VOLUME 2 ☐ NUMBER 12 DECEMBER 1965

IEEE spectrum

features

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THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

departments

the cover

Picture transmission by pulse code modulation is receiving renewed interest because of possible military and space applications, as reported in an article by Thomas S. Huang, of the M.I.T. Research Laboratory of Electronics, starting on page 57. The cover photograph is an enlargement of a portion of the digitalized picture presented in the article as Fig. 7(A).

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Spectral lines

The ASEE "Goals" Report. The American Society for Engineering Education (ASEE) recently issued the preliminary report of its "Goals of Engineering Education" study. This study, which has been under way for the last three years, has focused on the current practices in engineering education in the United States. The presently available report* is a preliminary one which has been distributed for comment before the final report is issued in the spring of 1966. Although the report relates only to engineering education in the United States, it will be of considerable interest to all engineers and in particular, to engineering educators. The "Recommendations" section of the preliminary report appears on pages 84 and 85 of this issue.

The study has been exhaustive, and undoubtedly exhausting to the committee that undertook the project. More than 175 academic institutions were visited by members of the staff of the committee; most institutions had organized faculty committees to answer detailed questionnaires and to comment on their concerns and problems. A survey of engineering graduates in industry and government was made that included more than 4000 engineers and upper-management personnel. Also, reports were solicited and received from professional societies as well as from governmental and industrial study groups.

The study covered both an undergraduate and a graduate phase. The latter phase was related to the faculty, doctoral students, and research programs under way in graduate institutions. It included publicly and privately controlled institutions of both small and large size, and considered the sources of funding available to support students and research projects. Significant data were collected in many areas.

The report, which is more than 100 pages in length, includes recommendations concerning degrees, structures, accreditation procedure, and needs for improving and extending engineering education. Its recommendations include increased emphasis on education of engineering students in the humanities and social services; a continued emphasis on the scientific and mathematical base of engineering studies; increased emphasis on the analysis, synthesis, and design of systems; and a greater degree of flexibility and diversity in engineering programs to accommodate the differing aims and talents of students.

Perhaps the most controversial recommendations relate to the degree structure. It is recommended that the four-year bachelor program be considered an introductory engineering degree and that the first *professional degree* be awarded upon the completion of a five-year program. This is a major change in the present practice in engineering institutions in the United States and its full implications are not immediately apparent. It is clear that if this recommendation is adopted, it will have a major effect on the engineering profession.

A related recommendation is that a master's degree be awarded at the successful completion of the five-year program and that this degree not include qualifying adjectives such as electrical, civil, mechanical, etc. Again this recommendation is a significant change from current practice in the United States, and its ramifications are not apparent.

Another significant change is implicit in the recommendation that accreditation of an academic institution, which is currently awarded on the basis of specific curricula, now be awarded on the basis of the overall qualifications of the institution. It has been rather widely recognized that the accreditation of curricula was largely a judgment as to the adequacy of the faculty, students, facilities, and administrative policies of the institution involved. However, the implementation of the new proposal will present some difficult problems to the Engineers' Council for Professional Development, which carries on the accreditation program in the United States. One effect of this change might be the development of more flexible undergraduate curricula.

The committee preparing this report wisely provided a period of time in which individuals, academic institutions, professional societies, and industrial and governmental groups might comment on its recommendations and so contribute to the final product. The exercise of this privilege is strongly recommended since it appears likely that the report will have a major impact on engineering education in the United States, and possibly other countries, over the next decade. The professional societies, in particular, can make a significant contribution if they are able to bring to bear forward thinking elements in the engineering profession.

The overall effect of this study can be a very positive one to the extent that it stimulates new and careful thinking by engineering educators about how well they have adapted to the changing technological and scientific environment of today. The need for such rethinking is apparent.

F. Karl Willenbrock

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The time for space exploration

Wernher von Braun *Marshall Space Flight Center, NASA*

Dr. von Braun was invited by Dr. Thomas F. Jones of the IEEE Editorial Board to write for IEEE Spectrum on the subject "How my dreams of space have changed." The accompanying article, with a different title and content, resulted from that request. Dr. von Braun felt that the suggested title would have led to a more provocative article. But, he states, his dreams of space have been marked more by consistency than change. The methods of implementing his dreams are what have undergone considerable change over the years.

The advanced technologies of our time have made it possible to remove man's long-held dream of space exploration from the realm of science fiction into the everyday world of practical reality.

The early twentieth century proposals of such visionary men as Constantin Tsiolkovsky, Hermann Oberth, and Robert H. Goddard were sound, but anachronistic. At the time that Dr. Goddard launched the world's first liquid-propelled rocket in 1926, science and engineering were responsible for many amazing inventions. Electricity, telephones, radio, and automobiles were commonplace, and even puddle-jumping airplanes were not a rarity. But the time simply had not arrived for man's entry into space. The technology of the day would not support the theories of the scientists

It usually takes time for ideas to mature. And this was especially true of the grandiose idea that puny man could leave the earth and soar into the space around it. The heavens had always been considered the exclusive habitat of the gods.

Good ideas usually materialize only when all the ingredients are present. And in 1926 an adequate technology was not the only missing element for exploring space—for outfitting a manned expedition to the moon, for instance. The general public was not seriously interested in learning more about space—and widespread public endorsement and sustained support are mandatory for such a gigantic and long-range undertaking.

The impetus given research in rocketry during World War II and its aftermath provided the technological base on which our current space program was built. The orbiting of Sputnik I by the Soviets provided the spark that kindled public demand for a dynamic United States space program.

The space program utilizes new advanced technologies in literally hundreds of different areas. These technologies are growing at a breathtaking pace to meet the stringent demands of performance and reliability required of space launch vehicles and payloads.

The computer is a good example of a recent technological advance without which there could be no space program. The first modern high-speed computer, the Mark I, was completed by scientists and engineers at Harvard University in 1944. The first high-speed computer with electronic rather than mechanical internal operations was the ENIAC, completed at the University of Pennsylvania in 1946. The computer industry thus has developed only within the last two decades.

The huge computers of today, relying on vacuum tubes and transistors rather than gears for operation, have an enormous appetite for information, which is digested at lightninglike speed. Without computers the task of developing a huge launch vehicle, such as the Saturn V, would be prolonged for years. Without computers, both on the ground and in the vehicle, we could not place our payloads in the desired orbits. And, finally, without computers the task of processing and analyzing the vast quantities of information received from our satellites and space probes would be endless.

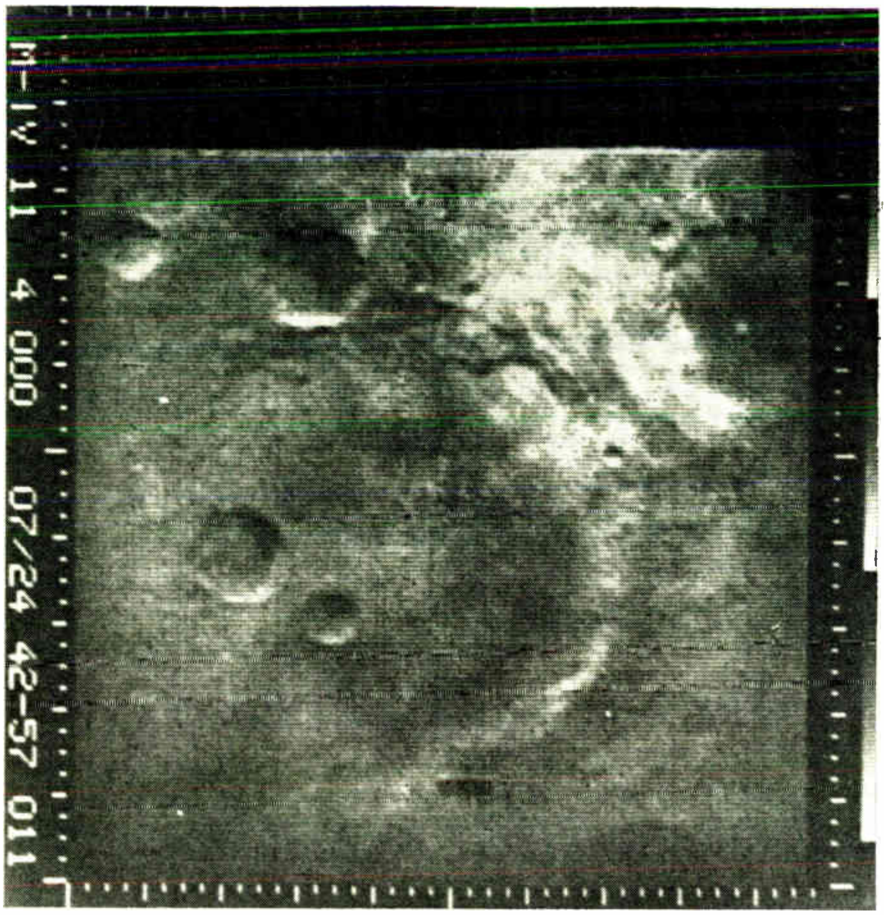
Rocket propulsion

The technology of rocket propulsion, which is the only means available for propelling ourselves in space, has matched the rapid growth of computer technology. The thrust of Dr. Goddard's 1926 rocket was about 60 pounds. The Redstone first stage of the Jupiter C that orbited our first satellite in 1957 had a thrust of 78 000 pounds. At the Marshall Space Flight Center last summer we static fired the first stage of the Saturn V/Apollo launch vehicle, with a recorded thrust of 7.5 million pounds.

This tremendous growth in power has been made possible by improvements in design and in materials, turbines, valves, propellant handling, and dozens of other areas. The upper-stage engines of all the Saturn launch vehicles burn liquid oxygen and liquid hydrogen, the exotic fuel combination that has opened up a completely new field of specialized knowledge in cryogenics.

Instrumentation, telemetry, and communications are other areas of technology that have expanded at a gallop during the past two decades, and which are being drawn upon heavily for the exploration of space. Mariner IV received commands from earth, and transmitted its pictures of Mars back to earth, over a distance of 134 million miles, with radio transmitter power of only 10½ watts. Printed circuitry and miniaturization, and even microminiaturization, have helped us to squeeze the last ounce of value out of the pounds of payload we have been able to send into space.

It takes time to develop these supersophisticated advanced supporting technologies. And the professional



Reproduction of frame number 11 of the series of photographs taken during the recent Mariner Mars Mission. The picture ranks as one of the most remarkable scientific photographs of this age in that it demonstrates the existence of Martian craters beyond question.

and technical people involved must maintain a clear vision and firm belief in the long-range goals toward which their knowledge and skills are being applied. It takes dedication to a worthwhile purpose to lift a person out of the ruts of routine existence, to extraordinary achievements.

In the United States today almost 300 000 people are working full time to give substance to the dream of manned space travel. Cataloguing all their specialized skills would be a lengthy process for even the most experienced personnel manager. The buildup of this team in the government and in industry—and the meshing of their efforts into a purposeful program—has been one of NASA's proudest accomplishments. This diversified and skilled team is necessary, for the pace, breadth, and depth of rocket research have placed it out of reach of the amateur experimenters who pioneered in this field a few decades ago.

Because of this massive buildup of highly trained people, progress in space exploration is exceeding the most optimistic predictions. The steps into space are being taken much faster than thought possible even 10 to 15 years ago.

Although the space program has reached maturity, there is still room within its ranks for gifted people. We need the best trained, best qualified, and most dedicated people we can find in all areas, for ours is an immense and difficult task. The design and development of launch vehicles and spacecraft systems, which are to operate far from earth for long periods of time in an unusually severe environment, demand the highest degree of originality, initiative, and technical proficiency.

Economic considerations

There is still another ingredient that is essential for space exploration: the economy must be able to support the effort. In the 1930s the United States was struggling through an economic depression. In the '40s its resources were funneled into the needs of warfare and defense; and in the '50s factories and construction boomed to meet the delayed demands of a growing population. Prosperity has continued during the '60s, and the gross national product has reached new heights.

The United States could not have afforded a space program in the '30s. NASA's current annual budget is $5.2 billion—a good bit more than the total expenditures of the Federal government in 1933 of $4.6 billion. But today the $5.2 billion allotted to NASA's space programs is only one-twentieth of the annual Federal budget. It is well within the limits of what we can afford to spend to respond to the insistent challenge of space.

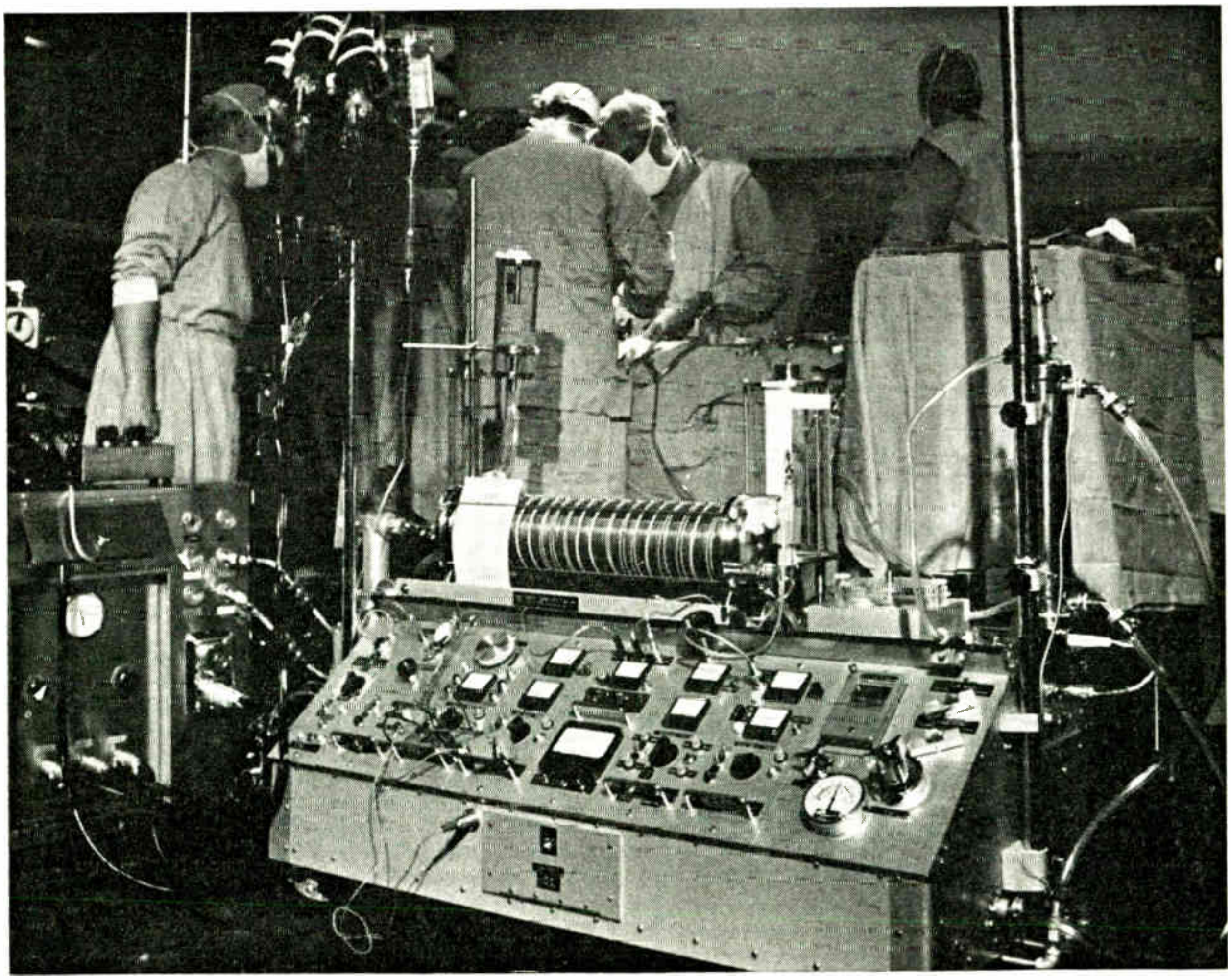
In its initial stages the space effort has been primarily a research and development effort, for we are simply doing something that has never been done before. The space budget is thus an investment in knowledge and capability, which will ultimately yield tangible returns far in excess of the cost of the program in manpower and resources.

All the ingredients for a dynamic space effort are present today. Our science, technology, and economy are adequate. We should not let our determination waver, and I do not believe that we shall. We have taken the first steps into space, and the world will never be the same again. As Dr. Goddard said, "Nothing is stronger than an idea whose time has come."

Biomedical engineering

Some of the challenges faced by the electronics engineer in understanding the elusive and almost limitless variables of the phenomena of life are emphasized in this review of the complex, interdisciplinary field of biomedical engineering

Alfred N. Goldsmith *Editor Emeritus and Director Emeritus, IEEE*



Biomedical engineering is among the most recent additions to the technological professions. Since its greatest triumphs and major contributions to humanity are still in the future, it is literally as new as tomorrow. It is a "cross-disciplinary" branch of engineering. And it results in large measure from the application of the skills and capabilities of modern electronics to the fields of biology, medicine, and surgery.

Its broad scope will tax the resources of the multidisciplinary training of its practitioners. But it will offer corresponding rewards through many accomplishments of benefit to the health and longevity of the inhabitants of this globe.

The worker in the field of biomedical engineering (BME) should have an unusual degree of eclecticism, and a natural taste for the study of broader, more generalized, and more complex topics and relationships than are likely to be found in most single or specific technologies. In a sense, BME therefore requires a partial return to the versatility of the scientists of the 19th and early 20th centuries. To some, such a prospect will be alluring, and its rewards—in fame if not in fortune—will be attractive.

In a way, the training of the biomedical engineer will resemble that of the patent attorney, who necessarily is both engineer and lawyer. Such dual skills in collaborative fields will be more common in the future. At first, biology may seem strange to the engineering mind. Many biological phenomena are highly labile, autodynamic, only approximately uniform, sometimes multicausal, very idiosyncratic, and only broadly controllable. They may also be extremely complex inherently and in their interrelationships. And they are possibly evolution-determined, or even not wholly controlled by known physicochemical principles. Thus the paradigms, or basic theories of biology, only partially parallel those of the physical sciences.

On the practical side, the biomedical engineer needs close contacts and information interchange with the user of equipment and its operational procedures as well as knowledge of medical and surgical problems. His activities will also impinge on the fields of distribution, sales, and maintenance of biomedical equipment. Safety of equipment and validity of advertising will present problems to him, as well as the inherent liabilities arising from faulty or dangerous equipment and possible corresponding claims of malpractice. Accordingly, the biomedical engineer must be thoroughly at home in the fields of medical practice and biological procedures.

Complex open-heart surgery, considered too risky a few years ago, can now be performed. A patient's heart and lungs can be bypassed for six hours without irreversible damage to the brain or other organs through use of a pump-oxygenator heart-lung machine, shown at the right.

One nonexclusive way of studying man is through biology, medicine, and engineering. For the purpose of concise and somewhat oversimplified scientific description, man (or any manlike extraterrestrial life form) is an organism sensitive toward his surroundings and reacting to them; enjoying motility and the feedbacks necessary for such effective reaction to environment; possessing an eclectic information storage and retrieval system; and capable of communicating comprehensive information or requests for information to his fellow men or similar forms of life. Man therefore presents a vast field for study in even these special aspects.

It is natural that biological engineering in its present early stage resembles a group of oases rather than a large, intensively cultivated area. Its divisions are only beginning to be clearly defined, and some of its areas are not only expanding but overlapping. In such a fluid field, the opportunities for accomplishment are many and diverse.

Since this article is inherently a brief summary of the subject, credits for individual devices or methods are not listed. Only broad principles are presented, generally without details and with a limited number of illustrative applications intended to show the scope, diversity, and capability of available apparatus. Some of the methods and equipment herein cited are in the research stage; others are in development; and some are fully operational. Specialized terminology is mentioned only where it is of particular importance or is frequently used.

Instrumentation

Measuring instruments form the solid basis of most scientific developments. The phenomena of biology are often encouragingly amenable to study, measurement, and orderly classification by the powerful methods that have recently been developed in the electrical and electronics field. Available, for example, are control sensors, networks, feedback, circuit simulation of biological processes, telemetry, information sensors, and miniaturization. The impedance changes of parts of the body yield significant information. Thus a high-frequency current may be passed through the thorax, and the respiratory rate and depth of inhalation related to recordings of the current variation. In progress are similar studies dealing with the thyroid function, certain glandular activities, changes in the nervous system, blood-flow variation, and eye movements.

The heartbeat, or cardiac cycle, generates systematic blood-pressure changes, and related voltages, which may be recorded by connection to electrodes in conductive contact with selected sections of the body (chest and legs). Such records are known as electrocardiograms (EKGs). Detectable magnetic fields that also accompany the cardiac cycle will permit further study of this cycle. Detection and measurement of heartbeats can also be accomplished by placing the subject on a freely movable platform and measuring the exerted muscular forces.

This technique enables studies to be made of the training of athletes and the causes of such handicaps as limps.

The electrocardiogram and its depicted heart pulses can be simulated by suitable electrical networks, and are subject to close mathematical analysis. They assist in the diagnosis of heart conditions.

Blood flow may be measured electromagnetically by various methods. It can also be determined by an ultrasonic meter operated by comparisons of ultrasound pulses transmitted up- and downstream. Electronic counters of the number and size of particles in the blood stream (sanguinometers) give corresponding information on the blood corpuscles. The location of internal intestinal bleeding can be found by Geiger counters placed at intervals along a "swallow tube" ingested into the intestinal tract after "labeling" the red blood cells with a harmless, short-life radioisotope.

Even automatic electronic equipment for blood-pressure measurement has been simplified to the point where its use by the public is said to be feasible. Further, by measurement of the electrical impedance changes as individual blood cells pass through a small orifice, the size and distribution of blood cells can be automatically registered.

By systematic, electronically controlled motion of a microscope stage, the desired viewed area can be fully scanned, and corresponding viewing or recording carried out. Photomicrographs can also be made automatically by simply pushing a button on another type of microscope and camera equipped with electronic adjuncts. Recording densitometers are available as a normal research tool.

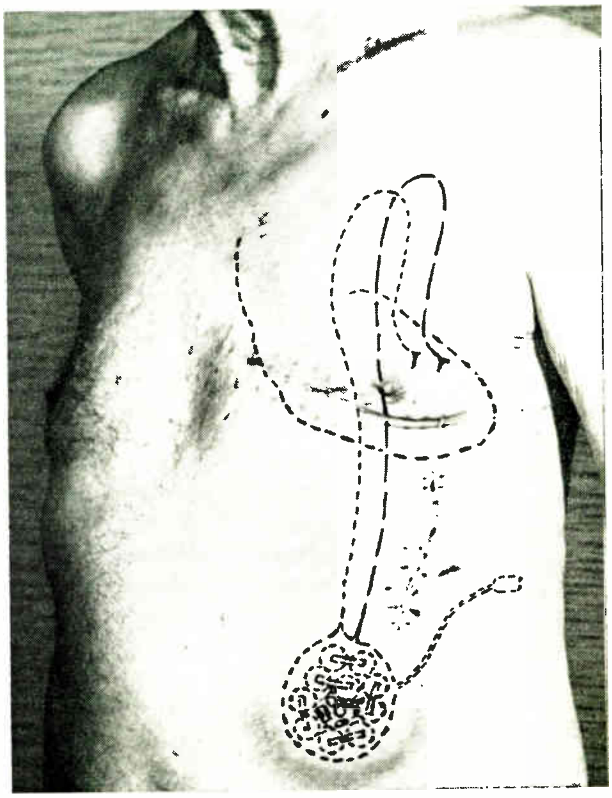
Blood velocity can be measured by applying an alternating voltage to two coils on opposite sides of a probe in one of the heart blood vessels (the aorta). The probe carries two electrodes which contact the aorta walls. A voltage is generated in the electrically conducting blood, flowing through the magnetic field of the coils. From this voltage, the blood velocity can be derived.

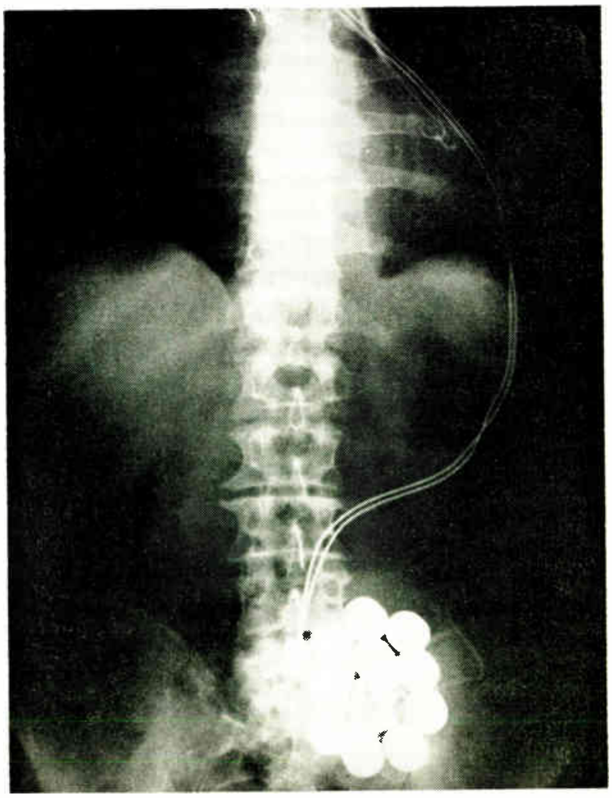
Voltages can be derived from other body activities and recorded as electroencephalograms (EEGs, or brain-wave records), and electromyelograms (EMGs, or records of muscle-activity waves). Myelograms, directly viewed on a kinescope, assist in the study of muscular and nervous disorders. Encephalograms assist in diagnosing brain lesions and areas involved in epilepsy, and are said to be useful in psychiatry. Records of potentials in the brain cortex (outer shell of the brain) are available through direct probes and are termed electrocorticograms.

Pressures in body cavities or on the body surface are measurable through tonometry. A piezoelectric transducer (e.g., a quartz crystal) is pressed against the sensitive area, and suitable electronic measurements enable derivation of the internal pressure. Strain gauges attached to the fingertip are known as plethysmographs. Tonometry is useful in the diagnosis of glaucoma (an ailment involving undue pressure within the eye), for detecting intercranial pressure in infants, and for measurement of abdominal pressures.

Respiration rates and the carbon-dioxide cycle in breathing can be measured and electronically studied by using analog computers. Stomachic activity (including peristaltic or digestive motion) can be registered, even on the body surface, by means of specialized amplifiers.

Top—Patient with diagram superimposed to show subcutaneously implanted pacemaker, an instrument that can stimulate failing heart action with electric impulses until the normal action resumes. Bottom—X-ray photograph showing an implanted pacemaker.





Thus electrogastrography permits systematic investigations of digestion.

Various types of eye movement can be recorded by electrooculography (EOG). The functioning of the normal and impaired eye motor system is thus recorded for diagnosis—often without any ocular restraint. Minute photoelectric or magnetic contacts to the eye are used. Ophthalmoscopy (examination of the eye retina) can be carried out for several simultaneous observers by the use of television techniques, including examination of adjacent areas, monochromatic viewing, and single-line scanning.

Internal body structures (including intrusions such as calculi, or stones) are visualized by ultrasonic means. A source of ultrasonic energy is focused through "sound optics" on the region to be examined. The reflected ultrasonic waves give an echo pattern that permits, for example, studies of heart-valve movements, blood clots (thromboses), tumors in the heart, and heart-valve constrictions. The location of the kidney, detection of gallstones, and location of uterine and ovarian tumors can also be carried out by ultrasonic means. The ultrasonogram may in time become a useful adjunct to the X ray.

Among the most powerful and useful electronic devices for biomedical applications are the electron microscope and the image amplifier. The electron microscope vastly expands the available magnification range (up to 200 000 times magnification with a resolution of 10 Å or better). It has been invaluable in the study of bacteria, cell structures, and viruses. The chromosomes (bodies in the cell nucleus carrying hereditary information) are made up of the basic flat or threadlike assemblies (genes), which contain orderly groups of the so-called nucleic acids and other chemical components. It is here that the ultimate hereditary information appears to be located. It is hoped that the electron-optical qualities of the electron microscope can be improved to the point where these sequences of nucleic acids can be seen, classified, and their significance visually decoded. The aforementioned image amplifier permits the X-ray dosage of the patient during examination to be reduced substantially by viewing the brightness-amplified image.

A convenient adjunct to biological temperature measurement is the thermistor, the stability, sensitivity, and thermal conductivity of which are advantageous.

Thermoelectric modules can be used for cooling in such procedures as surgical or dental probings, as well as for cooling of tissue sections for slicing (microtoming) and microscopic examination. This cooling property is also useful in connection with the transportation of blood or serum.

Acidity or alkalinity are measured by pH meters. Recently a glass-manufacturing company produced a wide-range, precise, temperature-compensated direct-reading pH meter by using a special electrode glass.

Considerable experimentation and mathematical development have gone into producing electrical networks that simulate the neuron (nerve) system. Efforts, in considerable measure successful, have gone into developing a readily adjustable, low-power, compact, and inexpensive positive- or negative-pulse generator that simulates the action of nerve impulses.

Here we can mention only briefly some of the more recent instrumentation techniques in the biomedical electronic field. Electron-spin resonance (ESR) enables study of unpaired electrons in vivo (in living tissue) as well as the formation of free radicals. Also under study is photosynthesis, which includes the effects of radiation on cells in vivo, and the metabolism (utilization in the body) of certain drugs acting as tranquilizers. Polarography enables identification of trace metals, which play a meaningful part in metabolic processes.

As the preceding shows, the techniques and apparatus of modern engineering, suitably modified, seem appropriate and largely adaptable to the needs of the biological arts. Further miniaturization, greater versatility, increased reliability, simplicity of operation, improved means of telemetering or carrying indications from the inside of the body, and reduced cost would be helpful in some instances. But broadly, engineering today seems to meet many of the simpler needs of present biologists.

It can be expected that new and more searching methods of studying the statics and dynamics of biological processes, particularly in the molecular realm, will soon be required. As these needs become imminent and clearer, corresponding solutions must be sought.

Laser applications

The utility of the laser for biological purposes stems from its peculiar capabilities (and limitations). Though operating at very low energy efficiency, it can produce coherent light of an output peak power up to the range of 1 to 1000 MW, in very brief pulses; power densities from 10^{12} to 10^{15} W/cm^2; and correspondingly high optical field strengths. It can be used in place of the usual spark or arc excitation for vaporizing materials in solid samples more than 50 microns in diameter, thus enabling spectrometric analysis. Obviously, the associated optical system (lenses and cement) must be capable of withstanding the brief, but extremely intense, energy surges involved.

So powerful a source may produce biological, therapeutic, or even genetic effects. It can be used to treat detached retinas (within the eye), or to extirpate intraocular tumors. If tissue portions are stained with a dark dye, the laser-beam energy will be selectively absorbed and the chosen tissue portion will be destroyed. Such treatments may be carried out even in the oculist's office without anesthesia and without the patient's experiencing any sensation. (The retinal exposure time to the prefocused laser beam is about 500 μs.) Accordingly, the laser may ultimately be used in submicroscopic surgery or even, conceivably, for cellular dissection.

Monofrequency laser beams passing through certain organic liquids emerge as multifrequency light, thus pointing the way to possible chemical analytic methods of usefulness in biology.

Like other powerful or ionizing radiations, however, the laser beam should be used only with due precautions. Personnel exposed to laser beams may suffer deeper effects than superficial lesions. Even the backscatter "plume" or diffuse reflection from a laser-illuminated target may be injurious. Accordingly, personnel exposure to the direct beam or the plume should be avoided, and dark glasses should be worn. These precautions are somewhat reminiscent of those long required by radiologists (X-ray practitioners).

Communication

Communication from within the body to local or distant points represents another field of interest in biomedical engineering. Data on physiological, chemical, or physical conditions in the tissues or cavities of the body can sometimes be secured from implanted or applied sensors, or by ingested combinations of sensors and signal-transmitting units (either inductive or radio "sondes").

Power for the signal transmitter can be supplied from outside the body by induction, the received energy being used to charge a small storage battery within the body. Alternatively, high-frequency energy may be received within the body, converted to direct current by a transistor that forms part of the internal transmitter oscillator, stored in a capacitor, and then drawn from the capacitor for signal transmission (e.g., of data on acidity or temperature) in the digestive tract. Miniature primary battery supplies are also usable.

Sometimes measurable by sondes are pressure, chloride ion concentration, bioelectric potentials, partial pressures of gases (such as oxygen or carbon dioxide), ionizing radiation intensity, motility, bleeding, respiration rate, and fetal heartbeat records.

In the "radio pill" placed in the intestinal tract, frequency- or pulse-modulation of a carrier in the 100-kc/s to 10-Mc/s range is used. Internal mercury battery sources may be employed, and signal transmission can be initiated or halted from outside the body.

Obviously, the signals from within the body can be processed by known electronic methods for extraction of the signal from superimposed noise, signal recording, analysis of waveforms, record retrieval, and transmission to remote points over wire lines. The general practitioner may even run such tests from portable equipment in the patient's home under normal conditions, and send the signals by telephone line to a central collating, analyzing, and diagnosing station. This procedure has proved to be helpful for nonambulatory neurospastic patients.

Some less usual applications of the sonde include telemetry of the condition of astronauts (e.g., blood pressure, body temperature, respiration rate, and cardiographic data). Bearing an odd resemblance to the preceding is the transmission of biological information from pigeons or large birds in flight. An industrial application of telemetry is the determination or recording of physiological or psychological changes occurring in the worker during the working day on a specific job. Sophisticated methods of electrocardiography also permit early study of the developing heartbeat in the fetus, sometimes making it possible to avoid or alleviate later difficulties.

As microminiaturization and improved signal-identification methods are developed in the electronics field, they will find ready and useful application to the biological sonde equipment and techniques.

Information dissemination

The steadily increasing volume of biological and medical literature imposes a heavy burden on those attempting to assimilate and recall available data on specific topics and on broad fields of study. Central repositories of information, statistics, abstracts, and current literature are required. Electronic methods seem capable of meeting many of these information needs.

The individual biologist, physician, specialist, or clinician will, in growing measure, require a modernized and comprehensive information-retrieval system to meet his current needs speedily and effectively. The corresponding concept of a "World Biomedical Information Center," while appealing, is perhaps too ambitious for complete and immediate realization. But local centers for the dissemination of requested information, perhaps in restricted fields, are frequently and hopefully proposed.

The individual physician, hospital, clinic, or biological investigator could call such an information center (by telephone or data circuit) requesting specific information and, through computerized techniques, receive a speedy answer. Such information requests might be of numerous types, such as information concerning any portion of a biological field, information relative to a particular disease, diagnosis corresponding to a list of symptoms and test results submitted by the questioner, a list of additional tests required for a specific diagnosis, statistical prognostic data corresponding to the suggested diagnosis and proposed or alternative treatments, and various additional services of an informational or advisory nature. Manifestly such a system calls for elaborate computer facilities and large-scale memory and retrieval methods as well as a competent collecting and collating staff.

Although such information centers could not replace the lengthy experience and trained judgment of the scientist, they would be useful, dependable, and readily available adjuncts or aids, and could be heavily drawn on by the corresponding professional workers.

Diagnostic information thus provided would be based not only on comprehensive statistical data but also on modern diagnostic methods (e.g., the use of electrical analogs of the human cardiovascular system). Prognoses would become more dependable if they were based in part on an analog study of the various relevant parameters and their effects. Thus, the result of surgical intervention might be electronically estimated, even in such complex cases as a combined cardiac insufficiency and stenosis (constriction.)

Information centers might also provide special aids to the physician. It is claimed, for instance, that films made of a psychotic patient, later projected before the patient, will sometimes improve his behavior.

Information integration and dissemination service in the life sciences, using modern electronic means, bids fair to provide a service of major human and professional value.

Hospitalized and ambulatory patient supervision

The magnitude of hospital operations in the United States is well indicated by available statistical data. In the 7000 American hospitals, 1.4 million patients receive care each day and about 24 million are hospitalized each year. The annual operating cost is $8 billion, about two thirds of which goes for labor. Although labor costs are not inherently high, they are increasing by about $500 million per year. Obviously, devices for reducing routine labor are urgently required.

Physicians cannot be used to advantage by requiring them to devote major blocks of time to the collection, recording, and abstracting of information required for treatment decisions. Physicians can more appropriately be asked to identify the complex groups of symptoms in disease, and to establish such valuable and helpful relationships with patients as will minimize patient worry, fear, or feelings of isolation. Nurses too should be relieved of tedious routine or clerical tasks.

Yet hospitals need elaborate data on patients, including identification, present illness, general history, results of examinations and tests, data resulting from consultations, X-ray studies, tissue data, provisional diagnosis (including indicated medication or surgical intervention), progress of the patient under treatment, later or more definitive diagnosis, and biopsy or autopsy results. Certain necessary data are obtainable in the operating rooms, wards, or private rooms, and may be electrically and continuously or intermittently sent and recorded at central monitoring stations, which, in turn, may be provided with automatic alarm systems responsive to unfavorable developments. Even electrocardiograms may thus be transmitted and analyzed for the physician or surgeon who may be speedily summoned in cases of emergency.

Systems of the foregoing types, of various degrees of scope, capability, and complexity, have been installed and show great promise. Portable sensors and signal transmitters can be provided for ambulatory patients.

Analogous recording systems have been devised for psychiatric cases, based to some extent on the patient's answers to a lengthy and largely standardized series of questions. It is attempted to elicit, record, and analyze (largely using electronic means) a complete history of the patient, his life and environment, and relevant data concerning his family.

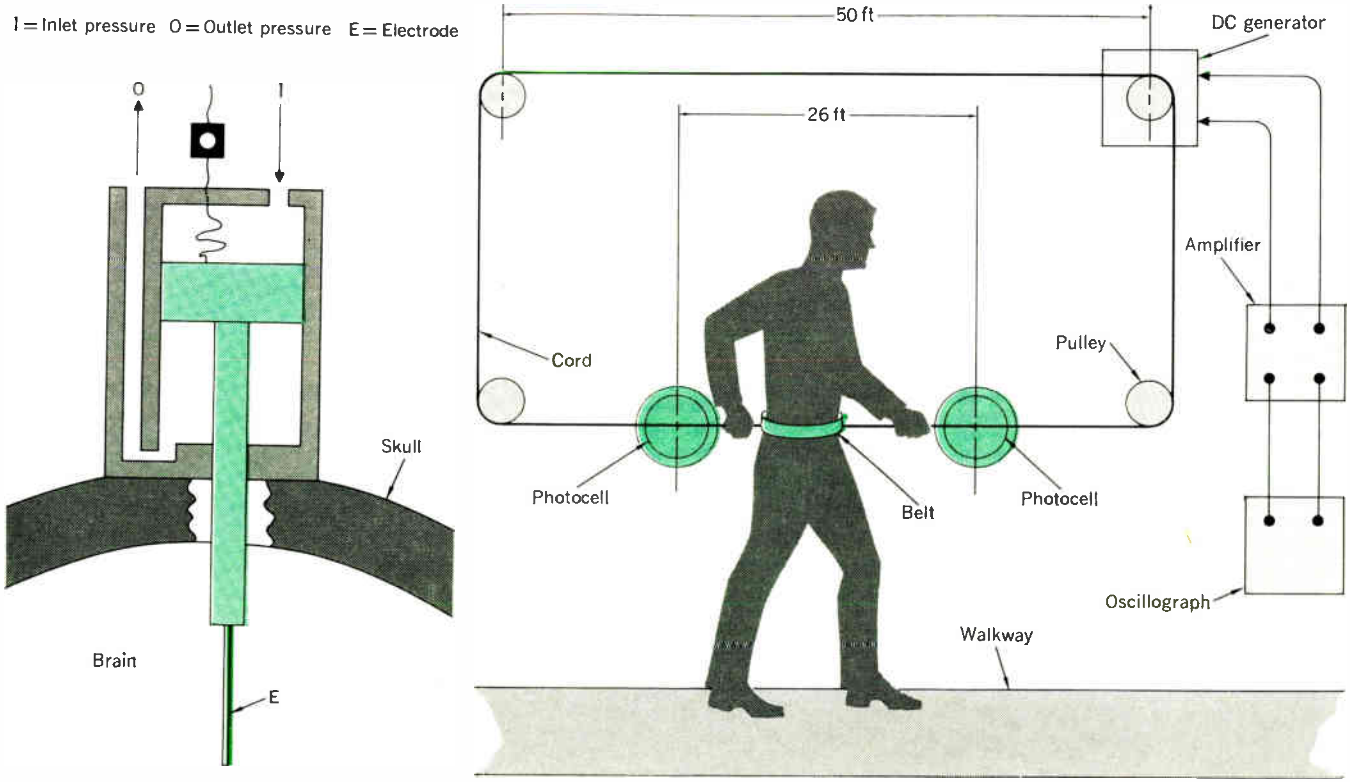
Major hospitals are increasingly aware of the need on their staffs of highly qualified experts in such formerly largely neglected posts as physicists, mathematicians, statisticians, and electronic computer programmers and operators.

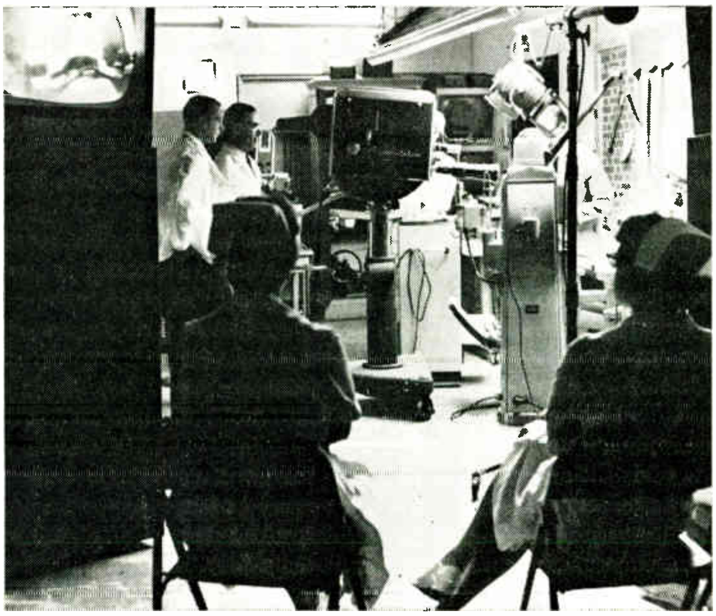
Prosthetics

Prosthetics primarily includes the temporary substitution of organs of the human body in emergencies or during operations, as well as longer-term replacement of essential organs. The biologist or physician sees the effects of biomedical engineering, like medicine, as directed to man's body. When accident, disease, or age damage the body's functions, medicine aims to restore them to normal. If medical means are insufficient, biomedical engineering is called on to provide machines (generally electromechanical) to take over the organ's functions temporarily or permanently. The human value of prosthetics is therefore high. At its disposal are the modern electronic expedients and components, with particular emphasis on feedback and automatic controls.

When heart action stops, the "cardiac pacemaker" applies timed electric impulses appropriately to stimulate heart action until it is restored to normal. More radical measures are required for some heart operations, where a "dry heart" or "open heart" condition is needed by the surgeon for fairly prolonged activities. Unless the heart were bypassed during this period by means of an external artificial heart (including blood aeration), the patient would die of anoxia (oxygen deprivation), which results in irreversible and lethal brain changes. It is

Below—Subminiature hydraulic lift that controls precise penetration into brain of a hibernating squirrel during studies of light processes. Right—Tacograph system, which records data about an amputee's walk across an instrumented platform in studies of artificial limbs. Pattern of walk is recorded by means of interrupted-light photographs taken of the amputee's artificial leg.





Top—Closed-circuit television at Johns Hopkins Hospital displays moving X-ray images. Examining-room camera is linked to TV tape recorder in adjacent room, permitting later playback and study. Bottom—At the University of Pennsylvania's School of Dentistry, closed-circuit TV system carries the pictures and the instructor's commentary to students at 16 monitoring locations.

hoped that a permanently implantable electromechanical heart will ultimately become available, or that replacement of heart valves or arteries by cardiovascular prostheses will become practicable. Extreme ingenuity has already been displayed in the design of the pump and timing systems and variation in their operating constants. A novel and special adjunct in this field is a device for the automatic control of blood-sugar levels in the case of diabetic patients.

Cryobiology (the use of extreme cold to deep-freeze tissue and, hopefully, to kill bacteria, viruses, or damaged cells) is under early study and shows some promise.

Under intensive development, and with considerable success, are artificial lungs and kidneys. A long series of important accomplishments in these and similar fields may be anticipated.

War-inflicted injuries and their repair greatly stimulated the development of prosthesis of limbs and hands. Something of the attained refinement of operation can be gained from a listing of the capabilities of an artificial arm, which is electronically controlled, uses external power, is preprogrammed (including storage of a number of programmed motions as well as patient selection between them or their modifications), and which has five degrees of freedom. Automatic hands provide a wide variety of chosen movements, either automatic action or voluntary control, as well as reasonable simplicity of construction and acceptable cost. Clenching of the hand and adjustable grasping with the fingertips are available. Some highly sophisticated pressure-sensitive controls, and also feedback at appropriate parts of movements for avoiding excessive pressures, are provided. Even completely incapacitated patients can be provided with a breath-operated pulsing switch, which may be coded to control a radio or television receiver, operate a typewriter, answer a telephone, or the like.

Various electronic aids for the blind are in an early stage of practical development. In one guidance equipment, an ultrasonic airwave generator produces a highly directional and narrow beam, which is reflected by the target or obstacle and picked up by a receiver (using a sawtooth FM signal) and earphone. Such devices are somewhat rudimentary and not as yet adequately satisfying to the user. In the meantime, techniques have been developed for permitting the blind to operate a telephone switchboard, for example. Talking typewriters, which will enable the blind to type, are also planned.

Although not strictly prosthetic devices, equipment for electromechanical translation of foreign languages should be mentioned here as being under intensive study and experimental development. It is likely that the syntactically correct and idiomatic mechanical translation of foreign language texts of wide diversity is a remote possibility. However, acceptably understandable translation of material in a restricted field (e.g., certain technical material) seems within reach.

Aids for the deaf (and dumb) also show promise. An "artificial ear" now under development calls for the design and construction of assemblies of suitable electronic components reasonably closely simulating the normal ear and its associated processing structures and nerves. Such assemblies include multitapped delay lines, difference amplifiers responsive to the nerve pulse frequencies, and simulation of the real-nerve interconnections by electronic assemblies. (Somewhat similar methods are hoped to be found effective in the visual field for pattern recognition.)

To assist in teaching deaf children to talk, visual depictions of sounds are prepared, and the corresponding depiction of the sound spoken by the child is compared by him with the correct picture.

The artificial larynx enables persons whose physical speaking capability has been lost to develop speech sounds of intelligible nature by this prosthetic device. It involves the resonant modulation, controlled by the user, of a buzzing sound generated by the device.

Stammer sufferers have been helped by the controlled production of a low-frequency masking tone which, when desired, prevents the patient from hearing his own voice.

In general, major progress in prosthesis may be anticipated through both broad and detailed improvements.

Computer applications

In modern physical research, interest is largely centered on the submicroscopic elements of matter—that is, the atomic nucleus, and the so-called "elementary particles," their arrangements and interactions, and their internal and external effects. In biomedical research, there is growing emphasis and great potential utility to be derived in the study of the submicroscopic elements of living matter, including the cell nucleus, the chromosomes and genes, their component amino acids and porphyrins, their arrangements and controls, the enzymes which are their "messengers," and the resulting life forms, bodily characteristics, and behaviors.

In view of the many and complex mathematical calculations that may be required in biomedical research, the electronic computer is being used more and more widely. For example, in a thorough statistical analysis of 300 cardiac patients, values of 60 separate clinical parameters were required for each patient. Fortunately, computers can supply huge memories and random-access retrieval of stored information, thus handling the necessary bookkeeping and enabling the physician to concentrate on tasks requiring his skill and on improving his patient relationships.

The monitoring and surveillance of patients can be facilitated by computers. In research projects, the computer permits speedy analysis and interpretation of facts or data, and permits ready tests of hypotheses by simulation through models, with consequent validation or disproof. Thus computers make possible many otherwise impracticable or impossible tasks.

The numerous details of their many and special uses are beyond the scope of this summary article. However, it is of general interest to mention the application in biomedical engineering of a now-accepted electronic method whereby the signal-to-noise ratio in the output of a device is increased by adding up a number of scans. Even if individual scan signals are so small that they are difficult to distinguish from noise signals, they can be made to be always positive and, therefore, additive. The noise signals, being both negative and positive, will usually largely average out. For example, computer averaging of 100 scans in a particular instance increased signal-to-noise ratio tenfold.

Such organs as the lungs, as well as muscles, blood vessels, and even the skin, produce variable and informative electric fields. A properly programmed computer can assimilate, analyze, and systematically help to interpret these field variations. Heart activity, as measured on the surface of the body, is usually shown in a somewhat distorted form because of interfering field forms. Computer techniques permit the detection, evaluation, and effective annulment of such unwanted artifacts and thus give the physician a correct record of heart action.

The convenience of portable electrocardiographs has been demonstrated by carrying such an instrument into some 500 homes and sending the resulting signals to a central computer over telephone lines. Significantly, some previously undetected heart defects were found.

By means of advanced pattern recognition techniques, electrocardiograms can be systematically classified and analyzed, and thus provide a useful aid in hospital administration.

Computers, in the psychological realm, can simulate the interactions between members of groups in which reward or punishment result from the response of the remaining group members to the proposals or responses of a particular member of the group. It seems to be within the scope of computers to study human behavior, through a model, as a function of its payoffs.

Other group studies that may be handled by computers involve simulating persons with problems. Psychological theories may thus be tested for validity. Each "person" considered by the computer is assigned ability and personality traits, such as his past history, his job preferences, his skill in meeting social problems, and his activities in such groups as family, clubs, and fellow office members. He is also assigned sets of needs, values, selected personal status symbols, recollections of his previous contacts with the other group members, ability to judge moral values, and correlation of his actions with resulting responses. Interesting and apparently useful results were obtained in a test of this system for studying problems of an individual within a group.

Computer service has been offered without charge or at cost by a nonprofit organization to investigators of weather phenomena (such as cloud formation or turbulence), to astronomers studying stellar evolution, and to students of certain radiation problems.

An unusual application of computers is the teaching of the proper accent in a foreign language. The student reads some foreign text. This is compared oscillographically with a correctly spoken version of the same text. The computer determines the student's correctness of pitch, loudness, and rhythm, and gives the student a corresponding grade. The process is repeated until the student achieves a "passing" grade.

In partial summary, a major role of the computer is as follows. Man's memory and his access to his recollections are both limited. This, in turn, slows or restricts his capability of original thought and his speed and certainty of wise decision. It may be found that the computer will substantially assist man in overcoming his limitations by at least speedily providing the necessary and specific background information, thus making possible prompt and effective decisions and even, in some measure, assisting original thought and creative effort.

Genetic studies and selective breeding

The biological inheritance of each human being is carried in detail, and later effectively developed, by complex chemical systems. Information governing the characteristics of the next generation is found in rather stable chemical configurations (genes, or heredity determinants). The genes are found as portions of larger threadlike structures (chromosomes) located within the nucleus of almost all living cells. When cell division (mitosis) occurs, the genes also replicate (duplicate) without change. Information from the genes is carried unidirectionally by "message carrying" materials to the point at which the final and desired chemical reaction and conformation occur. These and other cellular reactions are thus apparently initiated and guided by enzymes.

The basic or chief material within the genes, called DNA (deoxyribonucleic acid) is a highly polymerized giant-molecular substance of peculiar double-intertwined-helical structure. DNA and a sometimes accompanying material, RNA (ribonucleic acid), turn out to be made of four amino acids arranged linearly in a coded order and with systematically occurring gaps. Certain of these DNA groups carry, or are attached to, a molecule of orthophosphoric acid and thence to a molecule of a pentose sugar. Such an element (or nucleotide) individually carries a small quantity of information, but large groups of nucleotides can carry great amounts of highly specific information. Since the nucleotides are present in different amounts and in irregular sequences with intervening gaps within the gene, vast amounts of specific heredity information can be represented by them.

It has already been possible to identify the location of certain specific items of hereditary information with corresponding locations of genes within the chromosome (e.g., of the fruit fly). Yet it is clear that the decoding of the full information within the nucleotide chains, genes, and chromosomes is a truly colossal task for the biochemist, biologist, and the computer expert. Further discussion of this unfinished task is beyond the scope of this article. It should be mentioned, however, that when the computer has successfully contributed to the solution of the decoding problems here involved, important medical results will follow, such as understanding of the reasons for hereditary susceptibility to certain diseases such as cancer and hemophilia (uncontrollable bleeding), the action of carcinogenic (cancer-producing) chemicals, and chemotherapeutic methods of controlling cancer, as well as the role of viruses, cell mutations, and enzymes in diseases.

Some measure of rational genetic control may well follow from reasonably complete knowledge of the genetic inheritance of man. Human characteristics—including, for example, susceptibility to diseases—will be better understood and, hopefully, controlled in some measure. Whether selective breeding will be a practical or humanly acceptable expedient in these directions remains for the future to unfold.

Physical interference with the genetic structure is a complex and probably hazardous venture. It is known, however, that the utilization in plants of the energy of sunlight to form chemicals such as the green pigment (chlorophyll) proceeds in orderly and partly understood fashion. And a three-day exposure of cancer cells to a 4000-gauss magnetic field led to an inhibiting effect of statistically significant amount on all cellular growth. Further, even low-intensity microwaves (radiation as low as 1 mW/cm^2) gave an observable biological effect. What lies along these and many parallel paths will be determined to advantage in the decades to come.

Biomedical instruction

The role of electronic and other aids in the instruction of biological and medical students is a partly established and steadily growing one. It is stimulated by the problem arising from population increases, the raising of educational standards, shortages of qualified teachers, and the need for maximum utilization of available instructional talent. Even so, the advantages of biomedical-electronic education are as yet not fully recognized. Although less than 50 percent of queried college deans and hospital administrators answered a questionnaire on this subject, almost 80 percent of those returning the questionnaire were favorably disposed toward the field. About one half of the queried medical school deans and one third of the engineering school deans expressed the belief that biomedical-electronic instruction should be at the postgraduate level.

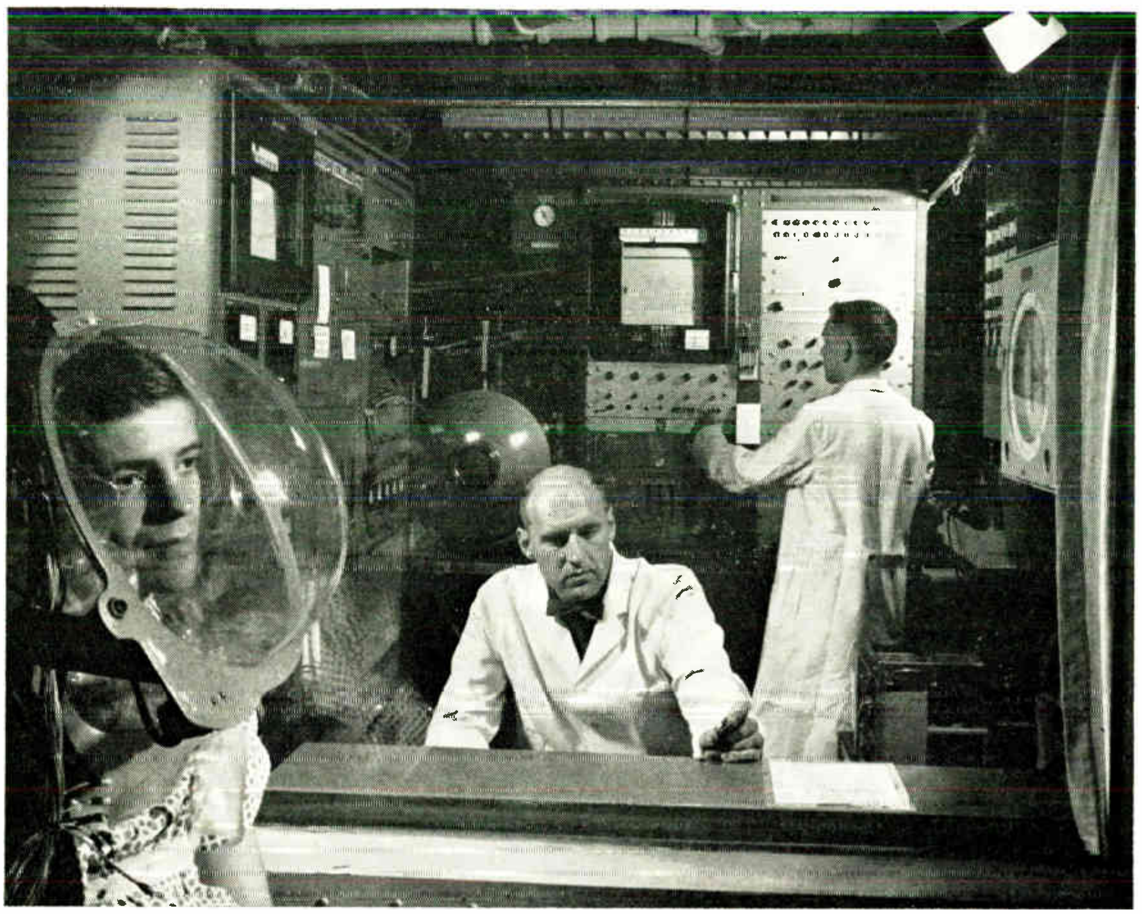
Television is an obviously desirable agency for medical instruction in general. Images can be shown to large groups. Inaccessible locations within the body can be displayed via the endoscope (an optical probe, sometimes using flexible fiber optics). Infrared or ultraviolet illumination can be used to produce a visible television picture. The television camera can peer through a microscope and thus show greatly enlarged images. Desired degrees of contrast and color can be adjustably secured. Textual and graphic material can be displayed on a large screen. And medical, surgical, or psychiatric patients can be viewed in one room while the physician or lecturer shows the images and addresses the students in another room.

Certain factors should be considered in planning multipurpose centralized television installations for medical education. These include initial, operating, and maintenance costs as well as requisite engineering and production facilities.

On the teaching side, it is necessary that the equipment and operation be of high technical quality, convenient and flexible in operation, and capable of growth even into the postgraduate field. Available statistics indicate that of the 86 medical schools in the United States, 40 use television, with a total investment of about $3 million in television and associated gear. Similarly, 30 of the 48 United States dental schools use television.

In a parallel field, hospitals have found television useful in general administration, patient monitoring, radiology, surgical teaching, inventory control (including pilferage detection), as well as in various associated activities, such as diagnosis and treatment. An interesting use of television is for the storage and reproduction of X-ray pictures and other medical views on video tape for later study and comparison with subsequent pictures. Other advantageous features are the placing of the student, in effect, at the best possible viewing location (that of the television camera), and the availability of simultaneous sound and picture (as in listening to heart sounds while viewing X-ray pictures of the heart). Pictures can be processed to show increased contrast, or a restricted and desired contrast range. Group therapy is more readily carried out televisually. And visits to patients by children are more convenient and controllable by television.

Color television offers added and sometimes essential advantages. In diagnosis by a group of physicians, color television is a most helpful aid. Operations—e.g., on the eye or ear—become more definitive and instructive in color. Microscope views can be shown effectively on



Metabolic chamber of the National Institute of Arthritis and Metabolic Diseases helps in investigations being made of life processes. Expired air that accumulates under the mask is collected by the use of continuous-stream gas analyzers.

large screens with the added color information. Instruction to nurses, refresher courses or timely information to practitioners, and even examinations of students are facilitated by the use of color television.

In certain mental cases, television recordings of the effect on the patient of various tranquilizers, as elicited in interviews, can be studied independently and at convenient times by various experts.

A highly ingenious method for creating informative artificially colored pictures has been invented and realized in practice wherein television images taken by illumination at three different ultraviolet frequencies are reproduced, for example, in a conventional three-color television system. The color pictures thus displayed are often highly instructive in relation to tissue composition and structure even though they are specialized artifacts.

A steady, though perhaps not explosive, growth in the use of television and other engineering methods for biomedical instruction, diagnosis, consultation, hospital applications, and research may be confidently expected.

Contributions of biology to engineering

Study of the physical (and psychological) behavior of animals has led to the formulation of rules or procedures which enable approximate engineering analogs of animal performance and controls to be devised. A new field has thus come into being, called "cybernetics" (derived from the Greek word for "the steersman"). In a narrow sense, cybernetics deals with physical or chemical feedback control in man and other animals. In a broader sense, this field (also termed "bionics") deals with methods existent in nature for the control and functioning of biological processes and their possible adaptation and application in man-made systems or artifacts.

The negative feedback has as its element the initiation of a movement, the sensing of the magnitude of the error in the movement, a feedback correction of the error, and repetitions of the preceding processes with the aim of minimizing the error in the final step. More broadly, though crudely, there is here involved an adaptive mechanism or control, including the completion of a part or all of a task, an evaluation of the correctness of its accomplishment, a correction of the preceding procedures usually by changing the control parameters in accordance with the preceding information, and repetitions of the process to maximize its effectiveness.

One obvious contribution of biology to engineering is that it demonstrates the solvability of certain difficult problems (though often by methods based on, but differing radically from, those found in nature). As examples, the soaring flight of sea gulls or condors showed that heavier-than-air flight was possible. The hummingbird demonstrates that hovering flight, as well as vertical or short takeoff and landing, are possible and that the ornithopter (flapping-wing) principle merits study. The bat shows that a highly precise and sophisticated "radar" or "sonar" system (using supersonic airwaves) is operative, thus indicating the feasibility of radar location and its further development. Man's retina and optic nerve system and his cochlea and aural nerve system show, respectively, that (at least in conjunction with the brain) image recognition and speech understanding are possible. Scotopic vision (in dim light) and phototopic vision (under normal illumination) show that wide ranges of illumination are feasible in producing useful luminous response.

Sensory systems of many animals have been intensively studied with possibly helpful or useful results in some cases. Among the animals in question are cats, cockroaches, dolphins, fruit flies, frogs, porpoises, and sea lions. It is also found that on occasion nature even provides alternative methods of achieving desirable results. For example, studies of the retinal structures of the frog and of the fly show methods of visual image production, and probably of perception as well, that differ widely from those of man.

Many unsolved problems remain, such as, for example, the lack of an adequate explanation for the guided migratory flight of birds—a subject under close study in recent times. It may be said that the old aphorism, "The proper study of mankind is man," has acquired a new and more specific meaning in that a proper study for engineering is also man himself.

It can only be mentioned here that modern cybernetics leans heavily on information theory, automation theory and practice, artificial and natural neural-network structures, communication theory, and methods for increasing reliability of operation using partly unreliable components. Further, the world of living organisms operates with dependence on so many variables interacting in such complex fashion that the usual mathematical theories of statistics and probability do not always hold for living systems; possibly, novel forms of logic will be required for further understanding of such systems. And there are other presently obscure areas awaiting investigation, such as the structure or nature of memory in living organisms. Since genetic information, for example, is highly stable and can be replicated, and since ordinary human memory can retain complex information for long periods, difficulties are experienced in applying theories of conventional molecular storage methods to living memory systems. Further study in this field may well prove rewarding.

Of late, much interest has been aroused in the possibility of extraterrestrial life, in the environmental factors helpful or prejudicial to such life, and even in the requisite tests and supplies required to sustain life in space. Broadly considered, extraterrestrial life should meet the following criteria. In an environment containing one or more energy sources, the living organism must spontaneously act as an effective energy sink and be capable of controllably utilizing energy for its vital processes and survival purposes. Such matters as the requisite structure of the organism, its mode of growth and reproduction, and its dependence on the terrestrially used DNA, RNA, amino acids, or the like remain open for further and prolonged study.

Survival of man in space may depend on use of shielding against high magnetic fields, various types of electromagnetic radiation including X radiation, meteorite impact, proton bombardment, and other injurious factors. Absence of usual gravitational fields may well prove to be so damaging, after prolonged exposure, that artificial gravity (centrifugal force) may be necessary in spacecraft.

Of necessity, such matters as artificial atmosphere, food supply, water supply, and reuse of waste exhalations and secretions must be considered. As an estimate, four to six men may survive for a year with a 90-day resupply of food (probably freeze-dried), toothpaste, and some oxygen and nitrogen—all delivered by space ferry. The necessary food supply is about 1.4 pounds per man per day, and the personal hygienic water supply is about 8 pounds per man per day. Available supply systems seem fairly complex. Their present, rather rudimentary stage of development may well be a precursor of workable and viable ecological systems.

Conclusion

Considering the wide scope, and major value to humanity, of biomedical engineering, it may fairly be said that in this era of often affluent scientific endeavor, engineering in the life fields has been a somewhat meager beneficiary. Its relatively limited (and far from large-scale) support contrasts sharply with the highly favorable opinion held by many thoughtful scientific analysts of its high relative and absolute importance to our present and future civilizations.

The field is, however, a difficult one in one fairly obvious respect. To "explain" a biological phenomenon implies its qualitative and quantitative understanding and the capability of its reasonably accurate prediction. It is true that many biological processes and their results can be measured with acceptable accuracy and sufficiency of interpretation by instrumentation based on presently known physical and chemical laws. However, we cannot presently exclude the possibility that some principles and methods outside of present-day scientific knowledge are necessary for a satisfying explanation and a logical understanding of many basic biological phenomena—for example, genetic structure and mitotic (cell-divisional) growth. It is not implied that some form of "vitalism" is needed for a fuller explanation of biological processes. Yet it must be admitted that the phenomena of life, their variations and limits of viable deviation, their orderly and elaborate sequences, their highly complex and multiple interrelations, and their inceptions and terminations remain at this time in large measure beyond any satisfactory or comprehensive explanations.

Whether new branches of science or other disciplines will be required for the desired broadened knowledge in the biological field, and needed for its engineering congener, only time will tell. Clearly the field presents challenging vistas of potential major advances. It is already certain that the rational thinker and original investigator will have ample opportunity for rewarding accomplishments in biomedical engineering. This is indeed a domain for the ingenious, the creative, the determined, and the tenacious. And its fruition bids fair to give much to humanity at large and to each of us in particular.

This article is an expanded version of an RCA technical paper published earlier in 1965 by the Radio Corporation of America.

Picture credits: p. 46—National Institutes of Health; pp. 51 (left) and 55—National Institutes of Health and *International Science and Technology;* p. 51 (right)—New York University.

PCM picture transmission

Because recent developments in integrated circuitry have resulted in reduced equipment cost and because more effective bandwidth compression techniques have been developed, research efforts on picture transmission by pulse code modulation are being intensified

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The transmission of pictures by pulse code modulation (PCM) has been investigated by various researchers[1,2] for more than a decade. Recently, interest has reached a new high, partly because of the possible military and space applications. The purpose of the present article is to describe briefly some of the research work being carried on in PCM picture transmission at the Cognitive Information Processing Group (CIPG) of the Research Laboratory of Electronics, Massachusetts Institute of Technology. Many other groups, notably the Bell Telephone Laboratories researchers, are also working extensively in this area.

The advantages and disadvantages of PCM, as compared with analog transmission methods, were excellently discussed in the classical paper of Oliver, Pierce, and Shannon[3] and in a recent review article by Deloraine and Reeves.[4]

In summary, the advantages of PCM are as follows:

1. By the use of repeaters, PCM can be employed to transmit signals over long distances without deterioration in signal-to-noise ratio.
2. It lends itself to time-division multiplex.
3. It simplifies switching problems in central stations.
4. It can easily be adapted to secrecy transmission.
5. PCM systems are most suitable for transmitting digital data and are easily coupled with digital computers.

The disadvantages are:

1. The transmitter and receiver for PCM are somewhat complicated.
2. PCM requires more bandwidth.

However, the recent rapid developments in integrated circuits have started to reduce the cost of PCM equipment drastically. In addition, research in bandwidth compression techniques indicates the possibilities of easing the bandwidth requirement in PCM picture transmission.

A block diagram of a PCM picture transmission system is shown in Fig. 1. The original continuous picture is first sampled in space and quantized in brightness to produce a digital picture. Assume $L \times L$ samples are taken and that the brightness is quantized to 2^B levels. Then this digital picture can be thought of as a matrix of $L \times L$ points; each point assumes one of 2^B brightness levels. The scanner converts the two-dimensional matrix of points into a one-dimensional sequence of points. The encoder assigns a code word to each brightness level. In the case of binary coders, to which we shall restrict our attention, each code word is a B-bit binary number. The output of the encoder is a sequence of binary numbers (represented physically by, e.g., positive or negative pulses) which is transmitted to the receiver via some channel. At the receiver, the process is reversed. The decoder finds the corresponding brightness levels for each code word; the scanner converts the one-dimensional sequence to a two-dimensional matrix of points; and, finally, a low-pass filter smooths the digital matrix to get a continuous received picture.

The research being carried on at CIPG in PCM picture transmission falls into two categories:

1. Investigations on how the quality of the received picture depends on various system parameters.
2. Bandwidth compression techniques.

Most of the studies have been done by digital computer

Fig. 1. A PCM picture transmission system.

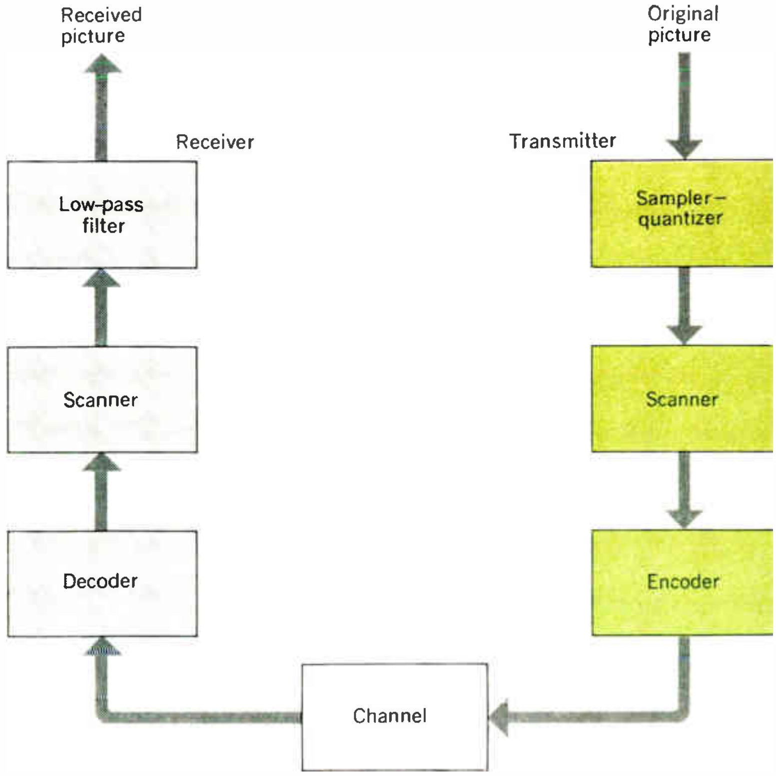


Fig. 2. Pictures of a face received through simulated PCM systems. A—Number of samples = 128 × 128; number of brightness levels = 64. B—Number of samples = 256 × 256; number of brightness levels = 16.

Fig. 3. Pictures of a crowd received through simulated PCM systems. A—128 × 128 samples; 64 brightness levels. B—256 × 256 samples; 16 brightness levels.

simulation. A special picture input/output device was constructed[5,6] to facilitate communication with the computer.

Sampling and quantization

If a picture is to be sent by PCM, it must be sampled in space and quantized in brightness; see Fig. 1. Let us assume for the moment that the channel is noiseless. Then, the received picture will look as good as the original, if the number of samples ($L \times L$) and the number of brightness levels (2^B) are large. However, since the number of bits per picture to be transmitted is equal to $N = L \times L \times B$ (assuming no bandwidth compression scheme is used), unnecessarily large values for L and B are undesirable. To obtain a received picture with resolution comparable to that of present-day commercial television pictures, about 500 × 500 samples per picture ($L = 500$) are required. To make the brightness of the received pictures look continuous, about 50 to 100 brightness levels ($B = 6$ or 7) are required. The use of smaller values for L will reduce the resolution of the received picture; the use of smaller values for B will introduce spurious edges (the so-called

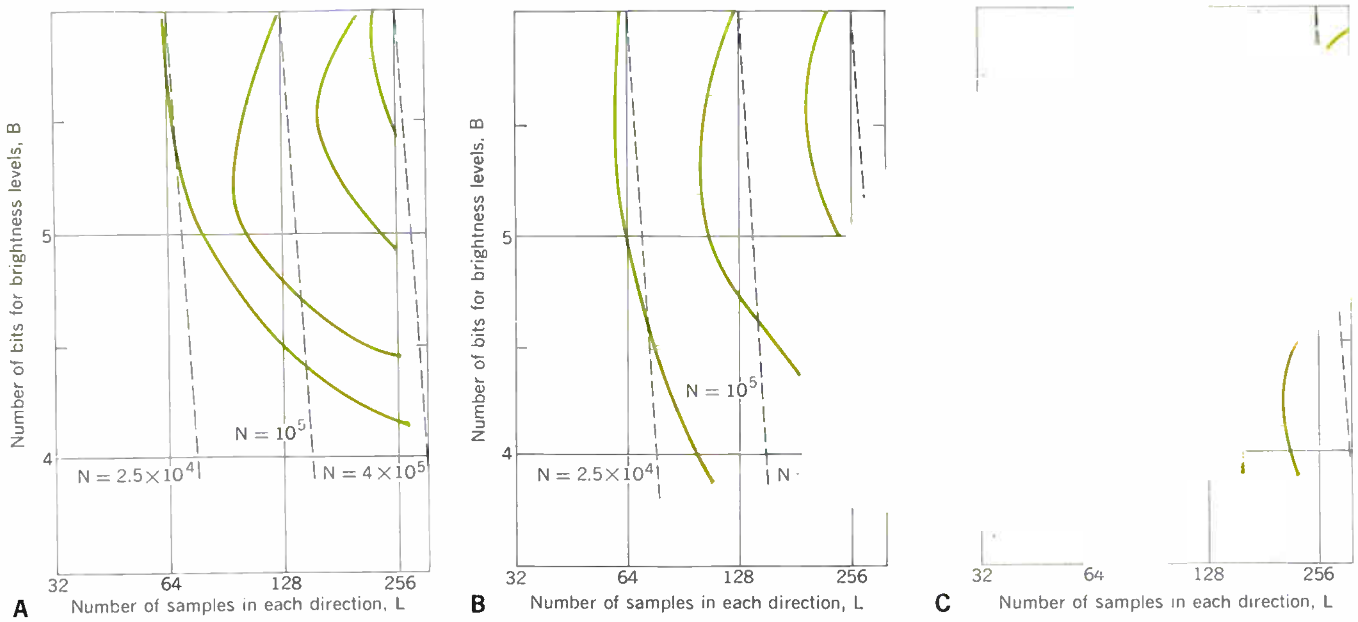


Fig. 4. Isopreference curves for (A) face, (B) cameraman, and (C) crowd.

quantization noise) in the received picture. Figures 2 and 3 show some examples of received pictures.

As mentioned earlier, the necessary number of bits per picture is $N = L \times L \times B$. The following question then arises: For a given value of N, how should we choose values for L and B to get the best received picture?

The answer, of course, depends on what we mean by "best." The requirements on a reconnaissance picture, for example, are quite different from those on commercial television pictures. For general-purpose pictures (such as commercial television and photophone pictures), the judgment on the quality of the picture is necessarily subjective. For this class of pictures, series of subjective tests[7] were conducted in an attempt to answer the question posed in the preceding paragraph. Three original pictures, containing different amounts of details, were used: a face (Fig. 2), a scene with a cameraman at the center, and a crowd (Fig. 3). Pictures with different values of L and B were generated, and observers were asked to rank order them according to their subjective quality. The results are presented in Fig. 4 in the form of isopreference curves in the L–B plane. Each point in the L–B plane represents a received picture, with values of L and B equal to the coordinates of that point. An isopreference curve is one on which the points represent pictures of equal subjective quality. Figure 4 also shows curves of constant N, which are dotted. By inspection of the isopreference curves, the following conclusions can be drawn:

1. The isopreference curves depart markedly from the curves of constant picture bit rate (N). Note that the pictures in Figs. 2 and 3, (A) and (B), have the same value of N.

2. The isopreference curves depend very much on the picture types. The curves become more horizontal as the picture details increase. This indicates that for pictures with a large amount of detail, only a few brightness levels are needed; see Fig. 3(B).

3. In some cases, for a fixed number of spatial samples, the picture quality will improve with a decrease in the number of brightness levels. A probable reason is that decreasing the number of brightness levels increases the apparent contrast of the picture.

Coding and noise

We mentioned earlier that if the digitalized picture in the PCM system of Fig. 1 has 2^B brightness levels, then the encoder assigns a B-bit binary number to each brightness level. The totality of code words for all the brightness levels is called a code. The number of possible codes is enormous, since each B-bit binary number can be assigned to any brightness level. If the channel is noiseless, the appearance of the received picture is independent of which particular code is used. However, if the channel is noisy, the amount of noise in the received picture will depend on which code one uses. The question then arises: Which code yields the least noisy picture? The answer to this question depends on the characteristics of the channel. A first-approximation model for many practical channels is the so-called binary symmetric channel (BSC). Such a channel treats each incoming bit independently: each bit has a probability p of being received erroneously. For a BSC, it can be shown[8] that if (1) in the digitalized picture all brightness levels occur equally frequently and (2) the probability of error p is small so that in any code word rarely is more than one bit received erroneously, then the "natural code" yields the least noise power in the received picture. (The natural code is the code in which the brightness levels from 0 to $2^B - 1$ have their natural binary representations as code words; for example, for $B = 6$ the code word for brightness level 3 is 000011.) Another code, which has some advantage over the natural code in encoder implementation, is the "Gray code,"[9] in which any two successive brightness levels have code words different in only one bit. It turns out that the Gray code yields only slightly more noise power than the natural code and is better than most other codes. Table I compares the noise powers of the natural and the Gray codes to the average noise power over all possible codes for various values of B. We emphasize that these results were obtained under the assumption that the input amplitude distribution is flat. If the input amplitude distribution is not flat, but rather, say, peaked at the center, the Gray code might be better than the natural code.[10]

Figure 5 shows two pictures received through a BSC with error probability $p = 0.003$. Figure 5(A), which used natural code, appears less noisy than 5(B), which used Gray code. It is interesting to note that the noise introduced by a BSC consists visually of isolated white and black spots, and looks quite different from analog noise (Fig. 6).

It is our conjecture that the natural codes yield the least noise power in the received picture for all values of $p < 0.5$ and for more general brightness distributions than the uniform distribution. However, so far we have not been able either to prove or refute this opinion.

Scanning

In the PCM picture transmission system of Fig. 1, the transmitter scanner converts the two-dimensional digitalized picture to a one-dimensional sequence of points, and the receiver scanner reconstructs a two-dimensional picture from the received one-dimensional sequence. Usually, the scanners scan the picture line by line sequentially. However, many other scanning patterns have been suggested. The so-called pseudorandom scanning, for example, can be used for secrecy transmission.

In pseudorandom scanning, the scanning beam hops from point to point in a seemingly random fashion. However, the transmitter and receiver scanners are synchronous, so the receiver scanner can reconstruct the picture. The coordinates of the successive scanning points are specified by a sequence of pseudorandom numbers, which can be generated, for example, by a maximum-length shift register generator.[11] Anyone who does not know the particular pseudorandom sequence will not be able to reconstruct the correct picture even if he should intercept the one-dimensional signal being transmitted. Figure 7 illustrates the situation. In Fig. 7(A), we have a digitalized picture (number of samples = 128 × 128, number of brightness levels = 64). This picture was pseudorandomly scanned and reconstructed by sequential scanning, resulting in the picture shown in Fig. 7(B), which is completely scrambled.

Assuming the transmitter and receiver scanners are synchronous, then the appearance of the received picture will be independent of the scanning pattern, if the channel is noiseless or if it is noisy but treats each incoming bit independently. In many practical channels, however, the noise tends to occur in bursts. For such channels, sequen-

I. Noise power comparison

Number of bits:	2	3	4	5	6
Code	Noise Power/$p(1-p)^{B-1}$				
Natural code	5	21	85	341	1385
Gray code	6	27	112	453	1818
Average	6.7	36	181.3	880	4160

Note: Peak signal power is $(2^B - 1)^2$. Input amplitude distribution is assumed to be flat.

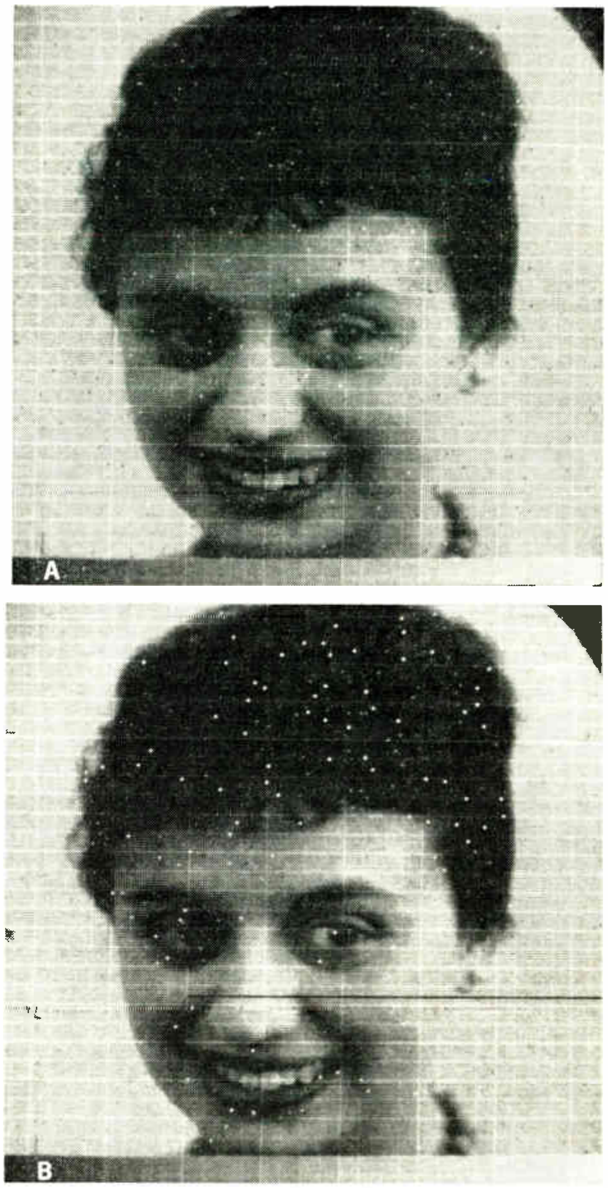


Fig. 5. Picture received through binary symmetric channel with p = 0.003, using (A) natural code and (B) Gray code.

Fig. 6. Picture with analog noise.

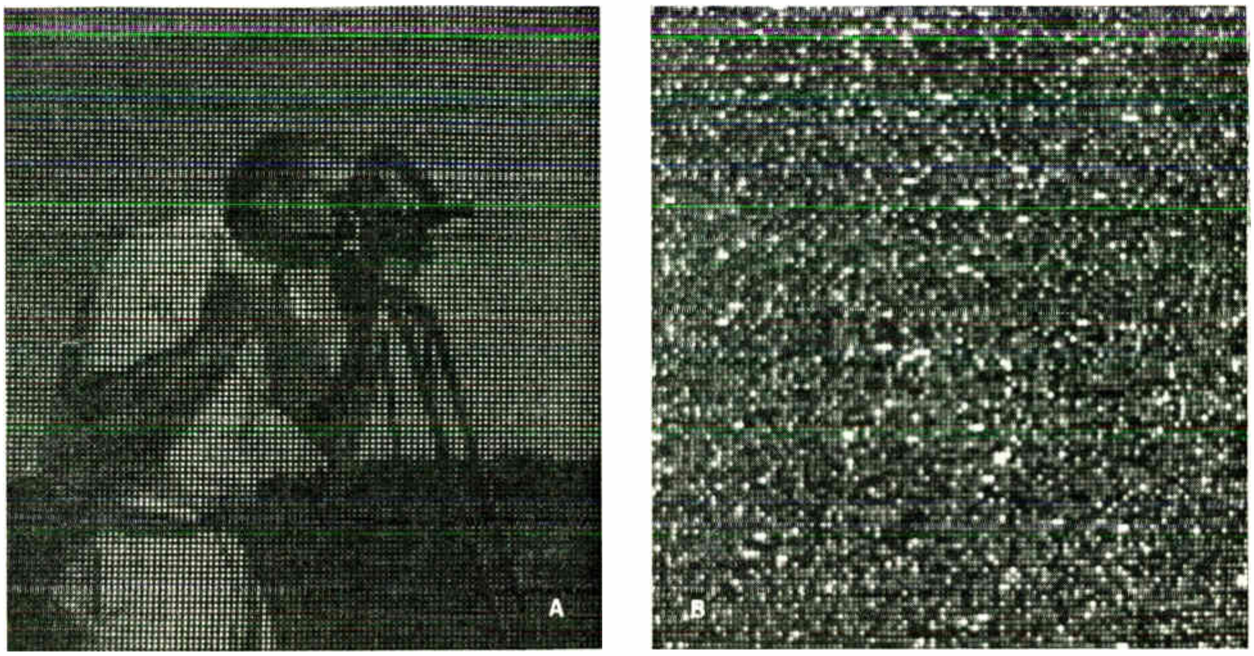


Fig. 7. Pseudorandom scanning. A—Digitalized picture. B—Same picture pseudorandomly scanned and reconstructed by sequential scanning.

tial scanning will yield received pictures containing errors that last over many successive picture points along the scanning direction, whereas pseudorandom scanning will randomize the noise so that the errors will scatter more or less uniformly over the entire picture. Subjective tests[12,13] indicated that randomly scattered noise is usually less objectionable than noise with local structures.

Bandwidth compression

Although, as mentioned earlier, PCM has several advantages over analog transmission methods, it suffers from the fact that it requires more channel bandwidth. To overcome this defect, various researchers have been trying to devise bandwidth compression techniques. Since the bandwidth required of a channel increases with an increase in the number of bits to be sent through it, it is desirable to reduce the number of bits needed to transmit a picture. Such a reduction is possible because of the following two facts:

1. There are statistical constraints among the picture samples. Therefore, the information content[14] of a picture is less than B bits per sample (assuming the number of brightness levels is 2^B). Up to third-order probability distributions of the brightness levels of picture samples have been measured.[15] From these measurements, one would guess that, by using only intraframe statistical constraints, bit reductions of 5:1 to 10:1 can be achieved. However, elaborate block codes and, hence, huge code books are necessary.

2. If the received picture is to be viewed by humans, then one can take advantage of the properties of human vision. Here, the purpose is to distort the picture in such a way that it can be described by a smaller number of bits; however, the distortion is not great enough to be noticeable or objectionable to the human viewer.

At CIPG, work has been mainly with monochrome still pictures, for the purpose of (1) finding out how much bit reduction can be achieved by the use of very sophisticated and complicated schemes and (2) investigating simple and practical techniques that give moderate bit-reduction ratios (around 5:1).

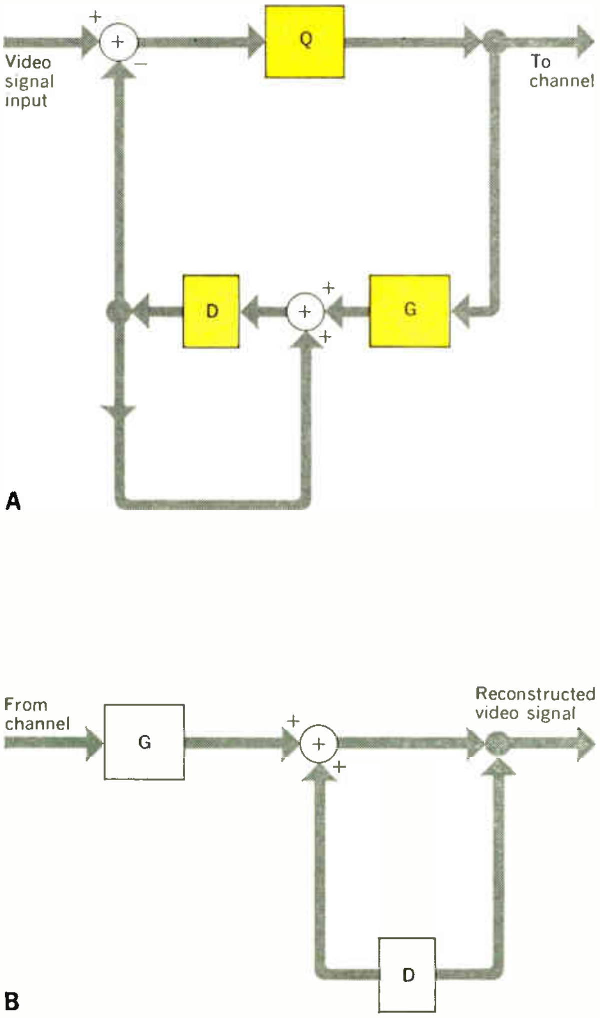
In the first category, we might mention Pan's attempt[16] to extend Schreiber's "synthetic highs" scheme[17] to two dimensions. Experiments indicated that the human eye tends to emphasize edges in a picture but is relatively insensitive to the amount of changes in the brightness over edges; however, in areas where the brightness changes slowly, quantization noise is easily discernible. Therefore, edges (the high-frequency part) and the slowly-varying areas (the low-frequency part) of a picture were treated differently. The low-frequency part of the picture was obtained by passing the picture through a two-dimensional low-pass filter. The edges in the picture were obtained by a two-dimensional edge detector. Whether a particular point was an edge point or not was determined by a threshold function, which depended on the neighboring points. The edges were then approximated by straight-line segments, and only the end points of the segments (plus the information on how to connect them) were transmitted. With this scheme, it was possible to achieve bit reductions from 10:1 to 20:1 (see Fig. 8); however, the received pictures had rather poor quality, even in cases in which the reductions were small. It was thought that this defect is caused by the *ad hoc* procedure used to obtain and to encode the edges. A possible improvement of the scheme was suggested by Schreiber[18] and is being investigated by Graham.[19]

In the second category, it seems that the most promising scheme is probably some modified form of delta modulation. The transmission of speech by delta modulation[20] has been quite successful. The application of ordinary delta modulation to picture transmission, however, gives very poor received pictures because picture signals vary much more rapidly than speech signals. A modified

Fig. 8. Picture from Pan's scheme. Bit reduction = 15:1.

Fig. 10. A—Ordinary Δ-modulated picture, with A = 2. B—Δ²-modulated picture, with $a_i = 2^{i-1}$, limited at 8. C—Same as (B), except that the channel is noisy (binary symmetric channel, $p = 0.001$).

Fig. 9. Delta-modulation system.



scheme,[21,22] called Δ^2 (delta-squared) modulation, gives much sharper pictures than ordinary delta modulation.

An ordinary digital delta-modulation system is shown in Fig. 9. Q is a two-level quantizer whose output is "1" when the input is positive, or "0" when the input is negative. G is a two-level generator that puts out A or $-A$ when the input is 1 or 0, respectively. D is a one-unit (time between successive samples) delay.

In the Δ^2-modulation system, the two-level generator G is replaced by a multilevel generator G_1. If in the input to G_1 we have a string of n 1's after one or more 0's, the output of G_1 corresponding to the string of 1's will be a_1, a_2, ..., a_n, where the a_i's are positive numbers. Similarly, if in the input we have a string of n 0's after one or more 1's, the output corresponding to the string of 0's will be $-a_1$, $-a_2$, ..., $-a_n$. To increase rise time, one usually chooses a_1, a_2, ..., a_n to be more or less exponentially increasing. Notice that G is a special case of G_1 with $a_i = A$.

Although Δ^2 modulation will give sharp pictures, it may introduce overshooting and ringing. To avoid excessive overshooting, some kind of limiting can be used; and by properly adjusting the output levels of G_1, a compromise might be reached between ringing and loss of edge sharpness. Computer simulation of Δ^2 modulation has been carried out, and some preliminary results have been obtained. The purpose of the computer simulation is to find an optimum combination of system parameters. Figures 10(A) and (B) show a Δ-modulated picture and a Δ^2-modulated one; the number of sample points is the same in both pictures.

In our discussion, we have assumed that the channel is noiseless. If it is noisy, the ordinary delta-modulation system illustrated in Fig. 9 is not practical. An error occurring in a scanning line ruins the remaining samples in the line. A single error gives rise to a white or black streak along the scanning direction. Δ^2 modulation suffers the

same defect; see Fig. 10(C). Hence, in practice we have to find ways of combatting noise. One possible method[23] is to separate the picture signal into a low-frequency and a high-frequency part. The former is coarsely sampled and sent by PCM, whereas the latter is sent by Δ^2 modulation in which the transmitter and receiver are modified by the insertion, right after the delay, of an amplifier having a gain less than unity. These and other noise-combatting methods are being studied.

Concluding remark

As mentioned at the outset, most of the experimental work described was simulated on digital computers. The speed and memory capacity of present-day computers have limited us chiefly to considerations of monochrome still pictures. Since most picture transmission systems probably will be used for transmitting motion pictures, this work can be considered as only preliminary in nature.

This article describes work done by many members, present and past, of the Cognitive Information Processing Group, Research Laboratory of Electronics, M.I.T. The author gratefully acknowledges their contributions.

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REFERENCES

1. Goodall, W. M., "Television by pulse code modulation," *Bell System Tech. J.*, vol. 1, pp. 33–49; Jan. 1951.

2. Carbrey, R. L., "Video transmission over telephone cable pairs by pulse code modulation," *Proc. IRE*, vol. 48, pp. 1546–1561; Sept. 1960.

3. Oliver, B. M., Pierce, J. R., and Shannon, C. E., "The philosophy of PCM," *Proc. IRE*, vol. 36, pp. 1324–1331; Nov. 1948.

4. Deloraine, E. M., and Reeves, A. H., "The 25th anniversary of pulse code modulation," *IEEE Spectrum*, vol. 2, pp. 56–63; May 1965.

5. Schreiber, W. F., *et al.*, "Picture processing research," Quarterly Progress Rept. No. 61, M.I.T. Research Laboratory of Electronics, pp. 133–135, Apr. 1961.

6. Huang, T. S., and Tretiak, O. J., "Research in picture processing," chap. 3 in *Optical and Electro-optical Information Processing Technology*, J. Tippet *et al.*, eds. Cambridge, Mass: M.I.T. Press, 1965.

7. Scoville, F. W., "The subjective effect of brightness and spatial quantization," Quarterly Progress Rept. No. 78, M.I.T. Research Laboratory of Electronics, July 1965.

8. Yamaguchi, Y., and Huang, T. S., "Optimum fixed-length binary block code," Quarterly Progress Rept. No. 78, M.I.T. Research Laboratory of Electronics, July 1965.

9. Susskind, A., ed., *Analog-to-Digital Conversion Techniques*. Cambridge, Mass.: M.I.T. Press, 1957.

10. Yamaguchi, Y., and Huang, T. S., "Optimum binary code—Part II," Quarterly Progress Rept. No. 79, M.I.T. Research Laboratory of Electronics, Oct. 1965.

11. Golomb, S., ed., *Digital Communication*. Englewood Cliffs, N.J.: Prentice-Hall, 1965.

12. Brainard, R. C., Kammerer, F. W., and Kimme, E. G., "Estimation of the subjective effects of noise in low-resolution television systems," *IRE Trans. on Information Theory*, vol. IT-8, pp. 99–106; Feb. 1962.

13. Huang, T. S., "The subjective effect of two-dimensional pictorial noise," *IEEE Trans. on Information Theory*, vol. IT-11, pp. 43–53; Jan. 1965.

14. Shannon, C. E., and Weaver, W., *The Mathematical Theory of Communication*. Chicago: University of Chicago Press, 1949.

15. Schreiber, W. F., "Third-order probability distribution of television signals," *IRE Trans. on Information Theory*, vol. IT-2, pp. 94–105; Sept. 1956.

16. Pan, J. W., "Picture processing," Quarterly Progress Rept. No. 66, M.I.T. Research Laboratory of Electronics, pp. 229–231, July 1962.

17. Schreiber, W. F., Knapp, C. F., and Kay, N. D., "Synthetic highs—an experimental TV bandwidth reduction system," *J. Soc. Motion Picture Television Engrs.*, vol. 68, p. 525; 1959.

18. Schreiber, W. F., "The mathematical foundation of the synthetic highs system," Quarterly Progress Rept. No. 68, M.I.T. Research Laboratory of Electronics, pp. 140–146, Jan. 1963.

19. Graham, D. N., "Two-dimensional synthesis of high frequencies in picture processing," Quarterly Progress Rept. No. 75, M.I.T. Research Laboratory of Electronics, pp. 131–134, Oct. 1964.

20. deJager, F., "Delta modulation: a method of PCM transmission using the 1-unit code," *Philips Res. Rept.*, vol. 7, pp. 442–466; Dec. 1952.

21. Witt, R., Private communication, Communications and Data Processing Division, Raytheon Co., Norwood, Mass., Sept. 1963.

22. Winkler, M. R., "Pictorial transmission with HIDM," *1965 IEEE Internat'l Conv. Record*, pt. 1, pp. 285–291.

23. Schreiber, W. F., "Picture coding," presented at the Picture Data Processing Seminar, Yeshiva University, New York, N.Y., Aug. 1963.

Satisfaction and success in the highly organized society

In this interview, H. I. Romnes, President of AT&T, says that today the individual engineer counts for more than he ever did

In his book *Growing Up Absurd*, the social critic Paul Goodman postulates this model of the youth of today: they see themselves growing up in an apparently closed room, that of the highly organized establishment, in which there is a large rat race as the dominant center of attention, and in which there is little leeway for them to live and work satisfactorily as individuals. In a more specialized sense, an important question for the community of professional engineers is whether or not the young engineers of today do not also see something of the closed-room aspect before them when they behold the giant organizations founded principally on the engineering arts. How do engineers view their chances for satisfaction and success, for doing worthwhile work, in today's technological situation which is generally admitted to be so different from that prevailing a generation ago? In actual fact, what *are* their chances?

It is unlikely that any single man could have all the answers to such questions, but there are some men whose unique view of the world of engineering gives their views an uncommon interest. H. I. Romnes, President of AT&T, is certainly one of these men, not only because of his engineering background and his position, but because of the crucial role that major communications systems play in a highly organized society.

Mr. Romnes first joined AT&T in the summer of 1927, working on a cable construction crew and later as a telephone installer. A year later, after his graduation from the University of Wisconsin with his B.S. degree in electrical engineering, he became a member of the technical staff at the Bell Telephone Laboratories, where he remained until 1935. Thereafter, he worked in many branches and in many capacities within the Bell System, rising to the presidency of the Western Electric Company in 1959, to the vice chairmanship of the Board of the entire system in 1964, and to the presidency on January 1 of this year. It is this experience that informs his outlook on the plight, prospects, and responsibilities of the individual engineer.—N.L.

The highly organized engineering project

Mr. Romnes, how do you think young engineers today feel about entering such a highly organized and developed society as ours has become, in which the projects have become gigantic, and in which there is the so-called information revolution that threatens those who lag behind with obsolescence? Would you mind talking about the characteristics you think are necessary for satisfaction and success in this situation?

It would not surprise me if young people today showed some reluctance to step into what they, and we, are told is an increasingly depersonalized society, a society so complex and intricately organized that the chances that any one of them might by himself make a contribution that could count for very much are remote indeed. And we live, we are told, in an era of fast-paced change in our technology, change that threatens the engineer with rapid if not catastrophic obsolescence of his skills. Characteristically, today's engineering projects are so massive in scope, so incredibly complex, calling for the combined efforts of so many scores, so many hundreds and thousands of engineers, as would seem to render the contribution of any one of them insignificant.

But I challenge this prospect, particularly insofar as it applies to today's young engineers. Quite simply, it is my belief that the individual—his capacities and character—is more important now than ever before to the success of engineering undertakings. Admittedly, though, almost everything we read and hear about what is happening in engineering would seem to belie this view. However, when I examine these two aspects of our technology—the pace at which it is changing and the scale on which it is organized—the implications for the individual engineer seem to me pretty clear. The scope and complexity actually place a greater, not a lesser, premium on the personal and professional capacities of the individual. Furthermore, in a time of fast change a critical factor is not so much what an engineer has learned but what he can *learn, not so much* what *he knows but* how *he thinks.*

Today industry needs people who are well grounded in the fundamentals of science and technology but, over and beyond that, who are possessed of the desire and the stamina—call it the professional ambition—it takes to stay abreast of change or, even better, to create it. This is a personal attribute. No school can teach it. No company can instill it. But in my observation of engineering work over the last 35 years, there is no more important factor in engineering progress.

This point is, the individual can *make a difference. And he can make a difference even in large-scale projects involving whole armies of engineers.*

Today the massive engineering organizations so characteristic of the '20s and '30s are being supplanted by engineering task forces, perhaps no less in total numbers, but deployed in smaller creative teams.

An important point to realize in this regard is the fact that the character of our technical undertakings, both industrial and government, has changed significantly. Increasingly, the ability to manage complex engineering undertakings depends on what we have come to call systems engineering. Today, I'm afraid, the term is used in more places than it is fully understood or the art practiced. Systems engineering, if it is to be more than a merchandising catchword, requires engineering effort of the most rigorous sort. In what we are told is an era of increasing specialization, it calls for people broadly equipped to weigh alternatives involving a variety of disciplines, to assess the feasibility of each in the light of what is known and what remains to be discovered, and, finally, to choose the optimum path to the desired goal.

But thinking in system terms cannot be confined to the engineers who happen to wear that label. Each engineer involved in a large complex project, whether his role is small or large, must develop an acute sense of the interrelationships of the parts of a complex whole—of his part to all the other parts—and an unswerving awareness of the end purpose the parts together serve.

Professional ambition and the threat of obsolescence

But doesn't this all imply, then, that only the strongest and most talented individuals will contribute and grow, while the greater mass of engineers who do not possess what "no school can teach" will be bewildered by the complexity of modern systems, will be relegated to smaller roles, and, precisely, will become obsolescent?

I do believe a lot of these engineers are threatened with obsolescence, but what I was trying to say was that surmounting this threat depends on personal qualifications that might not have been so very important in a more stable technology. I mean that through the energy, professional ambition, and plain hard work that it takes to keep up, if they work at it that way, they can surmount the threat. You suggest that because it is going to take a lot of ambition and hard work, only the strongest engineers will be able to keep pace and grow and not be kicked out in this process of the art getting away from them. I don't believe that that's so. I think that most engineers, the real engineers, want to grow professionally, at least to the limit of their personal capacities, and, given an environment that provides incentive and scope, I think they will respond to the opportunities to do so.

Why do you put emphasis on *real* engineers?

I make this distinction because many people who, during the period of acute engineer shortage, were hired as engineers and assumed the title of engineer, were not engineers by training, but technicians. Perhaps this problem is a little less severe now than it was ten years ago. Our tremendous shortages during the early days of the great drive to "catch up with the Russians" resulted in large numbers of employees moving from one outfit to another, so that the standards for engineers were quite low. I believe that these standards have improved since that time, although the engineering ranks still include people that I wouldn't call true engineers. I suppose that even some engineering college graduates have just let themselves drift into work that would be hard to define as real engineering in terms of the actual content of the job.

All I am saying here is that the ones I call the real engineers are those who want to grow professionally and to go just as far as they can, and I think, as I said before, they will respond to the opportunity to grow.

Industry can do a lot to help them grow, by encouragement and recognition and by the support that it gives to their individual efforts toward professional advancement. Many industries are doing that. I know that AT&T is very much involved. For example, wherever it is possible, we deliberately locate our engineering groups where educational facilities are available. We, ourselves, run very large engineering schools. Western Electric alone has an extensive engineering-updating program that is the equivalent, in terms of staff, budget, and everything else, to engineering schools with enrollments of a thousand students. These updating schools are all at the graduate level, and the students are engineers who are working in the field of practical application. We also encourage our engineers to continue their studies by paying their tuition, and so on.

We recognize, though, that these courses can only help—they are not a whole solution. The continuous professional development that these times demand is essentially a one-man job; it can only be done alone.

In essence, what I have been saying is that not only com-

petence but character will determine the individual engineer's progress in his profession and his contribution to it. And character as much as competence will determine the kind of contribution our profession makes to the world we live in.

The question that every engineer should ask himself is this: Will it be a better world or just a more complicated one for my having been here? He must realize that if the age offers uncommon opportunities to him as an individual, it offers uncommon responsibilities as well.

The "sense of the whole" and the systems approach

Earlier, you brought out a point about how success depends on a "sense of the whole," which you related to the systems approach to the job. What strikes you about the people you feel have succeeded in cultivating this sense of the whole? What sort of people are they?

The impression I've gotten is that those who have developed this sense of the whole, which is so important in today's engineering projects, in general seem to be the more imaginative and curious among the engineers. In our particular kind of operation, these are the people who want to know not only about the thing they are working on, but how it fits into the service objective of the particular project. Service, of course, is our business. I'll admit a lot of valuable engineering work gets done by sheer concentration on detail without a thought to the task as a whole; but someone has to think of it as a whole, someone has to think about how the pieces fit together to make this whole. What it gets down to is that we need both kinds of engineers, but my feeling is that over the years this sense of the whole, or the systems approach, has become much more important as projects have assumed greater complexity and scale.

The evolution of systems thinking

How do you view the evolution of this systems thinking? How has it become so prominent?

As far as systems thinking is concerned, I believe that we, in our business, have been leaders, primarily because we have been forced to be by the nature of our business. After all, a communications network is a very complicated system, a nationwide system, made up literally of billions of parts that all have to work together, and we learned the hard way that we have to think of this system as a whole and not just as pieces of hardware. I also feel very firmly that many in industry have had great difficulty adjusting to systems thinking because they had no need to. For instance, it doesn't matter whether a dishwasher made by one outfit and a toaster by another outfit are connected to the same power system. There is no need for these pieces of hardware to be compatible. But one telephone instrument needs to be compatible with another telephone instrument a thousand miles away. So we were forced into systems thinking.

Now, however, a large part of industry has been forced into it too, largely as a result of the tremendous defense effort. The defense system started out basically as a collection of hardware, but the defense industry learned that you just can't take collections of hardware and make a workable system. The missiles, the rockets, and all the rest of it, must be thought of as parts of a whole. So this sense of the whole is something that has developed very greatly in recent years.

I think that our whole economy can profit from it. For example, one of the deep problems in the field of transportation, in my opinion, is that we have not thought of the transportation question as a whole problem, but rather as separate problems concerning rails, air, highways, and so on. Someone works on the rail system, someone else on the highway system, someone else on the air system, and together these form our nation's transportation system. As you know, the overall system isn't well balanced in some respects.

Engineers and community problems

Are you in AT&T actually doing such systems work on these broader community problems? And do you encourage your engineers to do their bit in such work?

No, we don't work at this type of problem as part of our business. However, we do as individuals. A great many individuals in the Bell System contribute their time to the solution of some of these urban problems, which are system problems when you get right down to them. Perhaps because of our background our people have something to contribute. In fact, they have been brought in on a number of cases to help solve complex systems problems. One of our small subsidiaries, Bellcom, for instance, has a role in this. It was set up at the request of NASA to

In a time of fast technological change, a critical factor is not so much what an engineer has learned but what he can learn, not so much what he knows but how he thinks.

provide systems planning support for the Apollo project, which, of course, is very much a system. But, other than that, we concentrate on the communications business.

This doesn't mean that we do not encourage our engineers to participate in community problems, because we do—and a lot of them contribute their time and talents to the solving of problems outside their field. I believe that not only our own engineers but engineers throughout industry have much to contribute, because the world is becoming more technical. There is no question about that. Things aren't as simple as they used to be. It's pretty tough for, say, the councils of small communities, boards of aldermen, or what not, to handle all the problems that are involved these days. Engineers can contribute a lot, and do.

To go back a bit, even in our own organization systems thinking is becoming more important as time goes by. The reason can be found in the rate at which technology is now advancing. For years there had been relative stability. It was progressing all the time, of course, but it didn't have the tremendous force for change we now have. For example, in our own business, and for years—40 or so—we were working on switching systems which were electromechanical in form. They became highly developed as time went on, but the progress was a matter of refinement rather than the creation of an entirely new system; that is, the basic principles on which the system was organized had been pretty well articulated from the beginning.

But now we're deeply involved in a new system of switching—an electronic system—which is a whole new approach to switching, not only because it uses electronic devices instead of mechanical relays but also because it's organized in a different way, with electronic memories and all the rest of it. And you can do a lot of tricks with this new system that you can't do with the systems we now have.

Do you mean, for instance, that this new system will be much more effective than the present system, with fewer people involved?

As far as people are concerned, even with the electromechanical system, which we'll continue to use for years, the ratio of people to the number of calls we handle has gradually been reduced. On the other hand, the number of people we have in total is continually increasing. The reason for this is that the volume of business is going up, which more than offsets the fact that fewer people are involved in the calling. Back in the '20s, seven operators were required to set up a typical long-distance call all the way. Today, the vast majority of our calls take no operators at all, and even with the more complicated ones, such as person to person, one operator can handle the entire operation. In spite of that we have as many operators now as we've ever had. In fact, we have three times as many as we had in 1920. It's a matter of volume, which is increasing not only because the population has increased, but also because mechanization has continuously reduced costs so that demand is that much greater.

Automation and human problems

Everyone today is concerned, in one way or another, with the social consequences of greater mechanization, of automation and its depersonalizing effects. How do you look on this problem?

I know that we in our own industry, in directing our own engineering work, have been putting more emphasis in recent times on making sure that the human problems are taken into account. It is significant that so many people are worried about what computers are going to do to the human part of a business. You no longer deal with people, they say, you deal with a machine. A machine talks back to you if you ask for a quotation on a stock, for example. Isn't the whole thing being excessively depersonalized? In our business, of course, there is a personal quality in which we have taken great pride—the "voice with a smile." Now machines handle most calls. What can we do? Well, we think there is a lot that can be done if the individual engineers, and others who are working on this, keep this human factor in mind as they design new products and new services. There's still room for the personal approach. One of the examples I like to cite is the new electronic switching system. It is really a huge computer, a very complicated one, built with electronic memories, logic systems, and so on. You might think that it will wipe out all the personal relationships we have with our customers. Actually, it's allowing us to do some things of a personal character that we were never able to do before. For example, with our former switching systems and with human operators, there was a rather limited variety of services we could give. We couldn't tailor the service to fit a particular individual. As we went to dialing and as we added more and more telephones, we had to introduce more and more digits in order to provide for them. But with this electronic switching office, we can tailor the service to fit the particular individual. He can give us the numbers he calls most frequently, for example, and the system memory has enough capacity so that if he dials only the digits 3-4, let's say, the machine will know that he's calling his brother in Peoria and will supply the full ten digits needed. This is one way we can personalize the service. Another way is in our rate schedules. Up until now, we have been obliged to bill people according to fixed geographical areas. You might live at the edge of this area but do most of your calling into an adjacent area. That is, you might actually pay a dime to call across the street, whereas you can talk for no extra charge for 20 miles in the other direction. This causes some problems. But there is no reason why we can't look forward to the day when we can put a circle around pretty nearly every customer and simply instruct the computer which makes out the bills that a call within this range is within the customer's free-calling area covered by the monthly flat charge. So there's another way you can personalize.

A third way is in the matter of directories. Directories have to be made up to cover certain areas, and the directories are getting bigger and bigger. The growing problems with their use are pretty obvious. To provide tailor-made directories for small groups of people has been a very expensive proposition. But with computer methods of arranging type and photographic methods of making directories, we believe we can do it.

Is this sort of thing very far away?

All of these services are just ahead of us, and actual trials are going on here and there. I'm simply using these illustrations to show that if, in their design work, engineers do take into account the human side of the equation, we're going to *get much better results. There are great opportunities now, perhaps more than ever before, to develop better tools to work with. These will be useful, too, for instance, in the design of our own internal management information systems.*

So you view automation as serving you and serving the people much more than it used to? In a sense, you are saying that people used to be automated, and had to adjust to the system, but now the system is adjusting to the people. This is a revolution in itself.

Yes, it is that kind of a revolution. I know that many people—in fact, most of the general public—are a little scared of automation because they think of it as a very impersonal and unfriendly sort of a thing, and that they will be forced to adjust their living to what a machine can do. But what we're saying is that the reverse is true. We can adjust the machine to people because it is becoming more versatile. In the telephone company, for example, we will be able to accommodate the different, individual calling habits of you and me and everyone else.

Individualism in engineering through creative task forces

Mr. Romnes, you stressed the importance of the individual engineer today and the need for his having a sense of the whole. But what about the fellow who pursues a very narrow line, who doesn't think in terms of the whole project, but who unquestionably makes deeply creative contributions? How does he fit in? How do the organizers of R & D recognize and foster his type of individualism in engineering?

I did not mean to imply at all that there is no room for this kind of individual. There is. Today the massive engineering organizations so characteristic of the '20s and '30s are being supplanted by engineering task forces, perhaps no less in total numbers, but deployed in smaller creative teams, each member of which is looked to for contributions that cannot be duplicated by the others.

There are always many people who enjoy working in a fairly narrow field. That is, the sense of the whole is not so interesting to them as it is to some others, and they go into a particular area in great depth. There's a lot of room for them, too, because very complex and gigantic projects are made up of all kinds of disciplines in which you need these experts or consultants in many, many fields. Now more and more we've given recognition to this fact in our business. In the past, with the type of person who just liked to work in a narrow area, who became awfully good at it, and who became very valuable, the tendency was to compensate him by making him a supervisor or giving him some similar title. He then had to begin thinking in terms of the whole rather than the little pieces. But that wasn't what he liked, so that often he became a poor supervisor whereas he had been a very good individual engineer. To deal with this kind of situation, we have established categories in our hierarchy that allow us to keep challenging this fellow and to compensate him adequately for what he is doing. We have titles such as Senior Staff Engineer, which permit a fellow to grow in what may be a fairly narrow area but in which he can become really expert, and be compensated at a level equivalent to that of Third Level Supervisors, for example. And he is not burdened with the task of supervising a lot of people. We have quite a few of these engineers and researchers in our laboratories and are making very good use of them.

How long have you been doing this kind of thing?

The idea has been talked about for a long time, but I think we have been doing more to carry it out in the last ten years, and it might take ten more years to implement the program fully. Providing scope for individual creativity in engineering calls for more than improved office arrangements. You have to change your thinking because of the past tendency to associate the importance of a person with the number of people he has working for him. In research organizations, I think this has been understood much longer than it has among engineers. In Bell Laboratories, for example, we have research people who are working in rather narrow fields but who have done work so important that they have been awarded Nobel prizes. We have worked out, long since, arrangements so that these researchers can be adequately compensated and can have the prestige and all the other things that people work for, without the burden of supervising great groups of people.

To sum up, I think that having said that we must get people who think in system terms and have the sense of the whole, we must also recognize that, on the other side, there is perhaps a growing need, because of the complexity of the projects, for people who know a whole lot about a few things rather than a little about a lot of things. That's what we're saying—we need more of everybody.

Personal reflections

Now that you have talked about the situation for the individual engineer today, may we ask you what type of engineer you were when you started out?

When I started out in Bell Labs, my work wasn't in a particularly narrow field. I was concerned with the design of communication circuits, which in those days didn't use carrier, but used voice frequencies over pairs of wires. Broadly, the problem was that on a long-distance communications circuit—say, a cable from New York to Chicago—the change in temperature due to the sun shining on the cable would greatly change its attenuation. The result was that at night, when it was nice and cool, you could talk very well, but when the sun came up you just couldn't talk at all because the attenuation had become so great. It was a matter of automatically sensing this change and, in effect, turning up the volume control on amplifiers placed every 30 or 40 miles along the route. This was a very elementary problem as we now see it, but it was a complicated one in those days. So you see, my work wasn't too narrow in this sense and it did deal with a system.

Did this work satisfy you, or did you have a strong feeling about the direction in which you wanted to go?

Special
Conference
Report

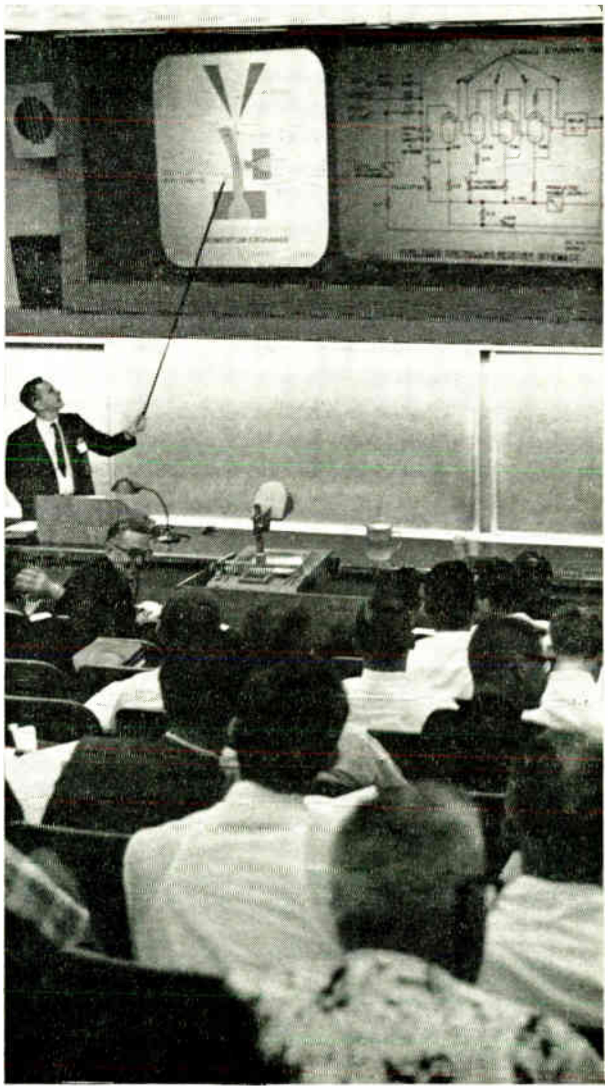
1965 Joint Automatic Control Conference

Robert N. Clark *University of Washington*

Diversity in the technical program characterized the sixth annual Joint Automatic Control Conference, held in June of this year on the campus of the Rensselaer Polytechnic Institute. This conference is jointly sponsored by the American Institute of Aeronautics and Astronautics, the American Institute of Chemical Engineers, the Instrument Society of America, the American Society of Mechanical Engineers, and the IEEE. It was founded to bring together, once each year, reports on the latest developments in automatic control theory, applications, and components. This year's conference, conducted by ASME, attracted some 700 attendees from the five sponsoring societies.

In past years, the technical program for the Joint Automatic Control Conference has been composed largely of contributed papers, and a disproportionate share of these contributed papers have been theoretical. A large part of these theoretical papers came from the universities. This year the conference steering committee, under its chairman, Prof. Sidney Lees of Dartmouth, achieved a wider coverage of the more practical aspects of control engineering by inviting specific authors to present papers on applications and components. About a fourth of the total 120 papers heard at the conference were so invited. Approximately half of this year's papers were from universities and about half from industrial firms. Only a few came from private or government research establishments.

At the plenary session the conference attendees were treated to an unusual duo of speakers: Leonard Woodcock, vice president of the United Automobile Workers, and J. Herbert Hollomon, Assistant Secretary of Commerce for Science and Technology, presented complementary viewpoints on the sociological



View of one session of the 1965 JACC. The speaker is B. G. Bjornsen of the Johnson Service Company, Milwaukee, Wis.

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impact of automatic control. The conferees were urged to become more aware of the potential social effects of their technological creations and to start to use the techniques of modern "systems engineering" on some of the great social problems of our time. The audience responded vigorously to these challenges, showing that some engineers present had already given considerable thought to the social and economic effects of automation along the lines suggested by the speakers. It was clear from this session that a great opportunity exists for the control engineer to become involved in such problems, provided he can initiate proposals for specific work to the appropriate agency.

Theory

Approximately half of the 25 technical sessions consisted of papers dealing with theory. Optimal control seemed to be the most frequently treated theoretical subject; this was also true at the 1964 JACC. The identification and estimation problem also received substantial coverage. Papers on nonlinear controls, stability, sampled data systems, and time variable systems, in about equal proportion, rounded out the theoretical portion of the conference.

One significant aspect of any given paper on control theory is its influence on the development of practical techniques of control system engineering. Only a few papers dealing with theory from past JACC meetings have proved to be of significance in this sense. Many JACC attendees during the past few years have voiced concern over the apparent "gap" that exists between modern developments in control theory and methods which engineers actually use to design control systems. There appears to be a real need for more work that will bolster the scientific reputation of modern control theory —that is, some demonstrations of correlations between hypothesis and experimental observation.

This year's crop of theoretical papers, as a whole, did little to alleviate this concern. Nevertheless, several theoretical papers were heard which hold promise of useful engineering results. Papers by Brockett and Willems, for example, presented readable interpretations and extensions of the celebrated "Popov method" for determining stability in an important class of nonlinear feedback systems. This information was presented in a form which engineers can readily apply to real problems.

Applications

The nine sessions on applications covered a wide spectrum of technical subjects. These included tutorial papers on reliability analysis and computer programming languages and a series of state-of-the-art papers on applications in the machine tool, chemical processing, biomedical, transportation, aerospace, and electric power industries.

Perhaps the liveliest exchange of ideas in the application sessions occurred in the panel discussion on programming languages for control computers. From this discussion it appeared that communication between man and computer poses some problems which cannot be met by new technological advances in the computers themselves. For example, the turnover rate in programming personnel was cited as a contributing factor to the expense and delay encountered in getting a control computer installation into service. Another problem, in connection with the sharing of programs, arises because the program itself discloses proprietary information about the process controlled. However, the general impression was that computer control of manufacturing processes has already gained a permanent place in industry and that improvements in programming will promote a continued growth of such applications.

The papers dealing with applications of control theory in the manufacturing and utility industries showed the remarkable economic impact of automatic control upon those industries. In these reports the role of computers was prominent in both simulation studies of processes and in on-line control and optimization. It was also shown that the availability of automatic control techniques has changed many manufacturing processes to the extent that manual control of these processes is now impossible. Automatic control techniques for the integrated control of whole business systems, including inventory control, order processing, warehousing, and transportation, as well as the basic manufacturing functions, were brought to the attention of the conferees.

An informative paper by Coulter and Updike surveyed applications in the biomedical field and gave an extensive bibliography. The authors showed that control theory and data processing are being widely used in basic physiological studies and in medical treatment. Cited as an area of great theoretical need is improved methods of mathematical modeling for most biological processes.

Components

Three technical sessions were devoted to components. These sessions seemed to be intended as state-of-the-art reports rather than as forums for reporting new research results or product developments. As such they were very useful to nonspecialists or to theoreticians whose daily activities do not afford them an opportunity to keep abreast of emerging hardware developments.

The current state of solid-state devices used in control systems was surveyed. A brief paper by Thurston outlined the advantages that integrated circuits offer to control system designers, and also pointed out some of the technical problems involved in their manufacture. Other papers treated various solid-state power control circuits.

A session on fluid components and systems provided the conference with a status report on this newly developing field. The analysis and design of fluid components was shown to be more analogous to that of electronic devices than to conventional fluid power mechanisms. Several applications of signal processing devices and digital computer elements were described; these descriptions strengthened the impression that the new devices might be thought of as replacements for electronic circuits in some applications. However, the physical differences between fluid devices and their electronic counterparts are so pronounced that the potential competition between the two in applications is more apparent than real.

Preprint volume

A volume of preprints entitled "1965 Joint Automatic Control Conference Preprints of Papers," is available at $25.00. Direct your purchase order to: William H. Larkin, American Society of Mechanical Engineers, United Engineering Center, 345 E. 47 Street, New York, N. Y. 10017.

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Dr. von Braun was born in Wirsitz, Germany, in 1912. He received the bachelor's degree in 1932 and the doctorate in physics in 1934, both from the University of Berlin. After several years in rocket development he became technical director of the Peenemuende Rocket Center in 1937, where the V2 rocket was developed. He came to the United States in 1945, with many of his Peenemuende colleagues, under contract to the U.S. Army. He directed high-altitude firings of captured V2 rockets at White Sands Missile Range N. Mex., and later became project director of a guided missile development unit at Fort Bliss, Tex. The entire unit was transferred to Huntsville in 1950. He and many of his associates and their families became U.S. citizens in 1955.

Alfred N. Goldsmith (F, L) received the B.S. degree in 1907 from the College of the City of New York, where he taught from 1910 to 1923. He received the Ph.D. degree from Columbia University in 1911. Since 1919 he has been affiliated with RCA, first as director of research and later as chief broadcast engineer and as vice president. He is now an honorary vice president and has been a consulting engineer to RCA since 1933. A noted radio, motion picture, and television inventor, he has also made many contributions to the medical and biological sciences. His earlier work led to the first commercial radio with a built-in speaker and to the first commercial color television tube.

Dr. Goldsmith was a cofounder of IRE in 1912, and served as President for 1 year, Secretary for 10, Editor and Editor Emeritus for 49, and Director for all 50 years of IRE's existence. He is Editor Emeritus and Director Emeritus of IEEE and holds two of its major awards, the Medal of Honor and the Founders Award. In addition to being an honorary member of the N.Y. Medico-Surgical Society and an honorary Fellow of the International College of Surgeons, he is a member or Fellow of numerous professional societies here and abroad.

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Dr. Huang is a member of Tau Beta Pi, Sigma Xi, Eta Kappa Nu, the American Association for the Advancement of Science, and the Optical Society of America.

Morris Grossman (M) received the B.E.E. degree from the College of the City of New York in 1943 and the M.E.E. degree from the Polytechnic Institute of Brooklyn in 1952. He joined the Industrial Scientific Corporation, now the Warner & Swasey Company, in 1942, where he did such diverse work as the pioneering of automatic vending machines, numerical controls for machine tools and precision automatic gauging machines, and research in infrared techniques for high-temperature measurements. He became chief engineer in 1952. He joined the Radio Corporation of America in 1959, where he has been engaged in the development and construction of data communications for such major programs as BMEWS and Minuteman, and in tape-controlled automatic system and circuit-testing machines. He presently holds the position of engineering leader at RCA's New York Systems Laboratory. Mr. Grossman is a coholder of several patents in infrared techniques, machine-tool control, and automatic gauging.

News of the IEEE

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ASEE announces preliminary recommendations developed by ECPD study on goals of engineering education

In 1961 the Engineers' Council for Professional Development was instrumental in establishing the Goals of Engineering Education Committee, to operate through the American Society for Engineering Education under a National Science Foundation Grant, for the purpose of studying engineering education in the United States. (See also Spectral lines, this issue, page 43.) The following recommendations are excerpted from the preliminary reports of the "Goals" Committee, released in October 1965:

"The steadily rising utilization of engineering manpower in the United States and the rising aspirations of individual students for higher levels of education, indicate that a substantial expansion of the national enterprise in engineering education must be planned for the next decade.

"Past and present trends justify the prediction that by 1976 the annual rate of graduation will be 75,000 bachelor's degrees, 40,000 master's degrees, and 6,000 doctorates. It is likely that as many as 40 institutions not now offering doctorate programs in engineering will be doing so by 1976, and that present programs will have grown steadily. Financial support of research in engineering schools must keep pace with this growth. The U.S. total was $160 million in 1963 and should increase to about $700 million by 1976. New demands on practicing engineers will require increasingly higher levels of professional competence, fuller preparation to accept new and varied responsibilities, and broader acquaintance with the many interrelated facets of modern life. In view of these and other considerations, the Goals Study recommends that:

1. The *first professional degree* in engineering should be the master's degree, awarded upon completion of an integrated program of at least five year's duration. This degree should be uniformly identified as the Master of Engineering degree, without qualifying adjectives or phrases. It is expected that implementation of this recommendation can be accomplished within a period of five to seven years.

2. Four-year bachelor's degree programs leading to an *introductory engineering degree* should continue to be offered.

3. The ASEE, educational institutions, and engineering faculties should immediately exert a positive effort to strengthen and improve the *liberal education* of engineering students to enable them to fully appreciate and discharge their responsibilities to society.

4. Curricula leading to the first professional degree in engineering should continue to be soundly based on *the physical sciences, the engineering sciences, and mathematics* (as recommended in the Grinter Report) and, in appropriate cases, on the life sciences.

5. *Analysis, synthesis, and design* of systems should be given increased emphasis in engineering curricula at all levels.

6. More *diversity and flexibility* should be introduced into engineering programs in order to accommodate the differing aims and talents of individual students. New kinds of learning experience and high-level creative activity are needed at all levels to prepare the student for leadership roles. Even the doctorate should be recognized as broad preparation for many aspects of professional life, and not as preparation for research alone.

7. *The excellence of faculty* is of critical importance in engineering education, and the creation of appropriate policies for faculty recruitment, development, and utilization should be given primary consideration by college administrations.

8. *Cooperation* should be promoted between colleges on the one hand and industry and government on the other, by encouraging practicing engineers to participate directly in academic instruction, and by arranging for teachers to gain practical experience in industry and government on a semester-long basis.

9. Arrangements must be devised to provide adequate *financial support of research* in the years ahead. Federal agencies which have been providing virtually all of this support must face the challenge of increased demand and gain the support of Congress on this urgent national need. New administrative arrangements should be devised to facilitate industry participation, possibly through a nation-wide private foundation patterned after the National Merit Scholarship Foundation, to pool contributions from individual firms and dispense research grants to professors and schools.

10. *Part-time graduate programs* of high quality should be extended to serve practicing engineers. They should be conducted by institutions having full-time programs of high standards. Daytime release for students employed near campuses should be encouraged.

11. *An institution aspiring to a significant role* in graduate engineering education must recognize that it cannot become a "center of excellence" merely by acquiring a special financial grant. But the actual experience of a number of schools mentioned in the Goals Report shows that a school with appropriate plans should be able to make good progress in the next decade.

12. Accreditation by ECPD should be changed from specific curricular accreditation to *accreditation of the over-all engineering unit* (e.g., the engineering college). Such accreditation will then be an assurance that all first professional degrees (Master of Engineering) offered by that unit are judged to be of acceptable professional quality.

13. *Accreditation of graduate curricula beyond the first professional degree* should be postponed until the engineering profession itself is ready to specify a second-level professional degree. (Other professions do not have such degrees, the nearest being certification by the medical specialty boards. These boards