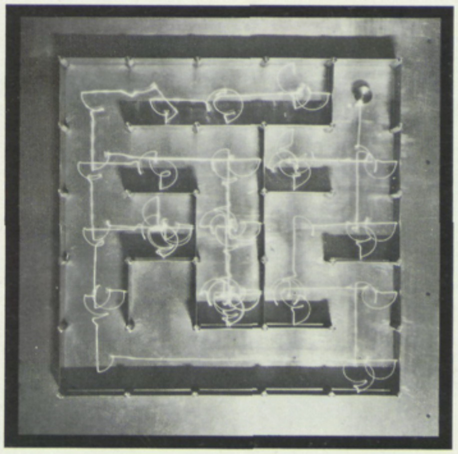
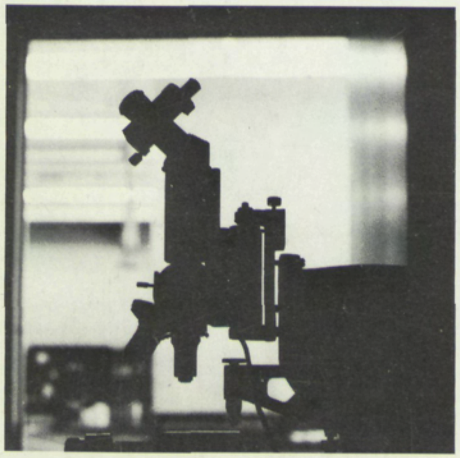
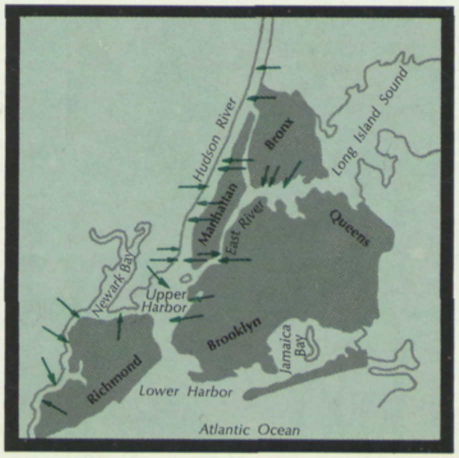
ENGINEERING

CORNELL QUARTERLY







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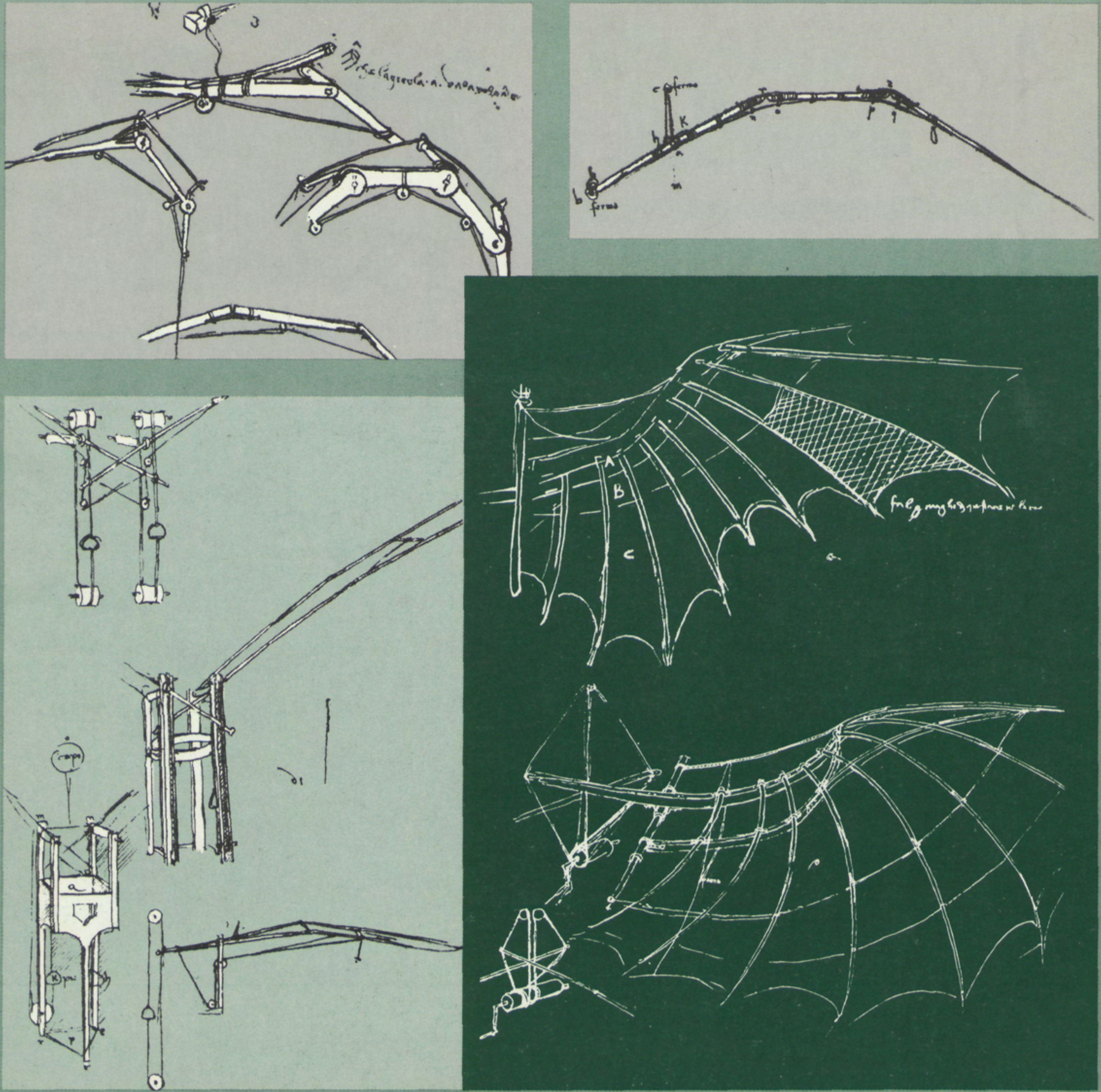
SOME ENGINEERING-BIOLOGICAL INTERFACES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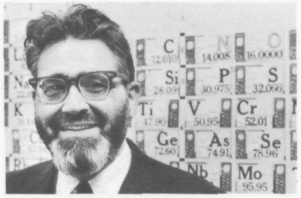
IN THIS ISSUE

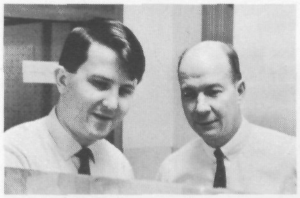
Bionics and Robots /2

Professor Henry D. Block discusses the implications of the emerging field of bionics for science and technology, and for our whole way of life.



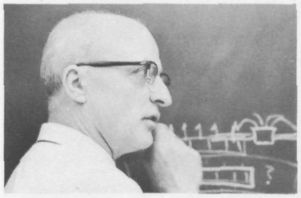
Living Chemical Factories /17

As more is learned about cellular chemistry, it becomes feasible to use microorganisms to perform industrial chemical reactions that are complicated, time-consuming, and expensive with present methods. Professors Robert K. Finn and Victor H. Edwards explore these exciting possibilities.



Education in Bioengineering /25

What is the best preparation for a career in bioengineering? Professor Nelson H. Bryant discusses the building of a curriculum wide-ranging and flexible enough to train engineers for this rapidly expanding field.



Ecology: Key to Water Quality Management /30

Man's activities, carried on with disregard for the biological processes, have caused a disastrous polluting of our natural waters. Professor Alonzo Wm. Lawrence explains how man and nature working together can rectify this situation.

Faculty Publications /41

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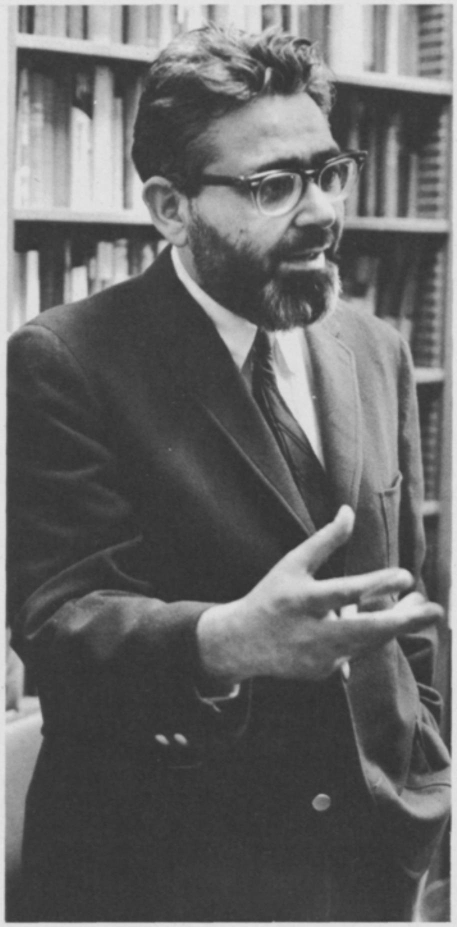
Opposite: Some of Leonardo da Vinci's drawings for his ornithopter, a man-powered flying craft. This is an early, dramatic example of the combination of biological observation and engineering.

BIONICS AND ROBOTS

By Henry David Block



By 1960, a number of engineers and scientists who were concerned with the interaction of engineering and biology felt the need for professional cohesion, and out of their concern was born the field of bionics. The word "bionics" was coined by Col. Jack Steele, M.D., of the Air Force Institute of Technology at Wright-Patterson Air Force Base, a flight surgeon specializing in psychiatry and neurology. By this term he meant the application to technology of the mechanisms used by living systems.

SOME CONCEIVABLE APPLICATIONS OF BIONICS

There are many "tricks" utilized by biological systems that clearly are marvels of engineering ingenuity. In one famous experiment a newly born manx shearwater was taken from its nest in England, uniquely marked, and shipped to Boston where it was set free after maturation. Twelve days later it was found again in its own nest in England. What neural connections within that tiny brain directed the navigation? If we understood the neural system, we presumably could use this knowledge to improve our own electronic navigational devices.

According to standard hydrodynamic theory, the dolphin shouldn't be able to swim as fast as it does. When we understand how it maintains laminar flow and low drag by boundary-layer control and how it attains high propulsive efficiency, we should be able to use this knowledge to improve the design of submarines and other craft.

Biological adhesives, such as the barnacle's glue, exhibit enormous strength and rapidity of bonding, even to such inert materials as Teflon, and are able to maintain their strength in a fluid environment for extremely long periods. If such adhesives could be developed on a commercial basis, they would have great use in technology as well as in dentistry and medicine.

To learn about achieving greater fuel economy, we might study the golden plover which flies 2,400 miles nonstop from Labrador to South America, losing only two ounces of weight in the process.

To improve lightweight structural design, we could study the giant frigate bird which has a seven-foot wingspread but has a skeleton made of hollow, tapered bones which weighs only four ounces.

Further, if the type of chemical reactions utilized by living systems could be applied to engineering, man's world would be revolutionized. Chemical energy, for instance, is used extensively by biological systems, yet relatively little in technology. For example, we might exploit the electric ray fish's means of storing electrical energy in its electroplaques; they generate a 50 amp. pulse at 60 volts which is 3,000 watts, or 0.1 watt per gram of body weight. Bioluminescence as a source of illumination is also conceivable, as is the use of biochemical fuel cells as a source of power. Our bodies efficiently store energy by means of adenosinetriphosphate (ATP) while engineering uses bulky storage batteries. The use of ATP or something like it may one day be possible in technology. Similarly, we may learn to use photosynthesis or an analogous process as a primary energy source.

In the area of systems control, chemical devices would have the advantage of being faster and more efficient, stable, and sensitive than presently used methods. Chemical communication, so widely used in the insect and animal worlds—by marching ants, snails, dogs, and cats, for example—has yet to be widely employed in technology. The body maintains homeostasis or equilibrium by means of hormones and enzymes which trigger the production of body "components" at all levels through chemical micropower which is both reversible and sensitive. It is conceivable that this type of communication and control could be used in industry to replace large relays and switching systems. Computer scientists often count the "generations" of computers as follows: electromechanical, vacuum tubes, transistors and cores, and integrated circuits; the next generation might be fluidics or cryogenics, but some future generation will be chemical or biochemical.

Another possible application of bionics might be the development of electrical conductors that work like neurons. The electrochemical neural signal suffers no attenuation because its power source, a concentration of sodium on one side and potassium on the other, is distributed all along the neuron. Perhaps electrical conductors will someday be made using a similar arrangement.

The half million fibers of a frog's optic nerve are able to reestablish their original connections with one another, even after the nerve is severed and one segment is partially rotated. This would be a very useful capability to build into telephone line cables.

The sensitivity and flexibility of the chemical control of muscles might be an example on which to base the design of engineering devices. The muscle's force is delivered by the individually regulated contractions of thousands of fibers. Such a mechanism, if translated into technology, would be invaluable in the handling of delicate parts by automatic machines. Better pumps might be designed by imitating the heart's distributed pumping action which is likewise performed by muscle fiber contractions.

The filter in the nostrils of the albatross that enables it to drink sea water might provide a useful model for man's

1. A model of powered exo-muscles which are attached to the operator at the forearms, wrists, and waist, and which mimic and amplify his movements thus enabling him to lift weights that are ordinarily too great for human strength.
Courtesy of *Press Tech. Inc.*

The structure (2) and movement of the seed pod (3) were the principles underlying the design of this glider (4).

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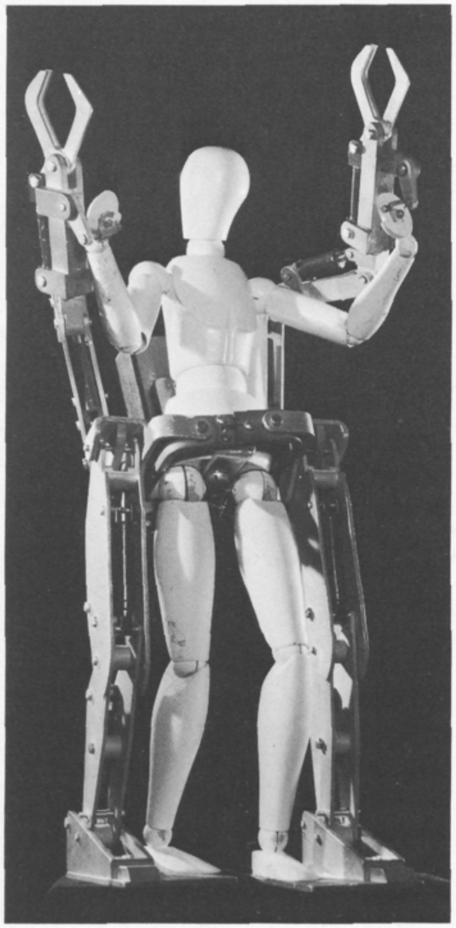

desalinization efforts. Mechanical gills which permit underwater breathing could have many uses.

The greatest challenge of all will be to understand at least some of the mechanisms of the human brain and to apply them in the development of very sophisticated computers and robots. Here the object is not primarily to imitate the *structure* of a biological system but rather to imitate its organization to achieve a similar *function*.

NONEXAMPLES OF BIONICS

The field of bionics is new, and has, therefore, a large number of detractors. They point to engineering devices that do not appear in living systems at all in order to prove the irrelevance of bionics. The wheel and axle has no biological prototype. One might wonder why so useful a device did not evolve in living systems. The reason seems to be that there were no viable intermediate steps leading to its development from a primitive form, as there were in the evolutionary development of the eye, foot, or hand. Radio communication is another engineering achievement which has no biological prototype. The answer to this type of criticism of bionics is that it is not intended to account for *all* technological progress; rather it is a method for stimulating *some* new developments.

Another criticism of bionics is that its practitioners have sometimes copied nature too slavishly. Da Vinci's ornithopter, which was to have been a man-propelled, wing-flapping plane, would have been a wonderful example of bionics if it had worked. In this case, what was observed in nature could not be directly copied for engineering use. Wing-flapping has not yet proved to be a satisfactory method of propulsion for man's flying devices. The answer to the criticism of slavishness is that it was the *idea* of flying that bionics contributed to engineering, not the technical details.

Critics of bionics also point out that in many cases where good engineering design is similar to the biological design, the study of biology did not aid the technological development. In these cases, the technological mechanism was developed first, and then it was discovered that living systems had

4

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mechanisms of the same type. Only after the engineering devices were made did we discover, for example, the jet propulsion systems of the squid and octopus; ultrasonic sonar in bats, owls, and dolphins; the coded signals of fireflies which enable them to discriminate friend from foe; or polarized light in the communication system of bees. And the causes of the apparently meaningless, erratic movements of the human nervous disorder called chorea were understood only after similar instabilities were observed and understood in feedback control systems.

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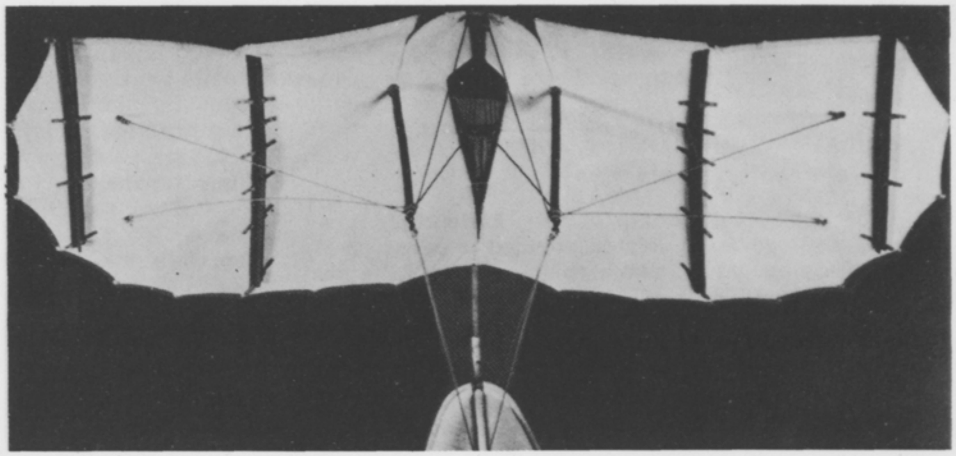

In other instances, biology and engineering have often evolved to the same point by separate paths. The reason for this has been noted by Nils Nilsson of the Stanford Research Institute who, in discussing the difficulties of discovering the functions and operations of the cerebellum, stated that:

> there has not yet been enough *engineering* experience with mechanisms having, for example, articulated limbs, and requiring complex, coordinated motor control. Biological mechanisms are usually quite mystifying indeed, until engineering has reached a certain prerequisite level of development. It is no accident that servo control techniques, for example, were *invented* before they were *discovered* in the spinal reflex arc. Engineering invention permits biological recognition and must precede it (not the other way around as the bionickers would have us believe). Perhaps then, the cerebellum (and other things, too) will remain a mystery until, spurred by engineering efforts, the appropriate concepts are invented.

This is a very cogent point and sheds light not only on bionics but also on the relation of science to engineering in general. Many people, including some engineers, believe that engineering uses the results of science, but not vice versa. We see here how incorrect this viewpoint is. It is only by building things (technology) that we acquire experience. On the basis of this experience we are able to recognize similar systems in nature. This recognition is at the heart of what we call "scientific explanation." Of course, engineering has made more obvious contributions to science without which science could not survive—electric power, measuring instruments, roads, chemicals, steel, tools, and computers, for example. But the crucial contribution of technology is that it provides the engineering experience which is the basis for explaining the mechanisms of nature. This has been largely overlooked, as Nilsson points out.

Clearly, bionics has its limitations. Yet, there is no doubt that man's early tools were probably imitations of biological prototypes, and observations of natural systems have triggered many engineering developments from Galvani's discovery of electricity in the

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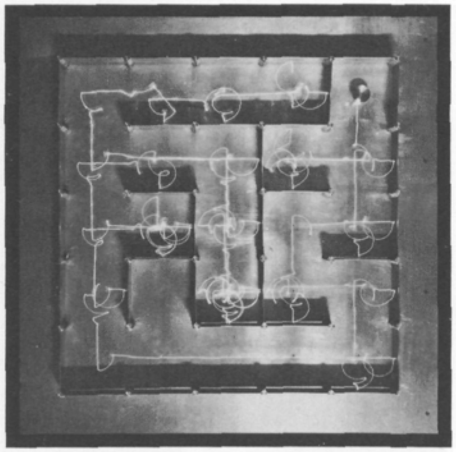

1. This mechanical mouse is capable of learning from experience. (2) shows the mouse finding its way through the maze by trial and error. (3) shows the mouse after it has learned the path.
Courtesy of Bell Telephone Laboratories.

4. (opposite page) The Broom-balancer is an adaptive control system with an eye of photoelectric cells (not pictured) which watches a human operator balance the broom-like object. It then sorts through the gathered data, and culls out the optimal balancing movements. From this, the control system "learns" to balance the broom by itself.
Courtesy of Stanford Research Institute.

frog, to the design of spaceship biosystems currently envisaged for extended interplanetary missions. In bionics, then, the relationship of biology to engineering is such that each discipline makes contributions to the other.

FROM COMPUTERS TO ROBOTS

It is in the development of more sophisticated computers and robots that bionics will have its major impact. The main obstacles to the development of robots, as we shall see later, are precisely those which the biological systems have overcome through millions of years of evolution. Now the question is whether technology can exploit nature's solutions.

The difference between a computer and a robot is that a computer is fed data in a specific format, processes it, and then returns the result in another specific format. A robot, on the other hand, moves about in the world, interacts with it, alters it, and is altered by it. The computer is pure brain which is protected from the environment by elaborate input and output devices; the robot is this, too, plus a "body" which interacts with the natural environment.

In the next twenty years we will see robots of increasing sophistication. One of these, scarcely more than a computer, might be the Robot Chauffeur. With this device installed in the car, the passenger would press a series of buttons indicating "I want to go to Cleveland." The robot's computer would then be in radio communication with other computers at the weather bureau and a traffic control center and would compute the optimal route to follow, taking into account extrapolated weather and traffic conditions. By reporting its own position to the control center, the computer also would make itself a part of the general traffic data. And, through optical or sonar devices, it would detect the presence or predicted presence of obstacles such as on-coming trucks, passing cars, and pedestrians and would make the appropriate response more quickly than could a human operator.

The question arises: "What about very unusual, unanticipated situations? We'd be at the mercy of the machine." But how do people react? Often they don't respond quickly enough; often

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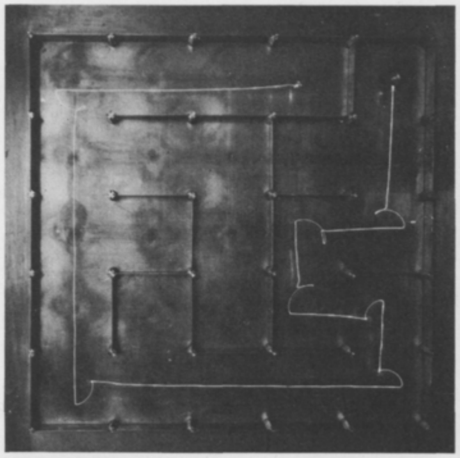

they make the wrong response; and sometimes they go completely to pieces. In learning to drive, people learn what to expect and how to perform. A robot can likewise learn if it is exposed to thousands of different traffic situations during a preinstallation training period. It can then continue to learn from experience. Because it will not be subject to senescence, the robot should become a master driver. The development of this Robot Chauffeur will differ from most robots of the past because it will have this capacity to learn.

Robots will be even more essential in the navigation of space craft. This is now done by computers which solve the differential equations of motion and determine the course of the craft. Unaided, man cannot solve the equations quickly enough; neither does he have an instinctive feeling for navigating orbital trajectories and programming fuel rates in space journeys that may last a month or more. Moreover, robots will be indispensable in exploring and then working in hostile, high-temperature environments such as Venus, in poisonous atmospheres, or in environ-

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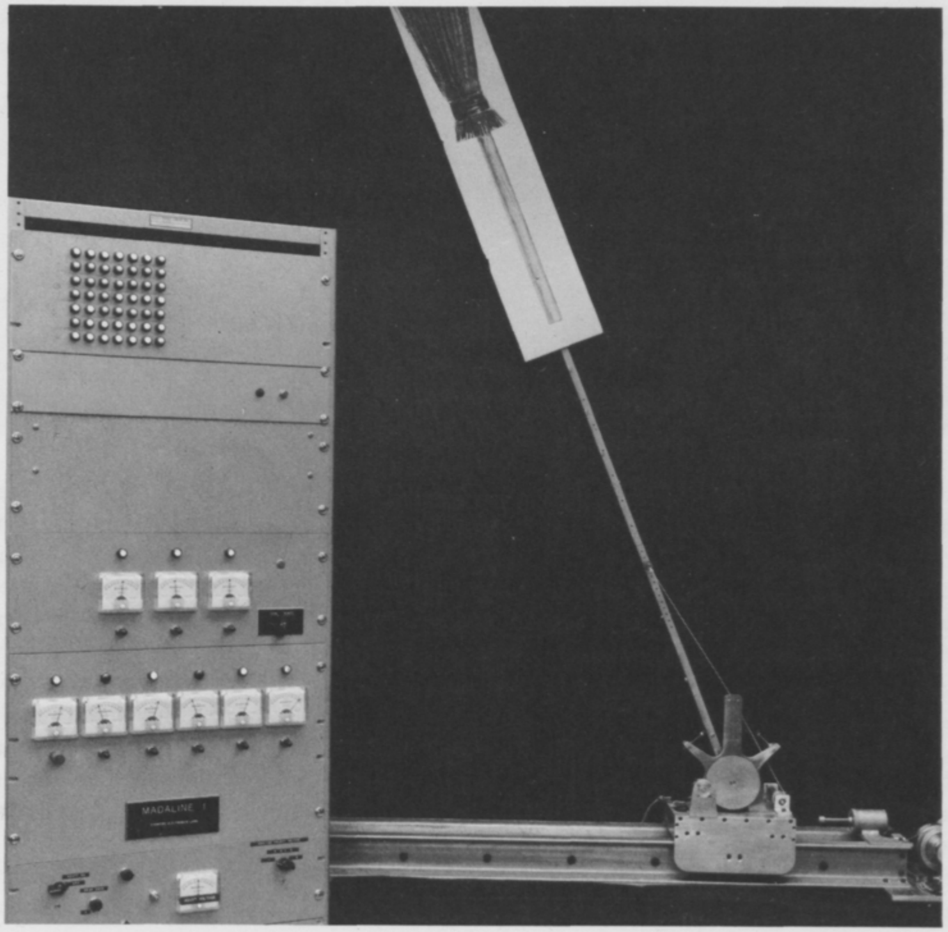


Below: A chess game played by a computer at Stanford Research Institute and one in Russia.

Opposite: The eye-hand apparatus is an initial step in providing computers with the ability to perceive and manipulate the environment. The camera locates the cube, then the computer traces the cube's size and shape in order to give the arm-hand accurate directions for grasping and placing it.
Courtesy of Stanford Research Institute.

ments of extreme radiation or disease.

In one sense, robots are already a part of our lives. A dishwasher might, in a limited way, be considered a robot, and, in industry, there are many "robots" which are doing elaborate and complicated tasks of machining, processing, and packaging. These robots, however, function in contrived environments. The next step will be the development of more intelligent, self-sufficient, and imaginative robots which can dwell in our natural environment. The day will come when robots will do housework such as vacuuming; washing, drying, and stacking away dishes; ironing; making beds; and cooking by programmed recipes with food which is cataloged in the refrigerator.

OBSTACLES TO GREATER ROBOT SOPHISTICATION

Curiously, many functions that are regarded as "high level" in humans are performed with great ease by today's computers, while functions that are considered to be more "primitive" provide problems for which no solution is in sight.

Some of these higher level functions include mathematical computation, solution of partial differential equations, optimization, symbol manipulation, logical decision making, puzzle solving, communications, control, and chess and checker playing. These are purely intellectual functions. However, if we are to have robots which interact with the environment, major advances must be made in understanding the more primitive functions of perception, language, thinking, and navigation.

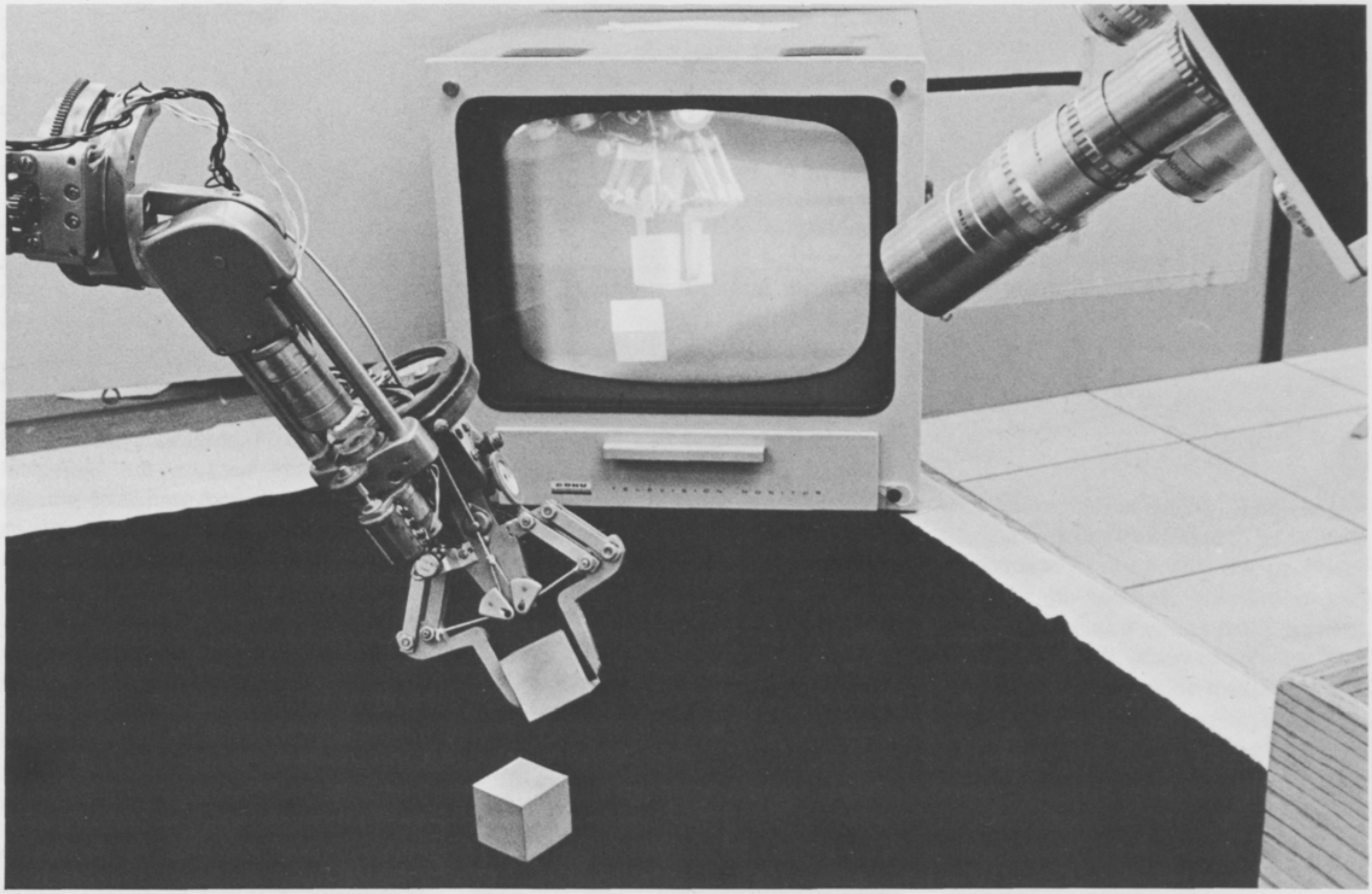
Perception

One of the low-level functions that robots have yet to master is perception, which could be illustrated as, for example, the ability to find a particular face in a crowd. If a dozen small objects, of which one is a fly, are simultaneously thrown in front of a frog, the frog unerringly flicks its tongue at the fly and at nothing else. Present-day computers are not so adept as the frog in perceptual activities and must examine the objects one by one.

In order to understand perception, we must also learn what the mechanics

STANFORD - RUSSIAN COMPUTER CHESS MATCH

	USSR White	Stanford Black
1	P-K4	P-K4
2	N-KB3	N-QB3
3	N-QB3	B-B4
4	NxP	NxN
5	P-Q4	B-Q3
6	PxN	BxP
7	P-B4	BxN
8	PxB	N-B3
9	P-K5	N-K5
10	Q-Q3	N-B4
11	Q-Q5	N-K3
12	P-B5	N-N4
13	P-KR4	P-KB3
14	PxN	PxNP
15	RxP	R-B1
16	RxP	P-B3
17	Q-Q6	RxP
18	R-N7 ch	R-B1
19	QxR mate	



of attention are. A present-day computer would be at a loss at a cocktail party because it would be unable to focus on one conversation and ignore the distracting hum around it. Similarly, it cannot focus its attention on one object in its field of view and relegate others to a level of secondary importance; yet babies soon develop this ability.

To develop a computer that will recognize "constancies" as we do is another challenge. A cigar box, seen by us at any angle, moving, or partly hidden, is still a cigar box. To the computer, it is a different object in each case. At whatever distance we see it, we can estimate the box's approximate size, but the machine is unable to do this. A basic technique in human perception, and eventually in robot perception, is involved here. This is *anticipated transformation*. As we see the box move away from us, it appears to become smaller; yet we know from experience, which we began acquiring in infancy, that the actual size is constant. When we look at or reach for the box, we compensate for its apparent size change. Therefore, it might be desirable to give machines an extended infancy in which they could learn by experience to make unconscious inferences. The machine's perception might then begin to approach that of at least a retarded human being.

Another aspect of perception is pattern recognition. On the lowest level, this includes recognizing simple optical images and auditory signals. On a slightly higher level are such abilities as reading addresses carefully written on envelopes or understanding spoken words. Computers with these abilities are beginning to appear on the market, but their capabilities are limited. We have not yet been able to build into them the ability to test context and meaning or to build computers which can understand language, which is a capability of a higher order. This will be discussed later. Further, very slight changes in facial expression and other tiny cues to meaning can be interpreted even by infants, but no machine can interpret these nuances yet. However, there is reason to believe that teaching them to understand this form of communication should be no more difficult than teaching them other forms of language.

There could be many uses for computers that are adept at pattern recognition. Computers have recently been used to analyze jet aircraft vibration patterns to diagnose malfunctions. In the future computers with pattern-recognizing ability might be used to observe weather patterns to make predictions; to trace patterns of medical symptoms for computer diagnosis, particularly in the areas of electrocardiography and electroencephalography; and in the control of industrial processes.

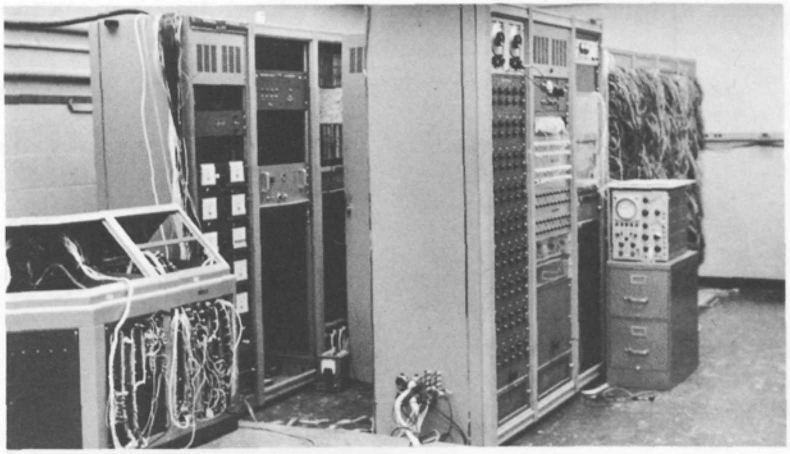
Before serious headway can be made, a method for determining the significant features of patterns must be found. The way in which neural mechanisms operate to detect features in optical patterns has been studied in the cat by Hubel and Wiesel, in the frog by Lettvin and Maturana, and in the king crab by Hartline. But there is still a great deal that we do not know about human pattern recognition. As we acquire more understanding of it, we may be able to teach machines to deal with such intellectual abstractions as "relation," "meaning," "implication," and "concept." After this goal has been reached, it may be possible to teach machines to ignore unimportant stimuli and to respond immediately to significant ones. As you look out the window, you ignore passing cars, strolling pedestrians, etc., but if your little boy raises a rock over the head of his playmate, you spring into action. Machines cannot make such judgments, but someday they may be able to.

Perception, thinking, guessing, judging, and other functions are more easily performed by biological systems than by computers because the biological systems have the advantage of *parallel processing* which is the simultaneous transmission and processing of millions of messages from all parts of the body at once. Although transmission of individual signals is relatively slow in the biological system, millions are being transmitted and processed simultaneously. Computers transmit and store individual signals very rapidly indeed, but can deal with only one signal at a time.

Now we are beginning to hear of parallel-processing computers, but thus far, this means machines with six, eight, or twenty lines in parallel, not millions of them. Electrical systems called neural networks are capable of parallel processing, but the theory of their operation is just in the developmental stages.

Biological systems are superior, too, in that they generally perform well despite malfunction of individual parts. Adults lose perhaps 50,000 brain neurons each day, yet their performance does not deteriorate noticeably for perhaps 30 to 40 years. In contrast, when one wire in a computer is removed, the output is ruined. Cornell's Perceptron

"Some people welcome change; some people fight it."



Cornell's Perceptron, designed by Professor Frank Rosenblatt, can be trained to recognize words or short sequences of words in any language. Presently, it is being used to find an optimum means for extracting such features from speech as the presence or absence of vowels, or sibilants.

has the attractive feature of being relatively impervious to malfunction of its components. Current computer design also is beginning to make possible reliable computation despite component unreliability.

Another type of perception is instantaneous recognition that a certain scene has been viewed before. This recognition is followed by the recall of the sequence of events surrounding the scene's previous appearance. Although no present computer can do this, a Cornell Ph.D. candidate has just finished his thesis on a mathematical model of a machine which might be able to.

Languages

Presently, robots are unable to understand natural languages. We shall discuss what we mean by "understand" later, but for the present we should note its relation to a very important type of memory that we shall call *semantic memory*. When we remember a conversation, we usually recall not the exact words, but rather their meaning. We are just beginning to understand how this type of memory might be incorporated into robots. Utilization of this type of memory could enormously reduce the amount of information storage space required, thereby making it feasible to attempt to have computers deal with nontrivial language problems.

It will be difficult for machines to learn natural languages because a given word may have several meanings, or may serve as several parts of speech. This is especially true in English. Additionally, shifts in emphasis and stress, facial or hand movements, idioms, proverbs, jokes, connotations, and ambiguous parsing also make understanding natural languages even more difficult.

Machine translation of natural languages, say Russian into French, for example, has proved to be much more difficult than anyone anticipated fifteen years ago. The great surge of activity in theoretical linguistics in the first half of this century suggested that we really understood how languages work and that the only barrier left was the building of adequate computers. The computers now are here, but machine translation isn't a reality. The elegant linguistic theory was found to be entirely inadequate to cope with the problems involved in machine translation and thus we see that it wasn't really a scientific theory at all. Many experts are now in despair that machine translation can ever be successful. Despite this, it is only a matter of time before machine translation will be a reality.

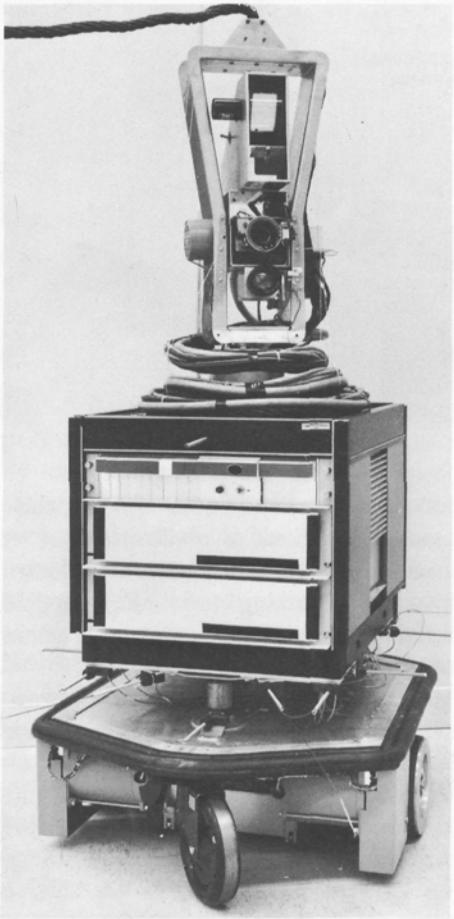
Almost everyone working in the area of artificial intelligence is either an optimist, believing that to a computer all things are possible, or a conservative who believes that there are properties unique to man which are forever beyond the reach of the computer. This dichotomy undoubtedly results more from personality differences than from differences in intellectual capacity or knowledge of the facts. Some people welcome change; some people fight it. Very little of value results from the fighting between the two camps. A case in point is the controversy over "thinking."

Thinking

"Can a machine think?" This is a nonquestion. Its meaning is too vague.

We can examine each word and find that we haven't defined a question at all. What do we mean by "can"? Do we mean today or ever? Do we mean in practice or in principle? What do we mean by "a"—a particular machine? or any machine at all? By "machine" do we mean an existing fabricated product or any system governed by the laws of physics and chemistry? If the latter, is a man a machine? What do we mean by "think?" Can all people think? Can animals? Which animals can and which cannot? What is the test? The question is too imprecise to admit a unique answer. Words mean what people mean by them, and this can be many things. If we devise a test for proving that machines can think and build a machine that can pass the test, there will always be someone who will not accept the test as a valid criterion of thinking. Therefore, arguing this question is very nonproductive and will always be so. The meanings of nontechnical words are vague, approximate, and changeable. It is not reasonable to fight over them.

A more constructive endeavor is to gain a better understanding of *heuristics,* the rough and ready, semilogical "reasoning" used constantly in everyday life that enables us to form subgoals, tentative plans, partial (but reasonable) strategies, guesses, etc. The problems involved in heuristics are, in a sense, more primitive than the general philosophical question about whether a machine can think, but the answers derived will be more useful. However, it is more difficult to deal with these "lower level" guesswork techniques than with rigorous and precise computer theorem proving.



Stanford Research Institute's robot with navigational abilities can explore its environment and record and continually update its findings.

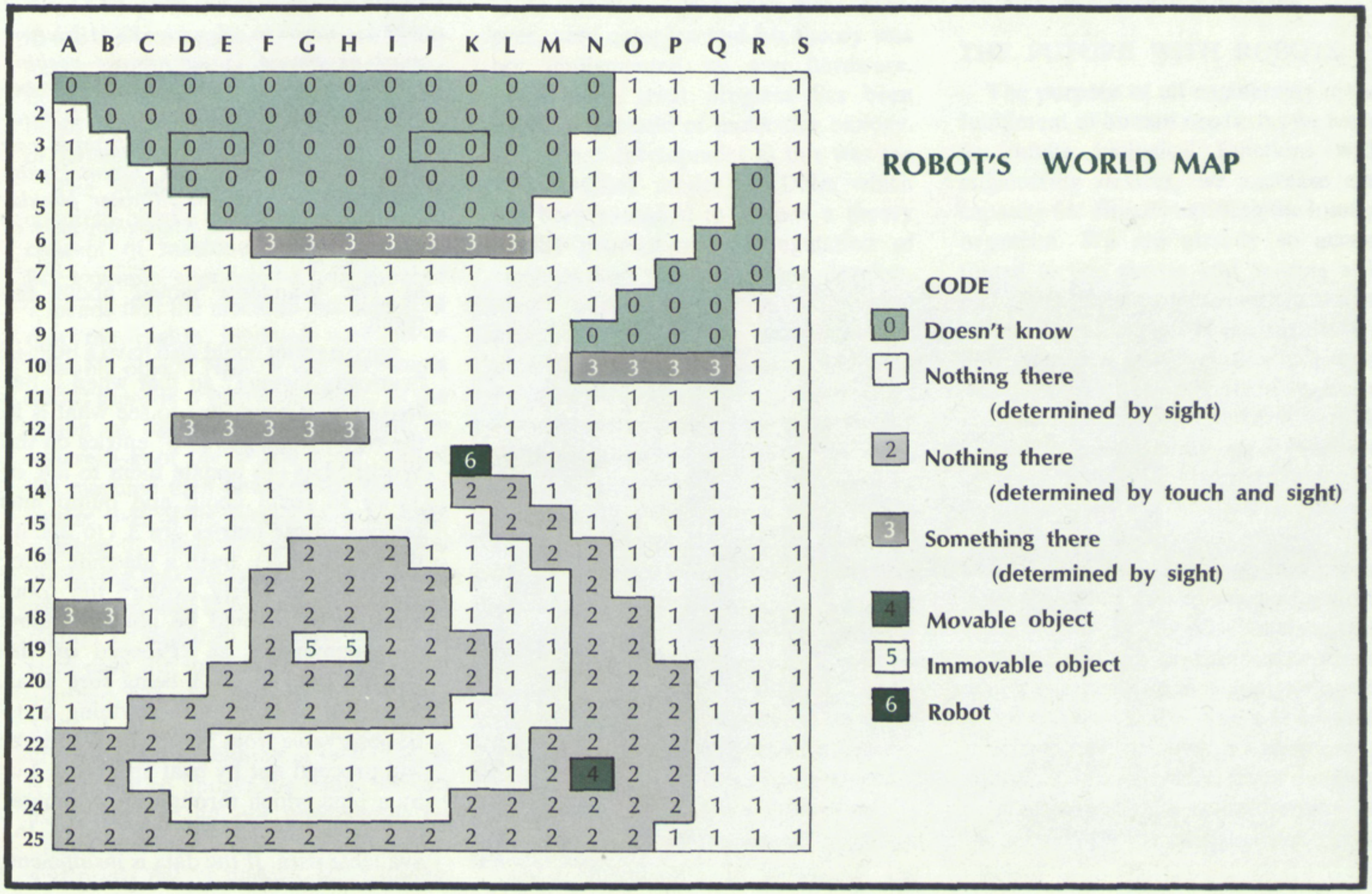
Navigation

A robot with navigational abilities is now being built at Stanford Research Institute. The Wanderer, as we shall call it, is a mobile robot which will be in radio communication with its computer brain. It is equipped with an eye in the form of a range finder, so that it can report to the computer what it sees in a particular region of the room. It also has bumpers which can report to the computer whether it has encountered a movable or immovable object.

In the computer memory is an updated record, called the World Map, of the robot's knowledge of the contents of the room. The World Map is divided into squares like a checkerboard. Each square corresponds to a small region of the room and contains a number which is a code for the machine's knowledge of what is in that particular region of the room. For example, the code might be like that in Figure 1. As the robot gains knowledge by looking or exploring, it updates the Map. Code number 6 indicates the position of The Wanderer itself. It moves about on the Map

> *"It is in the development of more sophisticated computers and robots that bionics will have its major impact."*

Figure 1



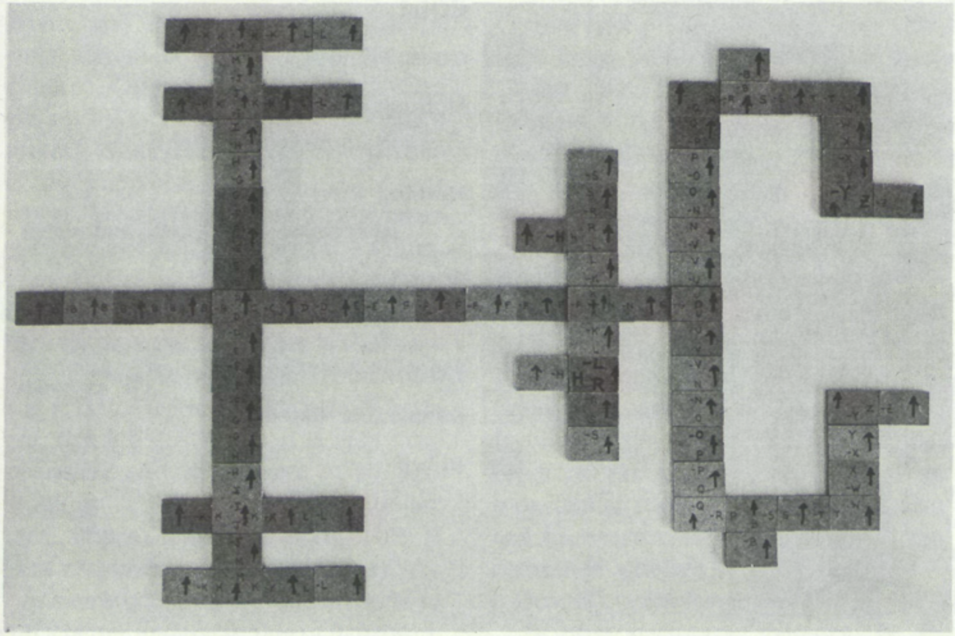
ROBOT'S WORLD MAP

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
4	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1
5	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1
6	1	1	1	1	1	3	3	3	3	3	3	3	1	1	1	1	0	0	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	6	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1
16	1	1	1	1	1	1	2	2	2	1	1	1	2	2	1	1	1	1	1
17	1	1	1	1	1	2	2	2	2	2	1	1	1	2	1	1	1	1	1
18	3	3	1	1	1	2	2	2	2	2	1	1	1	2	2	1	1	1	1
19	1	1	1	1	1	2	5	5	2	2	2	1	1	2	2	1	1	1	1
20	1	1	1	1	2	2	2	2	2	2	2	1	1	2	2	2	1	1	1
21	1	1	2	2	2	2	2	2	2	2	1	1	1	2	2	2	1	1	1
22	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	1	1	1
23	2	2	1	1	1	1	1	1	1	1	1	1	2	4	2	2	1	1	1
24	2	2	2	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1
25	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1

CODE

- 0 Doesn't know
- 1 Nothing there (determined by sight)
- 2 Nothing there (determined by touch and sight)
- 3 Something there (determined by sight)
- 4 Movable object
- 5 Immovable object
- 6 Robot

> *". . . many functions that are regarded as high-level in humans are performed with great ease by today's computers . . ."*



Professor Block's Monster Game is a self-reproducing model which simulates such properties of biological systems as bilateral symmetry, differential development, growth to adult form, self-reproduction, regeneration and self-repair, individual variations in features (both random and inherited variations with parameters of random variability statistically controlled by the coding of the chips), Mendelian genetics, and linked characters. A Monster is built by stacking two special gene chips at three control sites. These direct the Monster's bilateral growth and its inherited characteristics. The other chips are marked on each side with a letter, a letter preceded by a minus sign, or a blank. Chips may be placed together only when a letter is matched with its negative, K with -K. All letters must be placed in an upright position (indicated by arrow). Because nothing can be matched with it, a blank is automatically growth limiting. Offspring can be built which carry the parental gene characteristics, and the Monster population will demonstrate Mendelian laws of inheritance.

as The Wanderer moves about the room.

Such a robot could also have a built-in "curiosity instinct" so that when it has free time, it would try to see what is in the regions that have "0" entries on the World Map (to update them to a 1 or 3) or to roam about and bump into regions whose entries are 3 (to update them to 4 or 5). Such a machine, after being left to freely explore the room for a while, should be able to follow such commands as "Proceed on the shortest path to 18-A being sure at all times not to bump into anything or to be observable from 3-E." The Wanderer will proceed not by trial and error, but by a plan which through the computer it will determine for itself from the available data. If the data is insufficient, it will ask for permission to get more.

The Wanderer's computer maintains a copy of the World Map in addition to the original. The code numerals in the copy can be manipulated without altering those on the original map. In this way, the robot can answer speculative questions: "If the object at 18-H/19-H were moved to 3-K/3-L, would I be observable from 6-F at any time during my move to Point 12-I?" While the computer is working through the problem, the robot makes no overt movements, nor does it lose touch with reality as indicated by the original World Map. It should also be possible to use the two copies of the World Map to compute "anticipated transformations" of moving objects and in this way begin to deal with some of the problems of perception mentioned earlier.

The World Map gives us a very concrete handle on which to hang the concept of machine "understanding." For example, suppose the code number 7 means that the machine has been told that the region involved contains a movable object. Now, if the machine is told, "there is a movable object in the region of the room corresponding to square 3-E of the World Map" and if the machine then changes the entry in square 3-E of its World Map to code number 7, there is some justification for saying that the machine understood what we meant. If we reword the information or say it in German, and if in each case the machine enters the code number 7 in square 3-E of its World Map, it is reasonable to assert that it understood the meaning in each case. If it does not so update the entry, we can assert that it did *not* understand, no matter how many times it nods, bows, and prints out "I understand, I understand." We hope to develop similar techniques to apply to the problem of machine comprehension of natural languages, starting with word associations and connotations, and moving to such higher abstractions as concepts and analogies.

SELF-REPRODUCTION AND SELF-REPAIR

One of the characteristics of living systems is their ability to reproduce themselves. Von Neumann proved mathematically some years ago that it was possible, in principle, for a machine to do this also. His models were, however, very complex and his theory was not implemented by any hardware. Since then, great progress has been made in the field of molecular biology. A seminal development in this was the Watson-Crick model for DNA which has been extended to include a theory of the production and regulation of enzymes and proteins. These developments suggest that many biological processes soon may be understood in detail. The systems analyst could then build simplified hardware and computer simulator models of such systems for the purpose of eventually producing mechanical models of embryogenesis, which is the process by which a single cell develops into a complex individual with specialized organs. The difficulties encountered by engineers in designing devices to carry out these specific functions are paralleled by currently open questions in biological theory. As the biologist learns the answers to these problems, the systems analyst will be able to build more accurate models. Ultimately, one might hope to use this knowledge to build machines that can "grow" themselves. In particular, the elaborate internal connections required in a computer might be made self-organizing. The telephone system already has an error diagnosis and a self-repair capability in many of its switching circuits. This is another solution to the problem of building reliable systems from unreliable components.

When we understand embryogenic systems more completely, we can "engineer" individuals to desired specifications. The humanists are already bewailing this possibility, but let the Chinese start breeding 12 foot basketball players, or six-armed hockey players, and the stampede will be on.

THE FUTURE WITH ROBOTS

The purpose of all engineering is the fulfillment of human needs. As we learn to imitate biological functions with engineering devices, we increase our capacity for directly assisting the human organism. We are already so accustomed to eye glasses and hearing aids and insulin for diabetics that we almost regard them as a part of our nature. We have, now, the heart-lung machine, artificial kidneys, cardiac pacers, and sensory prosthetics. We will soon be able to control machines by eye movement, or even by mental effort. In the near future we will have bio-technological means for producing food, for eliminating pollution in water and air, for disposing of garbage and sewage, and for stabilizing the biochemical environment of the planet. But in this new world in which computers and robots will have a large role, we humans will have to develop new social goals and generate constructive enthusiasm for a new way of life. The merger of engineering with biology will revolutionize the human condition.

This computer-controlled device amplifies and feeds myoelectric signals from the trapezius muscle in the shoulder to the stimulator located over the paralyzed lower arm muscles thus enabling the patient to open or close his hand. The whole arm is moved by a computer-controlled gas-splint which is activated or halted by eyelid movements.
Courtesy of Case Institute of Technology.

Henry D. Block is Professor of Applied Mathematics in the College of Engineering's Department of Theoretical and Applied Mechanics.

Professor Block received the Bachelor of Science and the Bachelor of Civil Engineering degrees from the City College of New York. He then became an experimental flight test engineer and later a stress analyst for the Goodyear Aircraft Corporation, after which he was an aerodynamicist with the Fairchild Engine and Airplane Corporation. He received both the Master's and the Doctor of Philosophy degrees in mathematics from Iowa State University in 1947 and 1949.

Since then, Mr. Block has had an extensive career in teaching and in academic research. He joined the Cornell Department of Mathematics in 1955 and the Department of Theoretical and Applied Mechanics in 1958, having already taught mathematics at Iowa State University and the University of Minnesota.

Professor Block is a reviewer for Mathematical Reviews, Applied Mechanics Reviews, *and* Computing Reviews. *He is a member of the American Mathematical Society, the Mathematical Association of America, the Institute of Electrical and Electronics Engineers, the New York Academy of Sciences, the American Association for the Advancement of Science, the Society for Industrial and Applied Mathematics, the Association for Computing Machinery, Phi Beta Kappa, Phi Kappa Phi, Pi Mu Epsilon, Tau Beta Pi, and Sigma Xi. Mr. Block is also on the Faculty Board for Cornell United Religious Work (CURW).*

Professor Block and Professor Anil Nerode, of the Department of Mathematics, are coinvestigators in a study of robots which is supported by the Air Force Office of Scientific Research (Grant AF-AFOSR-1013-66) to the Cornell Center for Applied Mathematics.

LIVING CHEMICAL FACTORIES

By Robert K. Finn and Victor H. Edwards

Each living cell is an intricate piece of chemical machinery. Even the simplest bacterium, tiny speck of protoplasm that it is, contains several thousand distinct catalysts which promote individual chemical reactions. The unravelling of this complex cellular chemistry has been a major effort of biologists during the past few decades. These matters are of great interest to chemical engineers as well.

Such life forms as molds, green plants, and mammalian tissues, to all of which the same basic chemistry can be applied, have great engineering potential. On the cellular level, these life forms may be thought of as specialized microorganisms. One of their characteristics is plasticity. This means that by changing the environmental temperature, pH, or nutrient, even a single type of microorganism can be made to produce different chemical compounds. The engineer must have a basic knowledge of biochemistry, microbiology, and colloidal science, therefore, if he is to manipulate properly these "living chemical factories."

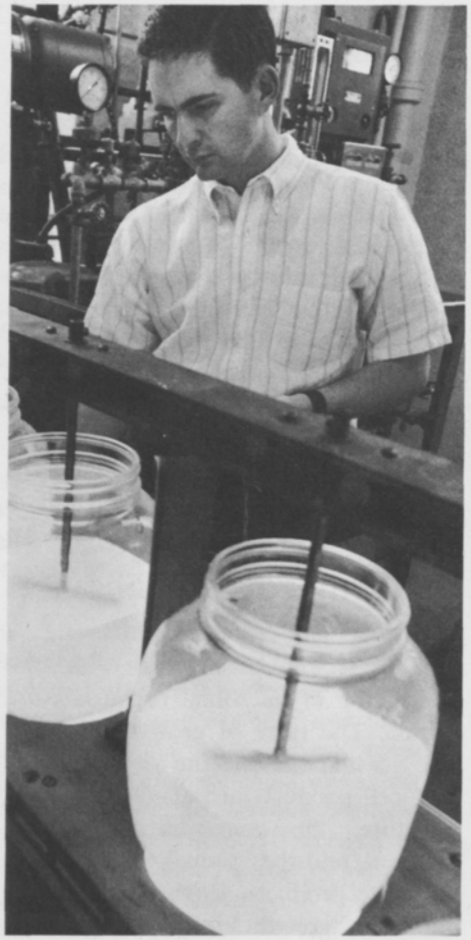
Among the cell products now being manufactured commercially, antibiotics such as penicillin spring to mind immediately, but there are others: enzymes for depolymerizing starch or proteins, organic acids such as citric used in soft drinks and other foods, microbially modified steroids with hormone-like activity, and vitamins such as riboflavin and B-12. Even though vitamin C is chemically synthesized, a key step in the synthesis involves an oxidation by bacteria. Not many years ago a certain amino acid, used as a flavor enhancer, was extracted from beet molasses. Today that route is obsolete, and millions of pounds are produced solely by fermentation. However, some such traditional products of fermentation as industrial alcohol are now chemically synthesized from petroleums which are cheaper than other source materials. But this time-consuming chemical process never will be economical. The lowly microorganisms such as yeasts, molds, and bacteria, work for less pay than do scientists or engineers, and the delicacy of their enzymatic reactions is unmatched by test-tube chemistry.

For the past ten years, Cornell's biochemical engineering efforts have encompassed processing, the development of engineering science procedures, and technology. Research has been directed toward the improvement of large-scale cultures of single cells to produce such products as antibiotics, insecticides, enzymes, and vitamins. Later, it may involve developing antiviral agents to fight the common cold, biological weapons to combat cancer, or proteins to nourish growing children. These and other bioengineering efforts will have great relevance in the future, because it is certain that man will depend increasingly on chemosynthesis by living cells.

GROWTH PROBLEMS IN THE MICROBIAL WORLD

The factors associated with the processing of microbial organisms are varied. The rates of growth of single-cell populations and the yields of cells and cell products are affected by temperature, the concentration of the nutrient, and the gradual accumulation of waste products. Engineering studies on such "growth kinetics" have been

1



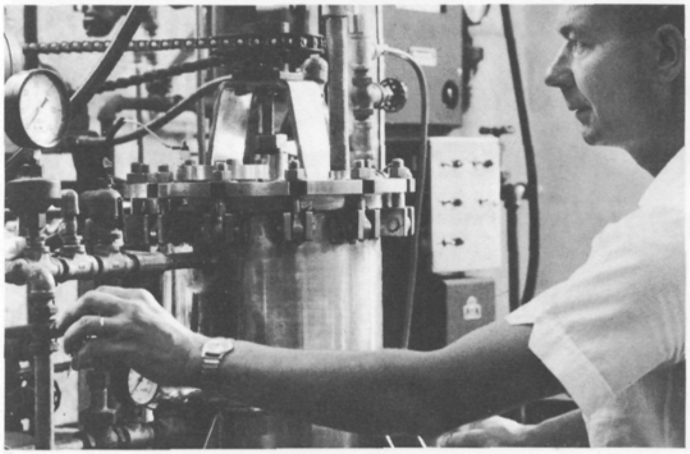
under way for some time at Cornell. The culture of microorganisms in small jars or tanks into which there is a continuous flow of fresh nutrient and from which cells are continuously harvested has been most effective. Studies of the performance of these stirred, aerated, "continuous fermentors" provide basic information on important kinetic parameters. Applied mathematics, biology, and reaction rate theory are brought to bear in such studies.

A major hindrance to rapid and dense production of single cell populations is that the end products of metabolism often slow down the cell growth and suppress the formation of further metabolites. One way to solve that problem would be to extract some of the end products into organic liquids that are not water soluble, thereby removing the suppression. This has been tried using pure paraffin hydrocarbons to draw off end products from cultures of bacteria and yeast.

Not all, but most cells need oxygen to grow. The demand for air is so great that even if the broth in which they are cultivated could be saturated with air, it would contain only a fifteen-second air supply. It is as if the occupants of a tenuously ventilated and crowded room were at all times just four deep breaths away from suffocation. This precarious state of affairs results when yeasts, molds, or bacteria are taken out of their normal environment where they grow sparsely and are submerged in rich liquors where they are induced to produce concentrated amounts of cell substance or particular chemicals. Aqueous solutions normally store little dissolved oxygen, and, under such forced conditions as these, a good oxygen supply can only be maintained by vigorous artificial ventilation.

The engineer is challenged, therefore, not only to study the conventional methods for gas absorption but also to find novel ways for aerating. One trick would be to mimic nature's use of hemoglobin to get oxygen into deeply placed respiring tissues. Unfortunately, hemoglobin itself is not stable in microbial cultures and becomes irreversibly oxidized, thus losing its carrying capacity. Emulsified fluorocarbon, in which oxygen is ten times more soluble than

2



1. A Cornell graduate student tests the flocculation of bacteria in a group of stirred, aerated tanks.

2. Professor Finn works with a forty-liter fermentation pilot plant which is used for the production of cells and enzymes.

it is in water, is now being tested for this use. Little droplets of such an oily material would then be acting as red blood cells to carry and store the life-giving gas.

Closely associated with adequate aeration of cell cultures is adequate agitation. Stirring is necessary to suspend the cells uniformly in the nutrient and must be vigorous enough to provide sufficient aeration. However, some cells, especially animal cells, are easily damaged by overagitation. Therefore, the authors have been studying how the size, shape, and speed of the impeller cause the single-celled animals, protozoa, to rupture. The results of such research are significant not only for the future production of animal tissues in tanks, but also in such diverse fields as sewage treatment, where one result of overagitation is that the flocs of activated sludge fail to settle out properly. This kind of research will be extended to include careful studies on the deformation and rupture of cells when subjected to pure shear (cutting action). Thus, engineering problems often lead directly to what the definition-minded might describe as "biophysics." Also related to this would be the study of the damage done to blood cells when they are pumped through the body's capillaries or through artificial heart machines.

Still another piece of work aimed at gaining a clearer understanding of cell behavior concerns the attachment of cells to surfaces of glass or metal. One outcome has been the finding that such attached yeasts and bacteria can be coated by positively charged colloidal alumina. These "ceramic coated" cells have a number of interesting properties such as resistance to autolysis and an increased tendency to flocculate. The tools of electron microscopy and microelectrophoresis are being used to discover what internal changes are taking place when the negatively charged biological cells are coated with positively charged macromolecules or colloids.

BIOCHEMICAL ENGINEERING

Research at Cornell during the past ten years has also dealt with special techniques for purifying and concentrating biochemicals and other natural products. Special attention has been given to large-scale electrophoresis as a tool for refining antisera and other proteins. Most biological substances are so delicate that they cannot withstand the usual operations of distilling or evaporation; however, their value is so great that exotic techniques which are inappropriate for the treatment of most other chemicals can be and are being seriously considered by imaginative biochemical engineers. The School of Chemical Engineering offers an elective course which deals exclusively with such novel separation methods as ion exchange, dialysis, and electrophoresis.

NEW ENGINEERING SYSTEMS

Basic to the further development of processes and the extension of technology, is the development of engineering science or methods of measurement. In bioengineering, this would involve finding new methods of measuring the state and properties of raw materials, products, or systems; finding new ways of analyzing the relationships between the many variables in engineering

". . . lowly microorganisms . . . work for less pay than do scientists or engineers and the delicacy of their enzymatic reactions is unmatched by test tube chemistry."

This figure illustrates how a microorganism population might change after a batch of sterile nutrient medium is inoculated with a pure culture of some species of microorganism. The growth cycle is divided into a variety of phases which are as follows:

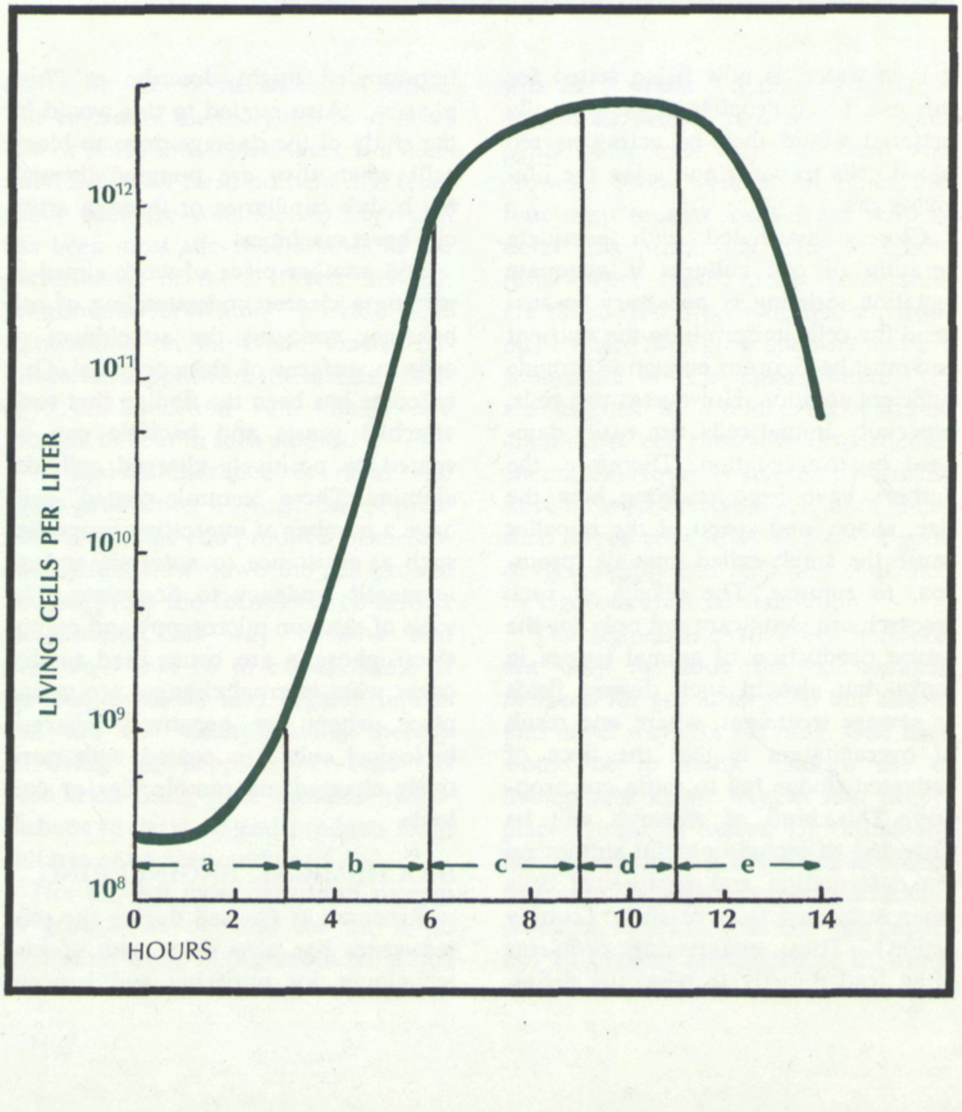
a. *the* lag phase, *in which the cells are not growing at all, or are growing only slowly while accommodating to their new environment*

b. *the* exponential phase, *in which the cell concentration increases exponentially with time. This is a logical consequence of the facts that the cells multiply by binary fission once every twenty minutes, and they multiply at a constant rate in the presence of excess nutrient and in the absence of inhibitory concentrations of toxic products of metabolism*

c. *the* deceleration phase, *in which the shortage of nutrients and/or the accumulation of inhibiting concentrations of toxic metabolites reduces the rate of growth*

d. *the* stationary phase, *in which growth has been stopped by an accumulation of toxic products and/or shortage of essential nutrients*

e. *the* death phase, *in which cells die because of an absence of essential nutrients and/or, the accumulation of toxic metabolic products*



The amount of protein in 1 lb. dried yeast

equals

The amount of protein in 5.5 qts. milk

or 2.3 lbs. beefsteak

or 5.7 lbs. rice

or 23.0 lbs. leafy vegetables

Yeast is already being used as a food and feed supplement. One variety, dried torula yeast, is produced from waste sulfite pulping liquors.

systems; developing techniques for predicting the influence of one group of variables on another; and devising the means to control these variables. Ultimately, this would enable engineers to design processes and equipment that will produce a desired product or effect a particular condition with a minimal expenditure of effort, and with safety. (Effort is usually expressed in terms of cost, which serves as a convenient, if approximate, quantitative measure of social effort.)

The purposes of the many biochemical engineering projects at Cornell are to discover the relationships between fundamental variables in biological systems and to determine rational procedures for designing engineering systems based on these relationships. For example, contrary to the harrowing plots of certain science fiction stories, bacteria or other microorganisms are not likely to engulf the earth, because their growth and metabolism follow laws qualitatively similar to those governing the cells in the human body. A shortage of nutrients or an accumulation of toxic metabolic products in either will inhibit growth and eventually cause the death of the cells. A growing culture of microorganisms with a fixed food supply is faced very soon with the same Malthusian dilemma that the world now faces with the human population explosion and the pollution problems of cities and other sites of intense human activity. The microorganisms too, are affected by overpopulation and pollution or waste accumulation. Therefore, a significant portion of the research at Cornell is designed to discover the quantitative effects of various environmental variables on the metabolism of cultures of cells of a single species. One principal aim is to develop accurate, usable equations to describe these relations. If sufficiently complete, these equations could be used in conjunction with conventional engineering techniques to predict the performance of any natural or artificial device in which cells could play a major chemical role. Our immediate objective is to develop engineering design methods that will make possible the more efficient production of drugs, antibiotics, vitamins, proteins, amino acids, bacterial insecticides, and the host of other microbial products that are needed by our society.

NEW USES FOR MICROORGANISMS

Much exciting research is being done on particular biochemical technologies. One of these is the diversion of chemical or food-processing wastes directly into the natural food chain via the single-cell protein. Presently, waste materials are degraded into carbon dioxide and water. To combat hunger, an increasing world problem, ammonia can be added to these wastes, thus converting them to proteins. At Cornell, researchers are currently investigating cell yields and process economics for converting several industrial wastes. An example of this is the work being done on sulfates.

Sulfates, like carbon-containing materials, often constitute either the impurities that must be removed from a material before it can be processed or the residues from a manufacturing process that must be eliminated in some economical way. And, as in the case of carbon-containing compounds, by-product recovery may also offer immediate eco-

Figure 1

Two processes describing the metabolism of sulfate by sulfate-reducing bacteria

with hydrogen serving as the reducing agent

$$4H_2 + SO_4^{--} \xrightarrow[\text{bacteria}]{\text{sulfate reducing}} S^{--} + 4H_2O$$

with a carbon compound serving as the reducing agent

$$\text{reduced carbon compound} + SO_4^{--} \xrightarrow[\text{bacteria}]{\text{sulfate reducing}} \text{oxidized carbon compound} + S^{--}$$

These processes provide energy for the proliferation of sulfate-reducing bacteria.

nomic advantages. It is desirable to turn this waste sulfur to some useful form rather than to add it to the load of materials that must go through the long natural processes that return them to their native states before man can again use them. In fact, this may prove to be more significant with respect to sulfur than to carbon, because sulfur is becoming increasingly scarce as a commodity, and hence more expensive. The following quotation from *Chemical and Engineering News,* November 6, 1967, states the situation succinctly: "It seems that ultimately sulfur may well progress from a relatively cheap material, which many phosphate fertilizer producers now throw away as waste gypsum, to a relatively scarce chemical of appreciable value that may have to be reserved for priority use by other industries."

Processes through which sulfate-reducing bacteria convert sulfate solutions to sulfide solutions and then to sulfur are known. Figure 1 outlines the conversion of sulfate by these bacteria. Sulfate serves much the same purpose for these bacteria that air does for humans. The bacteria "burn" organics or hydrogen to obtain energy, using the oxygen in sulfate rather than molecular oxygen as humans do. In fact, molecular oxygen is toxic to sulfate-reducing bacteria and they must be grown in its absence. The conversion of sulfate to sulfide by sulfate-reducing bacteria also requires a reducing agent. Either molecular hydrogen or an organic compound serve this purpose for most bacterial strains. The growth of the sulfate-reducing bacteria used in this process requires, in addition to sulfate, sources of carbon (carbon dioxide will often suffice), nitrogen (ammonium ion is usually sufficient), and lesser amounts of various minerals such as phosphorus, magnesium, and calcium.

One of the authors participated in a project at the University of California at Berkeley that was concerned with the removal of sulfates from salt brines by a process which employs sulfate-reducing bacteria. Sulfur is an undesirable impurity in many industrial processes which utilize natural salt brines, rock salt, or solar salt as a starting point for the manufacture of edible salt, chlorine, caustic soda, fresh water from sea water, and a variety of other products. Figure 2 is an outline of this bacterial conversion process. The study showed that the bacterial process was promising only for dilute brines, which are usually found only in the conversion of sea water to fresh water.

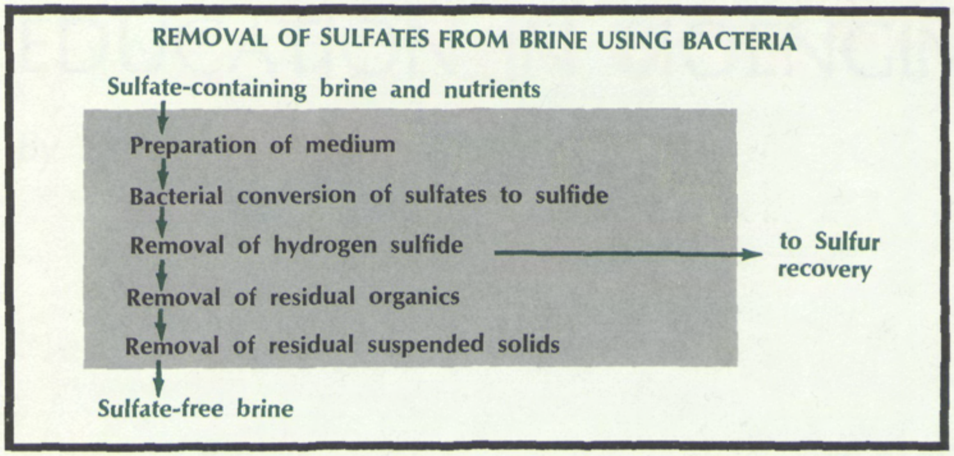
Of perhaps even greater promise is the application of a similar approach to the recovery of sulfur from waste gypsum. The possibility of using sulfate-reducing bacteria to produce sulfur from gypsum has been studied before by workers in England, India, Czechoslovakia, the United States, and other countries. At Cornell, studies are proceeding on several novel recovery methods that could make gypsum a more economical source of sulfur than it presently is. If the search for new deposits of elemental sulfur continues to be unsuccessful, processes which start with sources other than sulfur itself must fill the widening gap between supply and demand.

BIOCHEMICAL ENGINEERING A TOTAL APPROACH

Biochemical engineering requires of each researcher a one-person interdisciplinary effort. One example of a research area requiring such an approach is the design of biological waste treatment systems. Here the researcher is faced with a more than usually complicated case of many species of microorganisms growing in competition, cooperation, or independence in a liquid, semi-solid, or other physical state. Another and related example is the influence of drugs and other envi-

Shown opposite is Professor Edwards teaching a biochemical engineering course.

Figure 2



ronmental factors on the proliferation of a pathogenic organism in an infected human or animal. Much significant research has already been done on waste treatment by sanitary engineers and microbiologists and on environmental factors by pharmacologists, medical doctors, physiologists, biochemists, and microbiologists. Naturally, microbiologists, biochemists, physiologists, and other scientists were among the first to investigate cell growth and proliferation for its own sake and have contributed in many ways to the understanding of this subject. Their research often bears directly on engineering work.

The engineer who wishes to learn more about cell growth and proliferation is faced with the time-consuming task of learning the special languages used in the various disciplines to describe different problems. After collecting pertinent information from these disciplines, he synthesizes it in order to understand and to solve the research problem he has undertaken. This is a difficult task, particularly because techniques and philosophies vary greatly among disciplines. However, this method of attacking problems that span divergent fields can also be very valuable for finding "total" solutions. When fundamental principles and techniques in which he has been trained are applied to situations quite different from those with which he is familiar, the chemical engineer is challenged to develop a much more thorough understanding of his own field and its limitations. From any standpoint, further cooperation and exchange of information among the different branches of science, engineering, and medicine can serve only the good of all by bringing diverse techniques to bear on common biological problems.

OUTLOOK

The coming age will be one of biology. The world population is expected to double by the year 2000. Not three, but six billion people will have to be fed, kept healthy, and given freedom to recreate in a clean environment. Certainly, in that world, people will depend more and more on the biological activity of complex molecules. As the quality of the world's fossil mineral ores declines, mankind will look to biological systems to help wrest minerals from such reservoirs as the sea. Not only single cells but tissues and entire organs will be artificially cultivated. Engineers will have a role in making genetic manipulation possible. Life-support systems will be commonplace, not only in space, but underwater as well. Pigments, drugs, and flavors from the higher plants will one day be produced not by the harvesting of whole plants but by the selective growth of specialized tissues. Industrial rather than agricultural equipment will be used to grow, harvest, and refine.

These are just a few of the bright possibilities. Engineers qualified in physics and mathematics and in chemistry and biology as well, will help provide more livable conditions for society in the next century.

Robert K. Finn, Professor of Chemical Engineering, took both the Bachelor and the Master of Chemical Engineering degrees from Cornell in 1941 and 1942. He then worked for four years as a research engineer for Merck and Company, Incorporated, on recovery processes for antibiotics before returning to graduate school at the University of Minnesota where he took the Doctor of Philosophy degree in 1949.

After taking the doctorate, Professor Finn taught at the University of Illinois where he established a program of teaching and research in bioengineering within the Chemical Engineering Division. During that time, he consulted for the Commercial Solvents Corporation and the VioBin Corp. In 1955 he joined the faculty at Cornell where his principal interests have been continuous culture of microorganisms and the engineering problems of aeration and agitation. He now consults for the International Minerals & Chemical Corp.

Professor Finn was a delegate to the First International Fermentation Symposium in Rome, in 1960, and spent the academic year 1961–62 in Stuttgart, Germany, as a Fulbright Research Professor.

He is a member of the Program Committee for the American Institute of Chemical Engineers; is former chairman of the Division of Microbial Chemistry and Technology of the American Chemical Society; was Symposium cochairman at the Seventh Microbial Congress, Stockholm, 1958, for the American Society of Microbiologists; and is a Fellow of the American Association for the Advancement of Science.

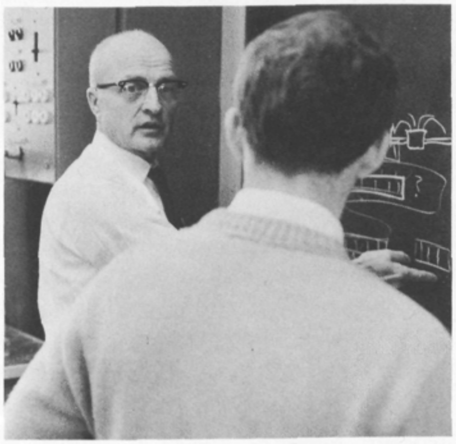
Victor H. Edwards, Assistant Professor of Chemical Engineering, came to Cornell in the autumn of 1967 from the University of California at Berkeley where he took the doctoral degree, and where he worked at their Lawrence Radiation Laboratory doing engineering analysis of the growth kinetics of sulfate-reducing bacteria. He took the Bachelor of Arts degree in 1962 from Rice University.

Professor Edwards has had wide-ranging industrial experience working for the Forest Products Laboratory of the University of California Richmond Field Station, the Shell Chemical Company, the Humble Oil & Refining Company, and the Union Carbide Corporation.

He is a member of the American Institute of Chemical Engineers, the American Chemical Society, the Society for Industrial Microbiology, Phi Lambda Upsilon, and Sigma Tau.

EDUCATION IN BIOENGINEERING

By Nelson H. Bryant



Engineering has always been concerned with planning for human needs and with improving the human environment, therefore, the expansion of the field of engineering to include work in the life sciences is a logical development. In the broad areas of medicine, biology, and physiology, there are many problems of a technical nature that are best treated by engineers. For example, in the development of prostheses an analytical understanding of motion and force is required in order to build artificial limbs that can be externally powered by small electric or pneumatic motors and by hydraulic devices which in turn are controlled by the body's own nerve impulses.

Great as the contribution of engineering is to the hardware requirements of the various biological fields, its insights and procedures are of equal importance. These contributions present perhaps the greatest opportunity for engineering and the physical sciences to join forces with the life sciences.

OPPORTUNITIES IN BIOENGINEERING

Although bioengineering has been spoken of as a separate entity only in recent years, research combining engineering and biology has been carried on for some time by individuals who were interested in applying engineering techniques to medical and biological problems. Many of them have done significant work. The late Professor C. L. Cottrell of the Cornell School of Electrical Engineering was working on biological problems thirty years ago. He made optical studies of muscle tissue, developed counter-circuits for some of the early radioactive tracer studies, and assisted biologists in making measurements of the electrical voltage of cells with respect to their external environment. More recently, another Cornell professor, the late W. C. Ballard, worked with doctors at the Cornell Medical College to develop a better means of determining the coagulative properties of blood based on electrical conductivity measurements. Now that bioengineering as a separate endeavor has come of age, far more engineers are absorbed in it.

This coming of age is also reflected in the growing number of engineering colleges throughout the United States which offer programs in bioengineering. Some of the programs lead to the Bachelor's, Master's, or doctoral degrees; others are bioengineering options within traditional undergraduate engineering programs. Some universities have centers for biomedical engineering, for environmental engineering, and for sensory communication. General interest in this field is also reflected in some of the summer short courses offered by various colleges of engineering—for example, "Systems Aspects of Bioengineering," "Physiological Systems Analysis," "Biotelemetry," and "Computers in Biology and Medicine."

THE ENGINEER AND BIOLOGICAL FRONTIERS

The skills and knowledge gained from combining the study of engineering and biology seem most readily applicable in the field of medicine, especially in the development of instruments. And, although the bioengineers' contributions to that field are vitally important, the engineering student of today who is interested in the life sciences has a much broader range of activities from which to choose. For example, he could become interested in such matters as controlling the human environment in space vehicles. Presently, engineers are utilizing aerobic bacteria to decompose passenger wastes. The wastes are then combined with carbon dioxide from human respiration and nitrogen and are used to grow cultures of algae. The algae, in turn, produce oxygen by photosynthesis for breathing. The success of the entire cycle depends upon the maintenance of a delicate balance among such processes as waste treatment, gas exchange, food growth, and water production, all of which are traditional engineering concerns.

The engineering student who is interested in the life sciences might find a meaningful professional outlet in the application of operations research to, for instance, hospital administration. Many hospital functions can be automated as readily as can industrial functions.

Shown here are two students of electrical engineering whose Master's thesis work requires the development of a video system to be used with a density-specific photometer. This device will aid researchers in differentiating and counting white blood cells. Their research is partially supported by the Virus Leukemia Research Grant of the New York State Veterinary College at Cornell.

Or, such a student might become interested in the development of man-machine systems in which it is necessary to consider such factors as the human attention span, physical make-up, psychological reactions, etc. in order to determine what combination of man and machine will result in the best performance. He would work closely with psychologists to answer such questions as how the machine should be designed, and what information should be given the operator (and how it should be given) during the work process. Many avenues of research are open to the bioengineer. By studying biological systems and representing their functions with analogues from the physical sciences, it is possible to formulate mathematical models of the biological systems. Thus, it may be possible, by electronic means, to stimulate visual patterns in the brain of a blind person and to restore his sight. This is a projection into the future but the basic questions—what

should be measured and how—must first be answered. Systems analysis has great promise as a research tool in this work.

COURSES OF STUDY

Although a few schools offer undergraduate degree programs in bioengineering, most offer only modifications of programs in some of the traditional engineering fields. These programs allow undergraduate engineers who are interested in biology to sample it before deciding whether to go on for graduate work in bioengineering.

Bioengineering education is, therefore, concentrated at the graduate level. At least forty colleges in the United States offer advanced degrees in biomedical engineering or bioengineering. In 1966, fifteen schools received grants from the National Institutes of Health for the support of graduate training programs in biomedical engineering. Most of these programs are offered through the engineering departments of the various schools, and most of them require a Bachelor's degree in engineering for admission. Occasionally a premedical student or one who majored in the biological sciences will be admitted to these programs. Such a student must first strengthen his background in mathematics and the physical sciences, whereas the engineer will need to strengthen his background in biology and perhaps chemistry.

Because of the engineer's lack of training in biology, it is difficult to develop a meaningful one-year Master's program in bioengineering. As a result, most require one-and-a-half to two years for completion. Obtaining a Ph.D. in this field may require from four to six years. Admittedly, earning a Ph.D. in any field may require four to six years, but in bioengineering this is almost a certainty.

Even the engineer who enters graduate school with some background in biology and organic chemistry faces the problem of combining biology and engineering into something that can be truly considered bioengineering. He must consider how he can best apply his skills in such areas as measurement, signal analysis, mechanics, transport phenomena, information processing, control theory, or energy conversion to such biological systems as the nervous, cardiovascular, respiratory, endocrine, muscular, and skeletal. If he were to simply take courses in biology, he would fail to make much use of his engineering skills. Therefore, it is necessary that the biology courses in these graduate-level bioengineering programs be designed especially for engineers, or at least be taught by engineering-directed biologists.

At present, Cornell has no formal program in bioengineering. The freedom that is provided by the undergraduate College Program in engineering, together with the general freedom allowed a graduate student and his advisory committee in working out his course and research program, have made the need for a formal bioengineering curriculum much less urgent than it is at some other schools.

At Cornell, engineering students who are interested in some phase of biology, fit into one of two categories: those who plan to go to medical school and those who plan to use their training in one of the numerous bioengineering areas. For both, careful program planning is essential. For the first, satisfying the medical school entrance requirements is paramount; for the second, priority goes to obtaining a sound engineering background.

UNDERGRADUATE ALTERNATIVES AT CORNELL

An undergraduate engineering student at Cornell who is interested in biology or medicine can follow either of two plans: he can enroll in one of the traditional engineering Field Programs, for example, electrical engineering or chemical engineering, and use his elective time to take courses in biological sciences; or he can enroll in the College Program. A student in the College Program, with advice from a committee of selected faculty members, plans his own course of study so that he will fulfill the basic engineering science requirements; majors in one of the traditional areas of engineering, taking perhaps half the course work taken by those who major in the field alone; and devotes the rest of his time to courses in biology, organic chemistry, and other relevant subjects. Thus, a student who is interested in medical engineering might take courses in anatomy and physiology; a student who is interested in food production might take bacteriology and microbiology.

In practice, the difference between Cornell's Field Program and College Program has not been as great as might have been expected. Most College Program students who are interested in biology feel that they must have strong backgrounds in their major engineering fields to avoid being "neither fish nor fowl"—neither engineer nor biologist. But they also feel that they must get more than the minimal amount of biology; they usually take extra courses and attend summer sessions in order to obtain a sound preparation in both areas.

Several undergraduates who have been interested in bioengineering have found learning and professional opportunities in the Engineering Cooperative Program. One of the cooperating industries, the Sanborn Division of Hewlett-Packard, has employed two Cornell students in its medical instrument design department. Further, during their sessions spent in industry, the Co-op students often have the opportunity to take a course or two in an area night school, and for some this has been the opportunity to do the necessary extra work in biology and chemistry.

GRADUATE AND PROFESSIONAL WORK

Several paths are open to a student after he receives his Bachelor's degree. Many of Cornell's bioengineering students have gone to medical school. They are more research-oriented than typical medical school graduates, and, as one might expect, a higher percentage of them eventually enter medical research.

Many engineering graduates wish to go to a graduate school that has a formal program in bioengineering. Of those who enroll for graduate study at Cornell, a few become so involved in biology that they ultimately choose a major subject in the biological

"Great as is the contribution of engineering to the hardware requirements of the various biological fields, its contributions of insights and procedures are of equal importance."

sciences. Usually, however, a student will choose his major from one of the engineering Fields, a minor from some area of biology, and do his research on some subject related to biology. The following theses titles are indicative of the kinds of research being done by graduate students at Cornell: "The Spinal Electrogram in Decerebrate and Deafferented Cats," "A Rapid-Scanning Spectrophotometer for Biological Materials," "Input-Output Relations of a Slowly Adapting Mechanoreceptor Found in the Skin of a Cat," and "Non-Parametric Learning Control."

Some of those now working in engineering-medical areas have an academic background which is purely engineering. Mr. Wilson Greatbatch, a Cornell graduate who took his degree in electrical engineering in 1950, is an outstanding example. His firm, Mennon-Greatbatch Electronics, Incorporated, in Clarence, New York, develops and manufactures intensive-care monitoring equipment and cardiac pacemakers. He works closely with medical doctors in developing this equipment, each member of the team contributing knowledge from his area of specialty. Although he appears to have an extensive knowledge of medicine, Mr. Greatbatch maintains that he is in no sense a medical authority and that his contributions in this field are entirely technological in nature.

BIOENGINEERING, A CHANGING FIELD

The cooperation between engineers and biologists began when biology ceased to be so much a descriptive science and became a precise one requiring the tools of mathematics and technology. As the field of bioengineering evolves, its research and educational programs are often not clear-cut. Work in bioengineering is being pursued throughout the country by small groups whose members have different scientific and technical specialities but who are working toward a common goal. To keep pace with such an unstructured and fluctuating field, educational programs of great flexibility will be required.

Nelson H. Bryant is a Cornellian who took both the Bachelor of Electrical Engineering and the Master of Electrical Engineering degrees from this University.

After obtaining the Bachelor's degree in 1939, he worked for the Westinghouse Electric Company as a lamp development engineer, then became an electronics officer in the United States Naval Reserve from 1944 to 1946.

While working toward the Master's degree, he was an instructor in Cornell's School of Electrical Engineering. After taking the degree, he became Assistant Professor, and in 1954 became an Associate Professor of Electrical Engineering.

Professor Bryant is one of several faculty members interested in bioengineering. His research has concerned instrumentation for measuring the oxygen uptake of living tissues and optical studies relating to metabolism. He is also interested in the development of course curricula for the emerging field of bioengineering.

Mr. Bryant is a member of the American Institute of Electrical and Electronics Engineers, Eta Kappa Nu, and Tau Beta Pi and is a member of the Faculty Advisory Committee for ENGINEERING: Cornell Quarterly.

ECOLOGY: KEY TO WATER QUALITY MANAGEMENT

By Alonzo Wm. Lawrence

"Water, water, everywhere, nor any drop to drink," describes the plight of Samuel Taylor Coleridge's Ancient Mariner. Add to this "nor any water to swim in, fish in, or to enjoy" and we have a succinct description of a growing number of American towns and cities whose lakes, streams, and estuaries are polluted.

Wastes from home and factory, drainage from chemically fertilized farm lands, heated industrial cooling waters, and silt erroded from lands which are stripped of vegetation, all contribute to the degradation of our natural waters. When we consider the nation's water needs for tomorrow, or for the year 2000, we must consider *both quantity and quality*.

ECOLOGY AND ENGINEERING

The study of the cause and effect relationships between living things and their environment, *ecology,* provides the basis for what is probably the only logical approach to environmental quality protection. This approach necessitates examination of the total biotic (plant and animal) and environmental response of a natural system to the stress imposed by pollution.

Those responsible for water quality management, sanitary engineers, must have a thorough understanding of the natural aquatic environment. These specialists are also involved with the treatment of water and wastewater (water quality control engineering) and water supply development. They must also be knowledgeable in the engineering sciences as well as in biochemistry, microbiology, chemistry, limnology (the study of freshwater bodies), ecology, and oceanography.

Prior to the 1920's, the sanitary engineer was primarily concerned with providing bacteriologically pure public water supplies through the destruction of water-borne microorganisms which caused disease. While he is still concerned with these matters, he is now equally concerned with the common "garden variety" microorganisms which are widely distributed in the natural environment.

Knowing the numbers and types of the common microorganisms to be found in a particular body of water significantly helps the sanitary engineer to foresee pollution problems. Further, this knowledge enables him to detect the indirect responses of natural aquatic systems to such engineering projects as draining swamps and dredging channels. These secondary responses, too often overlooked by project designers, can cause a deterioration in water quality which will negate or greatly compromise the original project goals.

Damming a stream, for example, causes increased water loss through evaporation, and also causes a reduction in the quantity of suspended material in the water because in the quiescent conditions of impoundment, this material settles to the bottom. The designers of the dam probably would anticipate that impoundment-induced reduction in suspended load would increase the potential for erosion of the downstream channel. However, a second, and less apparent, consequence of impoundment is that the released water may support considerably more algal growth than would be found in similar unimpounded water. Two factors speed this growth: the greater penetration of light into the water owing to the reduction of suspended materials, and the evaporation-induced concentration of plant nutrients.

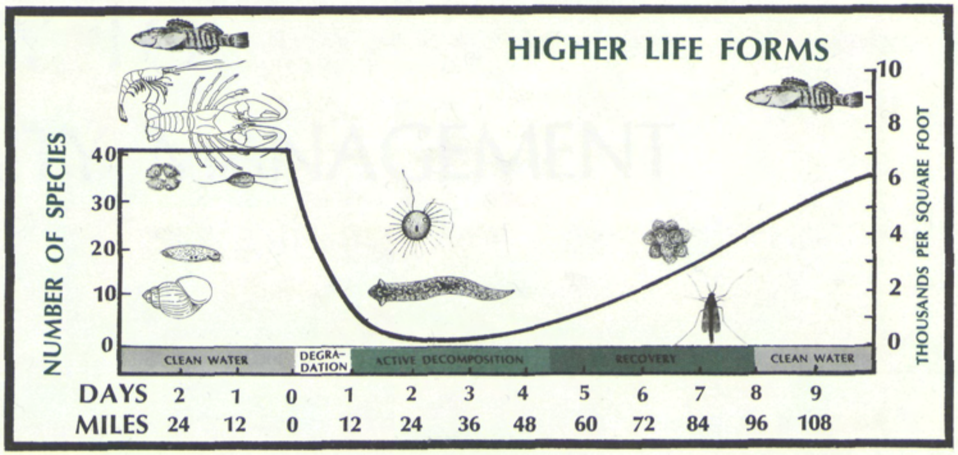
To produce a desired water quality in lake, stream, or estuary, the sanitary engineer must (1) outline the ecological situation in a given body of water, (2) formulate and implement an optimal water quality control program, and (3) continually reassess the adequacy of the program in terms of future ecological changes. This process may be called "ecological engineering," and its basis is the ecology of the aquatic environment.

AQUATIC ECOLOGY

Natural bodies of water are dynamic systems because of the constant interplay of physical, chemical, and biological forces. Gravity, thermal density gradients, and the action of winds promote or retard circulation and/or translation of the water mass. Chemical oxidation, reduction, precipitation, and dissolution change the composition of materials dissolved in the water. Such chemical changes may also affect the pH of the water. The biochemical transformations effected by flora and fauna are of particular interest in pollution control and water management.

The biological community in a lake, stream, or estuary includes bacteria, algae, protozoa, crustaceans, rooted aquatic plants, bottom-dwelling animals, and fish. Because bacteria and algae usually are responsible for the significant pollution-induced changes in water quality, these organisms receive the engineer's greatest attention. But, in maintaining the *balance* in an aquatic ecosystem, each form of life is important.

A stable ecosystem is characterized by a wide variety of life forms with relatively low numbers in each species. In a "clean" stream or deep mountain lake, the small floating plants, phytoplankton, feed on dissolved organic and inorganic compounds. These compounds enter the water via decayed plant and animal matter and the leaching of rocks and soil. Small floating animals, zooplankton, feed on phytoplankton and on each other. The planktonic community in turn, serves as food



As stream conditions worsen, fewer and fewer forms of aquatic life are able to survive. The more desirable fish species are the first to disappear from polluted waters.
Courtesy of Public Works Publications.

for crustacea and herbivorous fish which, in turn, serve as food for larger carnivorous fish such as trout and bass. This food chain is an integral part of nature's balancing mechanism.

The biological activity in a natural body of water is directly related to the type and concentration of primary nutrients present. The primary nutrients required for plant and animal growth are carbon, hydrogen, oxygen, sulfur, potassium, calcium, magnesium, nitrogen, and phosphorus. According to Liebig's "Law of the Minimum," *growth of a given species of organism will be limited by the availability of that growth nutrient present in the smallest quantity.* For bacteria, the limiting nutrients usually are organic carbon compounds; for algae, the limiting nutrients are nitrogen and phosphorus. When nutrients in the form of waste materials enter any balanced aquatic ecosystem, the equilibrium is upset. The increased availability of nutrients stimulates the growth of either bacteria or algae. It follows that the increased growth of one group of organisms in a food chain will sequentially stimulate the growth of other members. Thus, pollution might actually increase the number of fish present in a stream! However, the rapid and uncontrolled growth of bacteria and/or algae which usually accompanies pollution, changes the water quality in ways that are harmful to higher forms of life and precludes the survival, much less the proliferation, of many desirable fish species.

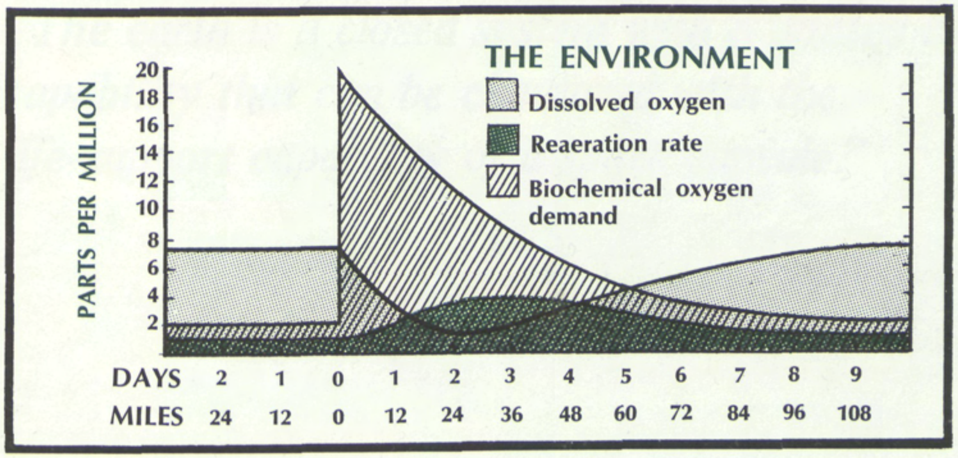
There are three major categories of pollutants: (1) oxygen demanding substances, (2) plant nutrients, and (3) heat and toxic materials.

OXYGEN DEMANDING SUBSTANCES

Oxygen is essential for the preservation of most forms of aquatic and terrestrial life, the only exceptions being those species of bacteria which require an oxygen-free environment. Aquatic organisms utilize oxygen which is dissolved in water. Because oxygen is only slightly soluble, it is not readily stored in water and must be replenished at essentially the same rate at which it is used. In unpolluted water, the rate of oxygen utilization by the biota is low and a near saturation concentration of dissolved oxygen is maintained by atmospheric reaeration which is the diffusion of atmospheric oxygen across the air-water interface and the subsequent turbulent dispersion of oxygen throughout the water. The atmospheric reaeration rate increases as the concentration of dissolved oxygen decreases.

The introduction of organic pollution stimulates bacterial growth and causes a corresponding increase in the oxygen utilization rate. This increased oxygen utilization will continue until the organic food supply is exhausted. If the discharge of organic waste into the water is continual, a new equilibrium between bacterial activity and rate of oxygen utilization will be established. Oxygen utilization by bacteria and associated microfauna during assimilation of organic waste materials is termed Biochemical Oxygen Demand (BOD), and is commonly used as an indirect measurement of the concentration of organic compounds present in a wastewater.

If the accelerated oxygen utilization rate exceeds the atmospheric reaeration



When the dissolved oxygen concentration of a stream is reduced by pollution, the reaeration rate rises to compensate. The graph shows the number of days and number of miles along a stream that are generally associated with each stage of oxygen depletion and recovery.
Courtesy of Public Works Publications.

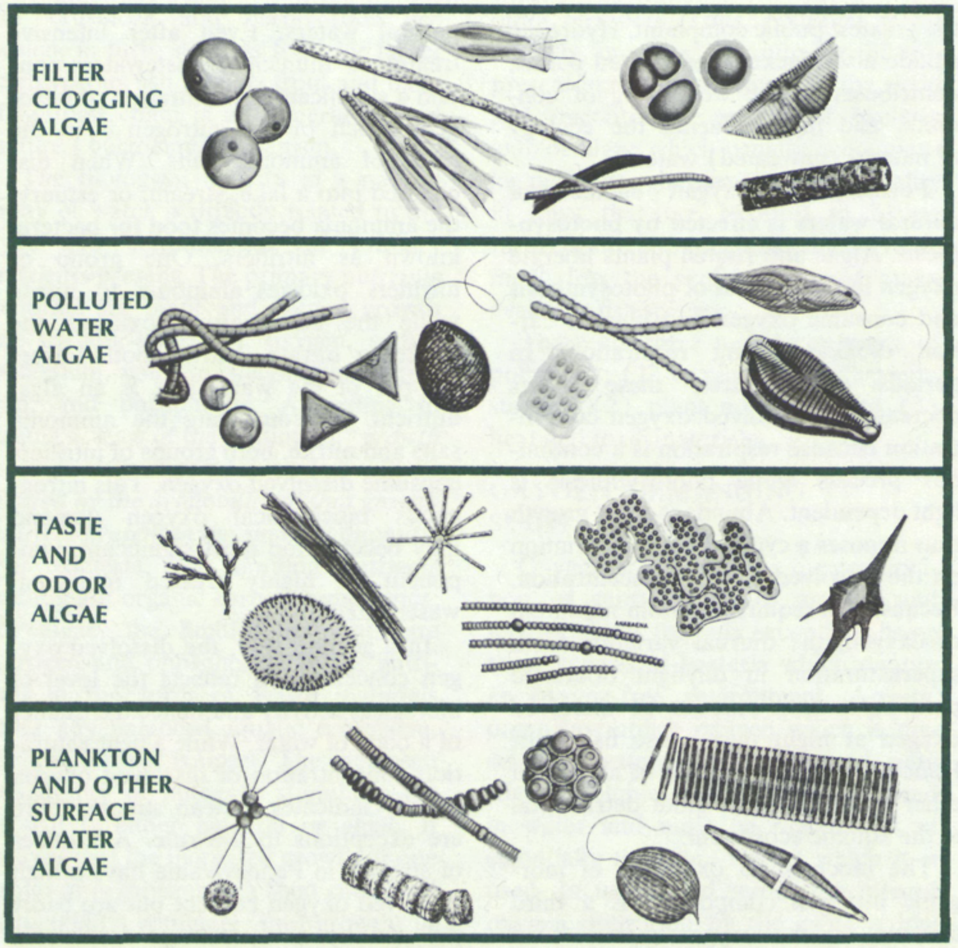
rate, the concentration of dissolved oxygen remaining in the water changes in one of the following ways: (1) the dissolved oxygen concentration will decrease until the organic material is consumed and then gradually increase toward its previous level; (2) if there is continual waste discharge, the dissolved oxygen concentration will decrease to a point where a new steady state dissolved oxygen concentration can be established, and the oxygen utilization rate equals the reaeration rate, or (3) the oxygen concentration will decrease to zero when the oxygen utilization rate exceeds the maximum rate of atmospheric reaeration. When the oxygen level drops, various species are unable to survive. Game fish, such as trout, are the first to disappear. If the dissolved oxygen concentration reaches zero, the system is anaerobic.

Under anaerobic conditions, bacteria produce methane and hydrogen sulfide gases and undesirable organic compounds which impart tastes and odors to the water. Hydrogen sulfide gas has a particularly noxious odor and is the aspect of polluted water which causes the greatest public complaint. Hydrogen sulfide also blackens lead-based paints, contributes to the weakening of concrete, and may influence the ecology of natural (untreated) waters.

Further, the oxygen balance of natural waters is affected by photosynthesis. Algae and rooted plants liberate oxygen in the process of photosynthesis and consume oxygen and liberate carbon dioxide during respiration. In periods of darkness, these plants decrease the dissolved oxygen concentration because respiration is a continuous process while photosynthesis is light dependent. Abundant plant growth thus imposes a cyclical diurnal variation on the dissolved oxygen concentration. Because fish require a certain minimum of oxygen, the diurnal variation from supersaturation in daylight hours to perhaps a zero amount of dissolved oxygen at night may cause fish kills. Hence, an overabundance of algae and other plants may be quite detrimental to the aquatic ecosystem.

The biochemical oxidation of inorganic nitrogen compounds is a third demand on the oxygen resources of natural waters. Even after intensive treatment, municipal wastewaters contain a significant concentration of nitrogen. Much of this nitrogen is in the form of ammonia salts. When discharged into a lake, stream, or estuary, the ammonia becomes food for bacteria known as nitrifiers. One group of nitrifiers oxidizes ammonia to nitrite while the other group oxidizes the nitrite to nitrate. Nitrate both lowers the pH of the water and is an algal nutrient. In converting the ammonia salts and nitrite, both groups of nitrifiers consume dissolved oxygen. This nitrogenous biochemical oxygen demand may become the most significant component of highly treated municipal wastewaters.

In a general way, the dissolved oxygen concentration reflects the level of biological activity and hence the quality of a body of water. While a near saturation concentration of dissolved oxygen usually indicates a clean stream, there are exceptions to the rule. A number of streams in Pennsylvania have a high dissolved oxygen content but are badly polluted by acid drainage from coal



mines. This drainage lowers the pH of the waters to levels that are intolerable for oxygen-using forms of life. Therefore, though oxygen measurements may be useful, they cannot substitute for a more complete ecological evaluation.

PLANT NUTRIENTS

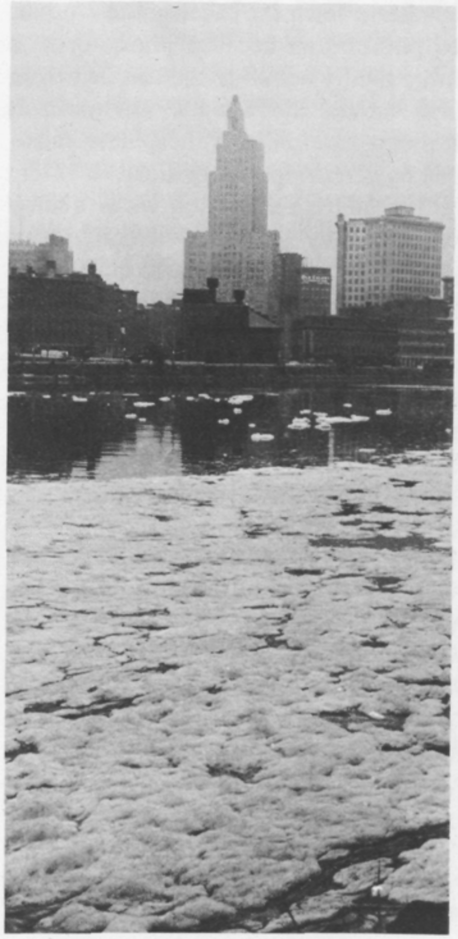
Large quantities of nitrogen and phosphorus, the two most important plant nutrients, enter our natural waters as a consequence of man's activities. These nutrients stimulate an overabundant growth of aquatic plants, both the rooted plants which inhabit shallow areas and the free-floating, planktonic forms. Generally speaking, the effects of increased plant production are undesirable. In "unpolluted" waters, the concentrations of nitrogen and phosphorus usually do not exceed 0.1 milligrams per liter (0.8 pounds per million gallons) for phosphate phosphorus, and 0.5 milligrams per liter (4.2 pounds per million gallons) for nitrate nitrogen. At such low concentrations, nitrogen and phosphorus will be the growth limiting nutrients since sunlight and carbon dioxide, the other major growth require-

> *"The earth is a closed system with a limited life-support capability that can be compared with the life-support capability of a space capsule."*

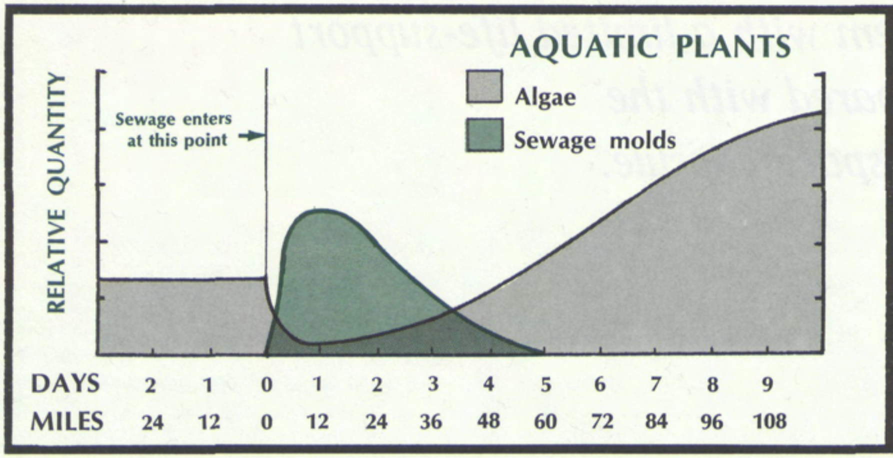
ments, are present in more than sufficient amounts. The effect of adding nitrogen and phosphorus to such waters is analogous to adding fertilizer to a field.

Municipal wastewaters are rich in nitrogen and phosphorus. Even after treatment, wastewaters may contain up to 20 milligrams of nitrogen per liter and 15 milligrams of phosphorus per liter. The magnitude of these concentrations is striking when compared to concentrations for natural waters cited above. Up to 50 percent of the phosphorus in municipal wastewaters is contributed by household detergents which contain 20 to 30 percent by weight of phosphorus compounds. Phosphorus is not a cleansing agent but a base or builder. With the annual consumption of detergents approaching 4 billion pounds per year in the United States, detergent phosphorus is rapidly becoming a significant water pollution problem. This problem should not be confused with an earlier detergent problem in which the organic compounds responsible for the cleansing action were not completely degraded or assimilated by bacteria in either wastewater treatment plants or natural waters. This accumulation of nonbiodegradable detergent material led to the production of foam which often covered streams to a depth of several feet. Detergent foaming is no longer a problem because all detergent manufactured in the United States today is biodegradable. Thus, a major industry has had to change its product to adapt to the bacteria process. Perhaps someday we shall see commercials advertising biodegradable and phosphorus-free detergents.

Modern agricultural activities are a second source of nitrogen and phosphorus in natural waters. Little information is available concerning the quantity of nutrients contributed by chemical fertilization of fields, but it is thought that the amount of nitrogen



Undegraded detergent foam as seen in 1962 on the Providence River, Providence, Rhode Island.
Courtesy of the *Providence Journal.*



FACTORS AFFECTING GROWTH OF

▨ **Algae** 🟩 **Sewage molds**

▨ **Light**

🟩 **Organic food**

▨ **Materials for making food**

◩ 🟩 **Dissolved oxygen**

▨ 🟩 **Suitable temperature range**

in nitrate form far exceeds the amount of phosphorus because phosphorus is more tightly bound to the soil. Nitrogen also enters the aquatic environment through fixation of atmospheric nitrogen by certain species of algae.

The adverse effects on water quality which result from the overabundant production of aquatic plants include the previously mentioned effect of photosynthesis on the oxygen resource and the release of undesirable compounds into the water following the death of algal cells. Some of these compounds are toxic to livestock and cause fish kills; others impart undesirable tastes and odors to the water. Removing these unpleasant tastes and odors increases water purification costs as does the reduced efficiency of algae-clogged water purification equipment.

Finally, the debris from floating and rooted plants contributes to the slow but inevitable filling-in and ultimate disappearance of lakes. This natural aging or dying is called eutrophication and it is greatly accelerated by nutrient addition. Eutrophication is, therefore, the most dramatic consequence of overfertilization of the aquatic environment.

HEAT AND TOXIC MATERIALS

The discharge of heated cooling waters from thermal electric power generating stations and other industries causes significant temperature changes in lakes, streams, and estuaries. Because the rate of biological growth is temperature dependent, these temperature increases accelerate the rate at which nutrient materials are assimilated and accelerate the concommitant utilization of dissolved oxygen. Accelerated oxygen depletion, coupled with reduced oxygen solubility at higher temperatures, can create a critical dissolved oxygen problem where none previously existed. Because many species of plants and fish are temperature sensitive, increase in water temperature may cause a shift in a water's flora-fauna composition from cold to warm water species. Spawning and migration are temperature controlled; thus abnormal changes in water temperature disrupt the life cycle of fish. Trout, for example, leave areas where the water temperatures rise above 60° F.

Some people contend that the discharge of heated cooling waters will have the beneficial effect of increasing the growth of fish food and minimizing the ice cover in cold water areas. The pros and cons of heated cooling water discharges have a special relevance for the Cornell community because a nuclear fueled thermal electric power generating station is slated for construction on Cayuga Lake. This facility will draw nearly 720 million gallons of cooling water per day from the Lake. The water will be put back into the Lake at a temperature approximately 25° F. higher than the temperature at which it was withdrawn. The change or lack of change that heated cooling water will induce in Cayuga Lake is largely a matter of speculation. It is hoped that an ecological study will precede the installation of the power station.

Toxic materials such as pesticides and other exotic chemicals can produce dramatic changes in the aquatic ecosystem. Each year, numerous fish kills are caused by the discharge of toxic materials. Several million fish were killed in the Mississippi River by the

Sludge deposits are most dense at points where sewage enters a stream. These deposits are reduced by molds, bacteria, and other organisms. As the amount of sludge is lessened and as the water becomes cleaner, greater amounts of algal life can be found. The chart shows the number of days and miles along a stream associated with the stages of pollution and recovery.

Courtesy of Public Works Publications.

accidental discharge of the organic pesticide Endrin. Metals such as copper and zinc, which are required in plant and animal metabolism in trace amounts, cause toxicity or death in higher concentrations. The list of toxic substances is long and includes copper, zinc, nickel, hexavalent chromium, cyanides, pesticides, and numerous petrochemicals. Extremes of pH will also cause a toxic response in most aquatic species.

CASE STUDIES

The activities to reduce water pollution on Lake Erie and the Delaware River are prime examples of the application of ecological information. Lake Erie is a classic example of pollution-intensified eutrophication, and the Delaware River is an outstanding example of "ecological engineering" applied to water quality management of a major watershed.

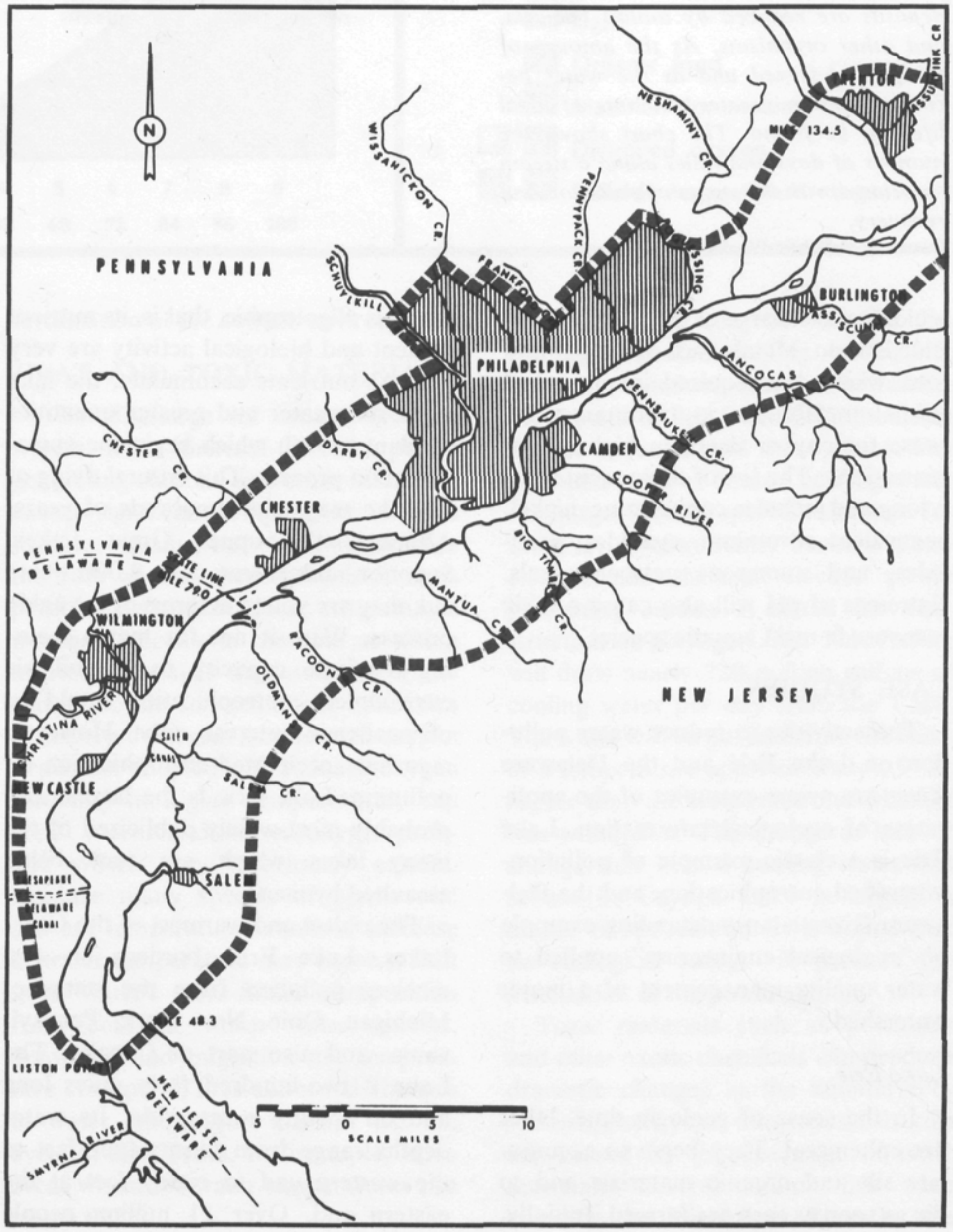
Lake Erie

In the sense of geologic time, lakes are ephemeral. They begin to accumulate silt and organic materials and to die as soon as they are formed. Initially, a lake is oligotrophic, that is, its nutrient content and biological activity are very low. As nutrients accumulate, the lake supports greater and greater quantities of plant growth which begin the eutrophication process. This natural dying of the lake may take thousands of years. Although the upper Great Lakes, Superior and Huron, are 8,000 years old, they are young in terms of the aging process. Were it not for man's seemingly infinite capacity to despoil his environment, eutrophication would be of academic interest only. However, man has accelerated eutrophication by pollution. Lake Erie is the largest and probably most widely publicized of the many lakes which are now being assaulted by man.

The oldest and warmest of the Great Lakes, Lake Erie, borders on and receives pollution from the states of Michigan, Ohio, New York, Pennsylvania, and also part of Canada. The Lake is two-hundred forty miles long and up to fifty miles wide. Its water depths range from twenty-four feet at the western end to eighty feet at the eastern end. Over 11 million people live in the Lake Erie basin and this population is expected to double in the next fifty years. A large portion of the municipal wastes generated by this population enters the Lake after receiving varying degrees of treatment. Large quantities of water are drawn from the Lake for municipal and industrial water supplies. The Lake is also used extensively for recreation and supports a declining commercial fishing industry.

Lake Erie's response to pollution is as we would predict. Massive amounts of algae impart tastes and odors to the water and deplete the oxygen levels. The numbers of desirable species of fish are greatly reduced; perch is the only high quality fish still present in abundance. At a 1965 water pollution control conference, a spokesman for the Michigan Conservation Department declared that Lake Erie's fisheries could be saved only through an all out effort to restore water quality to the high levels required by desirable species of fish.

While the publicity is a recent phenomenon, the degradation of Lake Erie has been in progress for many years.

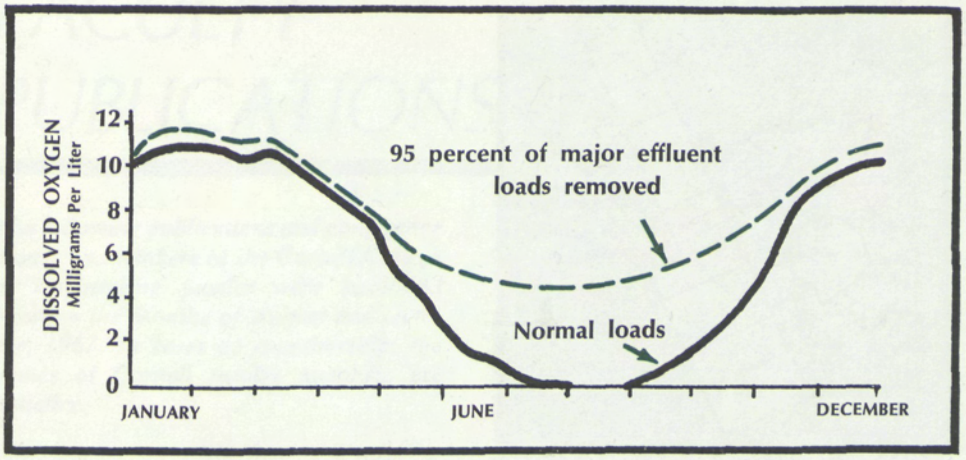


The Delaware River is a major waterway which drains a five-state area: New York, New Jersey, Pennsylvania, Delaware, and a small part of Maryland. The drainage area below Trenton, New Jersey, called the Lower Region of the Delaware River Basin, is shown here. This area was the subject of a federal-state study.

Courtesy of the Federal Water Pollution Control Administration, Philadelphia, Pennsylvania.

As early as 1930, reduced levels of dissolved oxygen were noted in the bottom waters. This condition is one of the first symptoms of advanced eutrophication. But not until recently have many people seemed to care that the Lake is dying.

Since 1963, Lake Erie has been the subject of an intensive Federal Water Pollution Control Administration study, and much information has been gathered in an effort to delineate the present conditions. The consensus of opinion is that Erie can be saved, that eutrophication can be slowed, and that water quality conditions in the Lake can be improved. These objectives cannot be accomplished overnight. If they are to be realized, the job will require significant upgrading of the treatment given to municipal and industrial wastewaters prior to their being discharged into the Lake. This improved treatment will have to include more complete removal of organic matter and almost total removal of the algal nutrient, phosphorus. The removal of phosphorus should control the algal blooms which are perhaps the most damaging element



This model of one section of the Delaware River shows how the amount of dissolved oxygen is reduced under normal waste discharge conditions and how it would dramatically increase if 95% of the waste load were removed.

Courtesy of the Federal Water Pollution Control Administration, Philadelphia, Pennsylvania.

in the eutrophication process. Toxic materials must, of course, be totally eliminated. After this, only time will tell whether Lake Erie can recover from the near mortal blow by man.

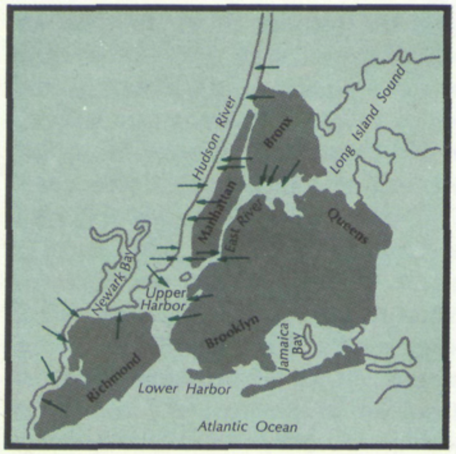
Delaware River

Of the many major rivers that are polluted, the Delaware River is unique in that its pollution problems have been studied extensively, and there exists a prototype federal-state organization, the Delaware River Basin Commission, which is responsible for basin-wide development and for the management of water resources. The results of a five-year federal water quality study in the tidal portion of the River have been released recently. This report includes the description of a mathematical model for predicting the response of various water quality parameters, principally dissolved oxygen, to the introduction of wastewater effluents at various points along the River. For dissolved oxygen, the model is based on the relationship between biological deoxygenation and atmospheric reaeration. The basic form of this model, first introduced in 1925, was known as the dissolved oxygen sag equation. The tidal dispersion of pollutants in the River complicated the development of this model. While not included in the original or the Delaware model, it is expected that further oxygen sag models will incorporate the effects of algae and nitrification on the oxygen resource.

The approach developed for the Delaware and now being used in subsequent river studies is to divide the river into sections using wastewater discharges and confluences of tributaries as convenient sectioning points. A mass balance is then performed on the oxygen and organic matter content of each section. The mass balance is written in the form of a linear differential equation, then these systems of simultaneous equations are solved by matrix manipulation methods using a digital computer. The result is a profile of the dissolved

"Man cannot separate himself and his activities from nature . . ."

1

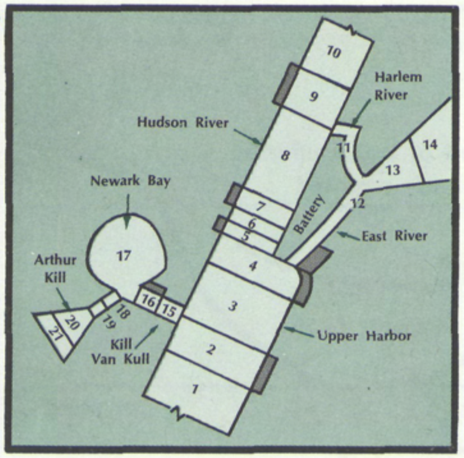


1. *The New York Harbor's waterways with the major points of waste discharge.*
2. *A mathematical division of the same area for computer analysis of the effects of pollution. The same type of computer analysis has been done on the Delaware River.*

Courtesy of *IBM Computing Report.*

oxygen concentration in the stream. By varying the point of application, and the magnitude of hypothetical waste loads, one can predict the effect of varying waste treatments on the

2



stream's water quality. The cost for achieving a particular degree of water quality then can be estimated by calculating the cost of the required wastewater treatment. In this manner, costs were determined for several levels of water quality in the Delaware River.

Thus, the sanitary engineer presents the federal-state decision-makers with a group of alternatives, that is, the various levels of water quality they can have and the cost of achieving each. The people, through political processes, decide what level of water quality they want and are willing to pay for.

FUTURE

The era of man's conquest of nature, if there ever were such a period, is over. The richness of the American continent gave rise to the myth of superabundance and the belief that our resources could be endlessly exploited. Timber, minerals, soil, water, and air exist in finite amounts. The earth is a closed system with a limited life-support capability that can be compared with the life-support capability of a space capsule. We finally are beginning to realize that man cannot separate himself and his activities from nature, and that the principles of ecology which govern pond and field also govern the entire world in which we dwell.

Alonzo Wm. Lawrence became an Assistant Professor of Water Resources Engineering in the Cornell School of Civil Engineering in the autumn of 1967.

Before coming to Cornell, he was an Assistant Professor of Civil Engineering at Drexel Institute of Technology from 1965 to 1967, and also worked for the New York State Department of Health as an assistant sanitary engineer. A lieutenant in the United States Army from 1960 to 1962, he served as a sanitary engineer with the Medical Service Corps.

Professor Lawrence took the Bachelor of Science degree from Rutgers, The State University in 1959, the Master of Science degree from M.I.T. in 1960, and the Doctor of Philosophy degree from Stanford University in 1967.

He is a member of the American Society of Civil Engineers, Tau Beta Pi, the New York Water Pollution Control Association, and Sigma Xi.

FACULTY PUBLICATIONS

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