THE CHALLENGE OF REPLACING HUMAN PARTS AND FUNCTIONS*

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SUMMARY

Problems in design of artificial organs, surgical implants, and prosthetic and sensory aids are discussed. "Tissue-friendly" materials with wider ranges of mechanical and electrical properties are needed. Junctions between living and inert materials must be more sophisticated. Some failures previously blamed on basic principles or on biological problems may really have been caused by errors in design. Improved controls are needed for artificial body parts, whether external prostheses or implanted organs. Miniaturization, especially of mechanical components, would be helpful. The disabled need more natural functional patterns as well as more normal appearance. Sensory aids require vast improvements. Undoubtedly information already available would help solve some of these problems if only communications were improved.

INTRODUCTION

Artificial internal organs, surgical implants, and external prosthetic and sensory aids are available at many levels of the body. The development of these devices is an outstanding example of cooperation of many fields of medicine and surgery with numerous specialties in chemistry, metallurgy, and engineering. Much work, though, is needed to improve all these devices. This seminar, hopefully stimulating the talents and interests of numerous new recruits, will review some developments in these areas as well as emphasize unresolved problems which require systematic further work.

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The rapid advances in preventing accidents or infections and in curing diseases and abnormal conditions are constantly saving more individuals and thus prolonging the average life span, but often permanent losses of function remain. Fortunately, devices of various types are increasingly being made available to help compensate for those residual losses which presently must be accepted with prolonged life. The improvement of supplementary devices such as orthopedic braces, artificial kidneys, or hearing aids is a challenge to the combined effort of many disciplines. The goal is not merely prolongation of life but of useful and happy activity for the survivor.

Likewise, surgical removal of a part, like amputation of a gangrenous limb or replacement of a defective heart valve, is sometimes the only way to prevent further deterioration or even death of the patient. Again the goal is not merely extension of life but restoration of maximum function through provision of a replacement part.

Regeneration of human body parts seems extremely remote. Thus far, transplantation of most tissues and organs is hampered by the immunity problem. Even if vigorous research overcomes this barrier in the next decade or so, there are practical, moral, and legal problems in finding donors, so the development of inert surgical materials and artificial mechanisms is likely to remain as a challenge.

There are many common problems extending across these various fields of artificial organs, implants, and prosthetic and sensory aids used externally to the body. Greater knowledge in many fields, improved materials, better understanding of control signals and feedback loops, further miniaturization (especially of mechanical components and of energy sources), and better communication among all concerned are examples of these common problems.

THE NEED FOR KNOWLEDGE

Increased fundamental knowledge in biology, in medicine and surgery, and in numerous fields of engineering is clearly a necessity. In spite of the great advances which have been made in the past century in understanding fundamental problems in all these fields, any serious investigator comes very quickly to a frontier in his subspecialty. Unfortunately, like the states of development of various devices, this frontier of knowledge is ragged and uneven, with considerable penetration into previous areas of ignorance in certain directions and particular specialties, yet relatively little advance in others, especially in some of the interdisciplinary fields between specialties. Even so, and perhaps even as a consequence of the great amount of progress, no single investigator uses as much as a small fraction of the knowledge which is already available somewhere in the world and in some specialty. Even in his own language and discipline, no research worker is

able to command a broad grasp of the past studies and to keep up with all new developments. Better means of information storage and retrieval, better translation services, and perhaps most of all more careful editing and abstracting are as important in the specialized fields of devices as in any other area of science and engineering.

MATERIALS

Truly "tissue-friendly" materials in a wider range of mechanical and electrical properties would facilitate design of mechanisms for use within the body or in close proximity to it. For some purposes, high ultimate strength is important. More commonly, high endurance limit under repeated loading is the crucial factor, because inert material lacks the self-repairing ability of living tissue. The patient may sustain failure of a brace, a prosthetic hip joint, or an arterial graft months after it is supplied and after many thousands of cycles of apparently satisfactory operation. Greater inherent resistance of the material to notches added to more meticulous design and more careful manufacturing methods to prevent stress-raising notches and crevices would be helpful. Stress corrosion and crevice corrosion with different oxygen levels are serious causes of failure of metal implants. In some designs, high rigidity is desirable, while in others great flexibility with long range of spring-like action is needed. It has been shown mathematically that there are inherent stresses at the margin between sections of different stiffnesses in the presence of external loading, so artificial materials should be carefully matched in stiffness to adjoining natural structures. Stiffness of the structure depends, of course, both upon the inherent modulus of elasticity of the material and upon the mechanical design.

Electrical conductivity is another important variable for various "tissue-friendly" materials. In many applications, conductivity is unimportant. In some cases, to prevent electrolytic corrosion of implants and especially of implanted assemblies, electrical insulation would be desirable, but the relatively inert metals used within the body are inherently good conductors. Further, they are immersed in a salty sea of conductive, oxygen-bearing, and potentially corrosive body fluids. One can hope to reduce electrolytic corrosion by using identical metals and to inhibit crevice corrosion by minimizing differences in oxygen concentrations in contact with different parts of the metallic structure.

In electrodes for such applications as pacemakers, muscle stimulators, or electromyographic pickups, both an insulating covering and an electrically conducting wire are essential. Conceivably a thin layer of conductive plastic could be used to isolate even the tip of a metal wire from body fluids and tissues.

Recently there have been indications that bone behaves as a semiconducting material, generating tiny electrical activity in response to stress, and that collagen fibrils align themselves in electrical fields. The suggestion has been made that a control loop, based upon electrical properties, might help to explain the well-known tendency of bone structure to align itself in order to resist stress and to change shape slowly when patterns of stresses are changed, as after a malunion of a fracture. One might then speculate that semi-conductive but relatively inert materials used as surgical implants conceivably might mimic some of these actions.

PASSING THE SKIN

Infection-resistant passage of an inert material through the skin or other outer layer of the body is typically rejected as an impossible dream by many people with biological training. They point to infection around splinters and to the normally desirable tendency of the skin to reject semi-buried foreign bodies. Nevertheless, intrusion of a foreign body through some portion of the outermost layer of the body is possible for brief periods, and some applications last for years. Experiments are made successfully for a few hours at a time with percutaneous wire electrodes, and fractures are often treated by skeletal traction applied by stainless steel pins passing through the skin for weeks at a time. Electrodes have been passed through the scalp for periods of years at a time in studies of electrical activities in the brains of schizophrenics.

Certain tissues and anatomical sites seem more suitable than the skin. Implant dentures have been used for over a decade, with a metal frame fastened to the jaw bone and small pegs protruding through the gums or mucous membrane to support dentures. Some movable plastic artificial eyes have been used for years, though the principle is not widely used clinically. An implant sutured to the rotator muscles so as to rotate within the eye socket bears a projection through the conjunctiva or outermost layer of the eyeball to drive the plastic eye. Most of the failures seem to have been caused by fatigue failure of the metal mesh or the sutures with which the muscles were attached, allowing imbalanced muscle torque and hence destroying the cosmetic value. Infection at the protrusion of the implant through the conjunctiva, contrary to fears and criticisms, has been rare. Semi-buried plastic lenses seem effective in animal experiments, at least. These relative successes, though, are rejected by some critics or considered limited to these special tissues. Dental procedures often cause bleeding of the soft tissue, yet the mouth is very resistant to infection. The peculiar structure of the eye allows far greater success with corneal transplants than is yet possible in other parts of the body.

Animal experiments are now under way looking toward the possibility of

skeletal attachment of external prosthesis. They have shown some hope for subcuticular implants of flexible perforated plastics, which might be used in a collar-like structure around the main load-bearing structure. Conceivably the same technique might be applied to facilitate the passage of tubes for shunting the blood to an external dialyzer or artificial kidney, to allow prolonged injections, and to protect percutaneous electrodes, whether intended to pick up internal bioelectrical activity or to apply external stimulation to internal structures. Clinically acceptable methods for life-long infection-resistant passage of a foreign body through the integument, if ever developed, would literally open new doors for treatment of a wide variety of conditions.

CONTROL PROBLEMS

Control of artificial body components and of prosthetic and orthotic devices, including feedback, constitutes another basis for analysis leading to improvement. As Norbert Wiener pointed out, a peg leg was a passive extension of the thigh stump, unsatisfactory in appearance and forcing an awkward gait pattern but at least giving the patient direct information as to the position of the tip of the peg through knowledge of position of his hip joint. In addition, the relatively simple pressure patterns upon the stump of the amputee provided fairly direct information as to the external loads applied to the peg leg. In contrast, later articulated artificial legs for above-knee amputation provided passive joints at the knee, ankle, and toe which were controlled by alignment stability, mechanical stops, and rubber bumpers. Thus, considerably less sensory feedback of positions and loading reached the amputee.

Control of a knee lock in an above-knee artificial leg or a long leg brace is an important problem. Numerous types of locks actuated by weight on the heel have been designed, primarily to give added stability at the crucial instant just after heel contact. Such a design, though, either may lock automatically when preferably it should be free or slowly yielding, as in descending stairs by some techniques, or may fail to lock under circumstances such that prevention of knee buckling is desirable. For example, the latter may be a stumbling situation with the toe catching with the heel off the ground, when the knee is bent so far that alignment stability is impossible. The normal individual, with intact spinal reflexes (demonstrated by the knee jerk when the patellar tendon has been struck), tends to react to the violent acceleration of such stumbling situations by rapidly and vigorously tightening the quadriceps muscle in front of the thigh so as to stabilize the knee to prevent further knee bending, then to begin knee extension, all without conscious thought. Such a normal individual has a good chance to recover from stumbling.

Conversely, the normal individual's reflex mechanisms, as well as con-

scious thought patterns, allow relatively slow bending of the knee directly after heel contact to provide shock absorption and more graceful gait than is possible for the above-knee amputee or the individual with paralyzed quadriceps who must pole-vault over a straight leg with a stiff knee joint. Considerable improvement can be made by better understanding of the relationship between moments about the ankle, knee, and hip. Some recent hydraulic leg mechanisms have been shown to increase knee stability and stumble recovery, as well as to extend ability to walk at a wider range of speeds. No available mechanism, though, provides any reasonable simulation of the spinal reflex control of the normal quadriceps action to apply a lock when necessary plus imitation of voluntary overriding control to allow deliberate yielding to descend stairs or to sit down. As yet there is no scheme for auxiliary power to aid in climbing stairs, curbs, or hills.

Improved control of auxiliary power likewise is a major challenge in upper-extremity prosthetics and orthotics. A conference on this topic was held, on an invitational basis, in early April, 1965, under the auspices of the National Research Council*. It explored such topics as anatomical sites for control, transducers (ranging from body harnesses through pickups for small body motions or forces to electrodes for electromyographic signals), processing of control signals, actuators, sensory feedback, and selection and training of the patient.

A number of laboratories are attempting to use electromyographic signals from remaining muscles or remnants. Skin electrodes tend to pick up extraneous signals. Though means for bringing wire electrodes through the skin for years without infection require further development to gain clinical acceptance, these stronger, clearer signals can be readily obtained, so far for relatively short-term experiments, from needle or wire electrodes placed in the muscles and passing through the skin. Even then there may be some difficulty in filtering the desired electromyographic signal from extraneous noises like the electrocardiogram signal, particularly for high bilateral arm amputees, such as shoulder-disarticulation cases, where muscles on the torso are generally used. (Signals from leg muscles, though possibly useful for wheelchair-bound cases, do not seem practicable for use in control of upper-extremity devices for ambulatory patients.) Electromyographic signals are relatively easily used with long forearm stumps, but such cases already can be fitted reasonably well with conventional body power and simple, easily removable harness.

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*This Conference on the "Control of External Power in Upper-Extremity Rehabilitation," by the Committee on Prosthetics Research and Development of the National Academy of Sciences - National Research Council, was held at Airlie House, Warrenton, Virginia, April 8 - 10, 1965, with the support of the Vocational Rehabilitation Administration and the Veterans Administration. See article by A. Bennett Wilson in this issue, for a summary of the conference.

Electrodes of all types require improvement. Skin electrodes would be desirable for control of prostheses, braces, and perhaps other devices. Ideally they should be used day after day in the same spots on the skin without dermatological problems. They should provide low resistance to allow high signal-to-noise ratios in the presence of strong fields, yet they should not require abrasion of the skin or use of electrode paste or jelly. While pellet-type electrodes have been used on the skin continuously for periods of a few days or even weeks, and perhaps some reapplied almost daily for months, it is still not clear that they can be used routinely for the remainder of the amputee's lifetime. Ideally, the electrode should be embedded in the wall of the socket or readily fastened over the desired spot on the skin, even if far from the socket. Unhappily the skin offers high impedance, though the internal muscle motor units are nearly short-circuited by conducting fluids high in electrolytes.

Surgically implanted amplifiers with radio transmitters to pick-up devices outside the skin are being developed, though there are still many problems of power supply and miniaturization. The fundamental problems of relatively inert materials within the body have already been discussed.

The electrical activity in electromyographic and electroneurographic signals is the result of ions diffusing through membranes. So far only the electrical activity is used.

Picking up of electrical brain signals or those passing along a nerve would seem attractive. In severely handicapped bilateral cases, only the proximal nerves may remain available, with the distal muscles amputated or completely paralyzed. Unfortunately, such neuroelectric signals (in microvolts) are very much lower in amplitude than the electromyographic signals (in high microvolts or even in millivolts) available from the muscle; in this sense the muscle may be considered as a biological amplifier.

Artificial stimulation of paralyzed muscles, directly or via a conducting nerve, by voluntary control or automatic command remains an attractive challenge. Both physiological and electronic knowledge are needed if widespread clinical application is to be attained. Again suitable electrodes for long-term electrical connection between inert material and living tissue present major problems. Merely balancing positive and negative energies in a full cycle is only a first approximation. The electrophoretic threshold for the drifts of certain ions or molecules conceivably may be exceeded by a spike in one direction but not attained by a long low pulse in the other, some think, so secondary ratchet-like drifts of ions may be allowed.

Heart rate is notably subject to control by normal physiological and emotional factors. High pulse rates accompany heavy labor, rapid running, and perception of danger. Poets assure us that love makes the heart go pit-a-pat.

At the other extreme, stopping of the heart traditionally has been clinically and legally considered a sign of death. In recent years, though, there has been increasing success in revival of the heart and of the body as a whole under many circumstances formerly hopelessly fatal. Indeed, to permit certain kinds of heart surgery, the heart is deliberately stopped while its function is replaced temporarily by an artificial machine; after the operation, the heart first is revived and then restored to the patient's physiological control, thus escaping from what formerly seemed inevitable death.

Electrical pacemakers providing artificial control of heart action are increasingly widely used to continue the life of patients with heart block, involving a defect in the normal anatomical mechanism transmitting physiological control of contraction of heart muscle. External pacemakers with temporary percutaneous electrodes have been used successfully. Originally only a fixed slow rate of electrical stimulation was provided by implanted pacemakers, but later several ingenious methods for voluntarily changing frequency were developed.

Animal experiments are being made on implantable artificial hearts. Both power and control offer serious problems.

In replacing some functions, like pumping and dialysis with artificial kidneys, breathing with respirators, or both pumping and oxygenation of blood with artificial heart-lung machines, most of the control functions normally responsive to physiological signals are transferred from the patient to a much larger external system. Sensing devices, such as pressure gages and temperature indicators, are monitored by a human operator, sometimes by an entire team. These operators in turn control the motor speed, the valves, the chemical constitutents, etc. Both the machinery and the control system are clumsy.

A miniaturized, implantable, self-regulating machine monitored by the body's own remaining signals, for any of several major physiological systems, is a fascinating challenge to many specialties of medicine and engineering. Again, there are problems of picking up signals from the body's nerves, processing this information, making decisions based upon them, and then controlling and actuating the artificial mechanism, all with minimum demand upon voluntary controls and artificial sources of energy.

RELIABILITY

In many cases life-long wearing of an appliance is necessary. Reliability, minimum bulk, and psychological acceptability then become important criteria. Moderate cost is desirable.

Sometimes reliability is a life-or-death matter. Heart pacemakers, in spite of careful quality control and elaborate methods of construction, some-

times fail slowly or catastrophically because of breakage of electrodes from mechanical fatigue or slow penetration of moisture through the encapsulating media. Still further improvements in quality control and in sophistication of design are needed to prolong the life of the device and thus often the user. Better understanding of electrodes might reduce the tendency for the threshold required to produce stimulation to rise over months of use.

Reliability of energy source is a major problem with many categories of devices. Implanted heart pacemakers have used specially selected mercury batteries estimated to be capable of three to five years of operation at very low drain. It is possible to estimate from X-ray pictures the drift of mercury as the battery runs down. The rate of the pacemaker, in some designs, drops slowly as the battery deteriorates, providing a simple indication of battery condition.

Rechargeable implanted batteries have been suggested for devices requiring more power. An implanted battery charger and loop would be powered by inductive coupling through the skin from an external source applied periodically.

Attempts to use biological power sources aim at reliability as well as economy of energy and small size. Piezoelectric crystals distorted by pulsatile expansion of the aorta can generate power to operate a cardiac pacemaker in a "bootstrap" operation, but there are problems in distributing pressure so as to avoid damage to the aorta. (Presumably pressure between the aorta and the device should drop substantially to zero between pulses. Two or more sets of crystals or actuating mechanisms in contact with different sections of the blood vessel might be used alternately to allow better nourishment of the temporarily relieved zone.) Conventional upper-extremity prostheses rather successfully use body power. The feedback of information through the socket and harness assists reliable operation. A bilateral shoulder disarticulation, though, has very few sources of independent force through adequate excursion, and even these decrease in reliability and dexterity as the amputee rapidly becomes fatigued, so he would benefit from reliable systems providing external power.

Reliability of mechanical parts has been a major problem in development of hydraulic artificial knee joints. Leaks, clicks, and squealing or swishing noises have only gradually been overcome.

Reliability of recognizing speech through a hearing aid is often adequate in quiet conversation but poor in a noisy environment. Improvements might be made in the design and manufacture of the hearing aid itself, the method for selecting a particular aid for an individual patient, and the techniques for training the patient to use his aid.

It is important to enable the blind person to maintain a straight path, as in crossing a street or a parking lot where there are neither acoustic

cues (like echoes of footfalls reflected from buildings) nor tactile cues (comparable to the edge between a sidewalk and a grassy lawn) perceivable by cane or foot. A method for detecting radio field strength, like a radio direction finder, is adequate in the suburbs but is unreliable in the presence of large steel-framed buildings. A compass, likewise, is inadequate in the presence either of magnetic materials or of strong electromagnetic fields from power systems. (Under special circumstances, though, even these distortions can be used as landmarks in a relatively familiar environment with other cues.) A gyro compass would seem desirable if it could be sufficiently reliable when miniaturized. A conventional gyroscope requires appreciable weight both for the gyro and for the power supply.

Certain concepts for reliable detection of curbs in a device for the blind have depended in a comparable way upon the development of a sufficiently small stable platform to support an optical system so as to eliminate the effects of arm swing and oscillation of the body during walking. An unbalanced pendulum with large moment of inertia but very small degree of unbalance is helpful under many conditions, but it implies considerable weight and bulk and it is inherently disturbed and set oscillating by acceleration of the body. While several ingenious optical schemes for curb detection have been tried on a limited scale, they should be reevaluated if a sufficiently reliable miniaturized stable platform should become available. The difficulties in warning the sighted public against unexpected ledges and steps emphasize the serious problems in developing a reasonably reliable electro-optical system.

PROBLEMS OF SIZE AND APPEARANCE

Some appliances or implants are designed to match the patients' own body size (perhaps discounted slightly to allow for the "size illusion" of an inanimate part). Plastic cosmetic noses, external ears, or skin-like gloves for artificial hands are examples.

In most cases, though, present designs of devices preferably should be smaller. In general, the self-repairing property of living tissue overcomes wear and prevents fatigue failure except under sudden increase of load or most unusual increase in cycles of loading. Thus natural joints, organs, and structures generally are smaller than their artificial replacements designed for conservative bearing loads and stresses.

Miniaturization has been adequately achieved in some fields, notably in certain aspects of electronics, but it is still woefully lacking in other aspects of these total problems. The rapid development of micromodules for electronic components is a hopeful sign of further compression of electronic equipment. (Amplifiers and analog equipment apparently are not so advanced in this direction as are digital applications.) Mechanical

components, though, in general, are relatively bulky. Prime movers, energy storage means, motors, gearing, clutches, pumps, and similar devices on a far more miniaturized scale are needed in many fields. Perhaps the greatest hope for both miniaturization and high efficiency is utilization of the body's own power. Only in recent years have very large power plants approached the efficiency of muscles, but small engines and motors are notoriously far lower in efficiency.

Small high-speed motors need substantial reduction gearing to match practical speeds for most pumps or the modest (and preferably variable) speeds of motion of prostheses providing pronation and supination, elbow flexion, etc. Thus the gear box may be as big as the electric motor. Even a small motor, acting through a large gear reduction, will have very substantial effective inertia, causing problems in response times. Therefore, control by direct starting, stopping, and reversing of the motor may not be as satisfactory as engagement or release of a clutch with the motor allowed to accelerate and decelerate while disconnected from the load. Unfortunately, mechanical clutches to allow a single motor to select and control any of several potential motions are also relatively large.

Severely handicapped patients must perforce accept almost any device which offers appreciable improvement in function, regardless of bulkiness, poor appearance, cost, or other disadvantages. Many patients, though, tend to reject presently available devices which they consider of marginal utility if they can achieve some limited function unaided.

At the end of World War II, very few unilateral arm amputees wore the artificial arms and terminal devices which were then available, preferring to use their remaining normal arm and hand, assisted by exaggerated body motions and by conspicuous use of the amputation stump. Though considerable improvement has been made in rehabilitating freshly-amputated unilateral arm amputees to wear a properly prescribed artificial arm after appropriate training, many of the older amputees have never been convinced and may even have developed pride in ability to perform independently, if awkwardly, without a prosthesis.

A comparable challenge still remains in the case of arm braces or orthotic devices for patients with unilateral arm disabilities. Very few appliances of that type, useful as they have proven to be for severely handicapped bilaterally-involved patients, are accepted by unilaterals. Rejection, sometimes psychological but often very realistic and understandable, is particularly common in the case of a hand appliance which would be visible to the casual bystander. Unfortunately, all types of braces must be worn on the outside of the body, where bulkiness and unsophisticated design are especially noticeable. In many cases the relatively bulky mechanical joints must be opposite the bulbous human bony joints, so they are particularly

noticeable even if the muscles are severely atrophied along the shaft of the bones.

Some appliances, like plastic artificial eyes, only attempt to restore the appearance of normality. Typically plastic artificial eyes merely restore the appearance of looking essentially straight ahead; the range of motion is limited and perhaps negligible. The experimental reading machines and guidance devices for the blind which are now under development restore neither the appearance nor more than a small fraction of the many functions of normal eyesight. These machines, of course, are very much bigger than a human eye, though already transistors, "cordwood configurations," and micromodules have reduced desk-top models to handbag and pocket sizes.

The occasional suggestion of a tiny television camera carried in an eyeglass frame or even in a plastic artificial eye and "plugged into the visual nervous system" is, thus far, extremely unrealistic. The notion implies not merely tremendous advances in miniaturization of components, power supplies, and microelectrodes, but solution of the problem of intrusion through the integument (possibly imaginable at the conjunctiva of the eye as in integral eye implants for moving plastic eyes) and development of techniques for life-long transmission from inert electrodes to living nerve cells, including consideration of biochemical effects. Presumably the greatest difficulties, though, involve matching of the "television" coding to the relatively unknown coding schemes used at one of the many levels of integration of the human nervous system.

Prosthetic devices exhibit various combinations of function, miniaturization, and imitation of normal appearance. Certain artificial hands, closely matching normal dimensions, attempt to combine modest levels of function and reasonably normal static appearance, including skin-like cosmetic gloves. Because of the paucity of independent sources of energy and control, an artificial hand typically presents only a single attitude, in contrast to the fluidity of motion of the normal hand with its elaborate and finely coordinated neuromuscular control. This limitation in simulating natural activity can be partially overcome by a certain degree of "stage presence" on the part of the amputee.

Split mechanical hooks, used as terminal devices on artificial arms, stress greater restoration of function even at the expense of abnormal appearance. One may compare the hook with the airplane; either may be made in whatever size and form is needed for maximum function. At any state of development of control systems for upper-extremity prostheses, the hook can always be superior to the artificial hand, just as the airplane can be superior to the ornithopter with its deliberate imitation of a bird.

Engineering design can improve imitation of natural form and size and can control unnatural patterns of locomotion, hand action, or other func-

tions, thereby increasing acceptance of devices by the patient, the family, the employer, and society as a whole. Improvements in plastics, in anodizing and finishing of metals, in fabrication techniques, and in a variety of other areas likewise can contribute towards this improvement of appearance. As in so many other areas, more artistic and effective use of available materials and techniques would be helpful.

The outstanding problem in miniaturization and appearance is emphasized by comparison between computers and the brain. Artificial means for making decisions and for storing information in artificial memories are notoriously big, clumsy, and energy-consuming in comparison with the human nervous system. Rehabilitation rather than a prosthesis so far is the effective way to help the mentally retarded; from the viewpoint of an Einstein, all of us need such assistance.

Thus far, perhaps fortunately, there is no prosthesis imitating human affections or free will.

COMMUNICATION PROBLEMS

Perhaps the most important step toward meeting these many challenges in engineering for human needs would be the further development of better communication and broader cross-fertilization between fields. It is important to stimulate and support individual creativity, enterprise, and expertise. The individual, though, requires self-discipline and responsibility if he is to function effectively. No one is omnipotent, but specialization helps; thus an individual expert can best carry out each specific task, whereas experts from other fields would be amateurs in his. In contrast, a team can best make up for the fact that no one is omniscient. Team work of individuals from different disciplines and with different points of view is needed to reach wise decisions with a broad consideration of all relevant aspects. A team should not be a mere mob acting without leadership; generally speaking, the leader should be the one best able to offer relevant and correct information as well as inspiration. (Indeed, experiments have indicated that other members of a group making decisions from scattered data spontaneously recognize as their leader that person from whom they have received the most correct information. With certain organizational structures, though, some groups considered one individual to be a bottleneck, whereas he considered himself to be the boss!) A delicate balance between centrality of information and yet means for passing information around a bottleneck is desirable for maximum effectiveness. These considerations seem particularly relevant in interdisciplinary activities where there is a natural human tendency for each discipline to resent leadership, and especially self-appointed dominance, by a representative of another field.

Not only constant increase of information but also its diffusion among all the individual experts on a team are particularly important. In some areas, interdisciplinary short courses have been very effective. The Prosthetics Education Program, for example, for years has sponsored courses of one to a few weeks in length for doctors, therapists, prosthetists, orthotists, and others to communicate the most recent research results, to foster true cooperation of prosthetics clinic teams, and thus to raise more rapidly the level of service available to amputees and brace wearers throughout the country and, indeed, the world. The Prosthetics Education Courses are conducted routinely at three universities across the United States. Similar intensive international and regional short courses have been sponsored through the International Society for the Rehabilitation of the Disabled in widely separated lands.

Formal courses in bioengineering are conducted, usually at the graduate level, in an increasing number of universities throughout the country. These typically attract both doctors and engineers. There is also an increasing tendency to include certain aspects of bioengineering or biotechnology as graduate theses and in the undergraduate engineering program, either as formal courses or as student projects. The reading of books and journals from other related fields permits the individual practitioner to educate himself.

Finally, meetings such as this can catalyze reactions among the favorable raw materials available to accelerate the progress of our generation toward meeting the many challenges of replacing human parts and functions.

SUGGESTED READING

NOTE: Instead of conventional references keyed to specific points, an initial reading list of books and periodicals related to the many fields covered seems appropriate. As in other interdisciplinary fields, the literature is widely scattered.

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