prostheses are sensory prostheses for hearing and vision. In both cases the information flow is high, and the stimulation pattern that must be generated is complex in both space and time. A proposed auditory prosthesis for the profoundly deaf is based on electrical stimulation of the auditory nerve in cases where the transduction machinery of the cochlea is totally defective. This stimulation produces the sensation of sound if the auditory nerve itself remains viable. Considerations based on both auditory physiology and speech theory indicate that the independent stimulation of eight to ten subsets of auditory nerve fibers is required to convey the information content of speech to the brain. A formidable problem remains with regard to developing suitable algorithms for recognizing and mapping spoken speech into a pattern of stimulation for the electrode array (*10*).

Conclusion

Microelectronics and computers have been used in nearly every phase of medical research. In medical practice, they have been effectively applied to collect, store, retrieve and manipulate medical data and to augment, amplify, and assist the judgment of experienced clinicians in medical decision-making. Powerful new noninvasive diagnostic instruments such as the computed x-ray tomographic scanner and ultrasonic imaging systems with arrays of acoustic sensors are based on dedicated microelectronics and computers. The utility of clinical laboratories and sensitive analytical instruments such as the GC-MS has been increased through the application of computers. Computers are now widely used as adjuncts for diagnostic tests such as the ECG and as monitors of critically ill patients. Morale-building accomplishments, social contacts, and job opportunities available to handicapped and homebound individuals have been substantially enhanced by the computer. Prosthetic aids for those suffering afflictions such as loss of limbs, paralysis, speech impediments, deafness, and blindness have advanced markedly through incorporation of microcomputers in their design. Health care represents one of the most promising opportunities for improving the quality of life in society through microelectronics and computers.

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Ultrafast Phenomena in Semiconductor Devices

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Summary. Evolving high-speed semiconductor technology requires a more complete understanding of semiconductors on a picosecond time scale. This article discusses ultrafast phenomena that may influence device performance and describes new experimental methods utilizing short optical pulses to investigate materials and device structures.

The building blocks of future ultrahigh-speed computers will be products of rapid advances now taking place in device technology. During the last 30 years there has been remarkable progress in the evolution of new high-speed devices. Semiconductor circuits have been increasing in speed by approximately a factor of 10 each decade. A number of new high-speed device technologies are being developed. In this article we will limit the scope of our discussion primarily to the fundamental aspects of emerging high-speed semiconductor technologies.

As semiconductor electronic devices become smaller and faster, we must extend our understanding of ultrafast processes in semiconductors, which will ultimately determine performance. New experimental methods are being developed to explore semiconductors on ever finer time scales. We will discuss the basic concepts that will influence semiconductor device performance and present recent experimental results.

In Fig. 1 we compare the time scales of existing high-speed technologies. The solid lines indicate achieved performance and the dashed lines projected performance. Clearly, the speed of optics exceeds that of all other high-speed technologies. Although they are not electronic, techniques involving short optical pulses have pushed our ability to resolve events in time to a fraction of a picosecond (*1*) and are valuable tools for fundamental investigations of high-speed electronic devices. Optoelectronics combines the fields of optics and electronics and shows considerable promise for the development of high-speed devices that can join some of the high-speed capabilities of optics with electronics. Superconducting electronics, based on Josephson junction logic devices (*2*), has advanced to the point where cryogenic computer systems are being constructed (*3*). The intrinsic speed of response of a Josephson junction is limited by the superconducting energy gap (that is, $\tau = \hbar/\Delta E$, where $\hbar$ is Planck's constant divided by 2π). In typical Josephson junctions this time is a fraction of a picosecond; in practice, device capacitances limit per-

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