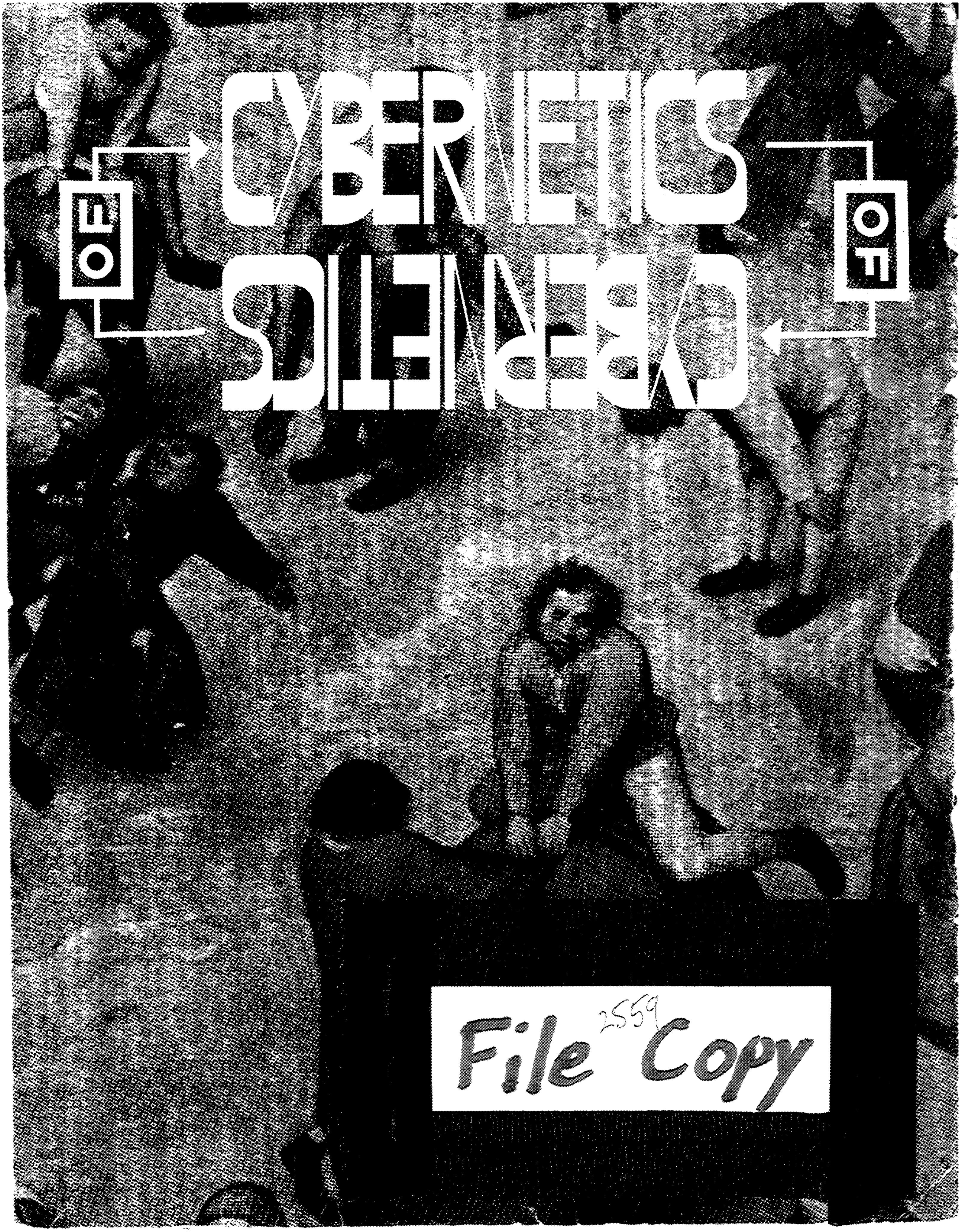
CYBERNETICS OF CYBERNETICS



COVER: DETAILS FROM "CHILDREN'S GAMES" BY PIETER BRUEGHEL THE ELDER

Thanks to a grant by the POINT Foundation to the Biological Computer Laboratory, I was in a position to offer the students who enrolled in my sections of the general topics courses --given by the Departments of Electrical Engineering and of Physiology and Biophysics (EE 272/490 and BPh 199/491)-- a course with a tangible goal in which the process by which this, or any other goal may be attained was to be the center of attention. The tangible result of this course on the "Cybernetics of Cybernetics" is compiled in the following pages; the processes that led to this compilation must be inferred.

The responsibility for making this result visible to those who did not participate is, of course, mine.

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CYBERNETICS OF CYBERNETICS

OR
THE CONTROL OF CONTROL AND
THE COMMUNICATION OF COMMUNICATION

PRESENTED BY

ROBERT ABRAMOVITZ
ROBERT BATES ALLEN
HERBERT BRÜN
GEORGE CARTER
DEBRA CLINK
PATRICIA CLOUGH
RODNEY CLOUGH
BRIAN DUNN
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HEINZ VON FOERSTER
DAVID VRANICAR
KENNETH WILSON
BOB ZIELINSKI

THE PARTICIPANTS IN "CYBERNETICS OF CYBERNETICS"

15 MAY 1974

SPONSORED BY A GRANT FROM THE POINT FOUNDATION TO
THE BIOLOGICAL COMPUTER LABORATORY
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS
61801

Q What is Cybernetics?

A I would like to call Cybernetics an offer.

Q What does Cybernetics offer?

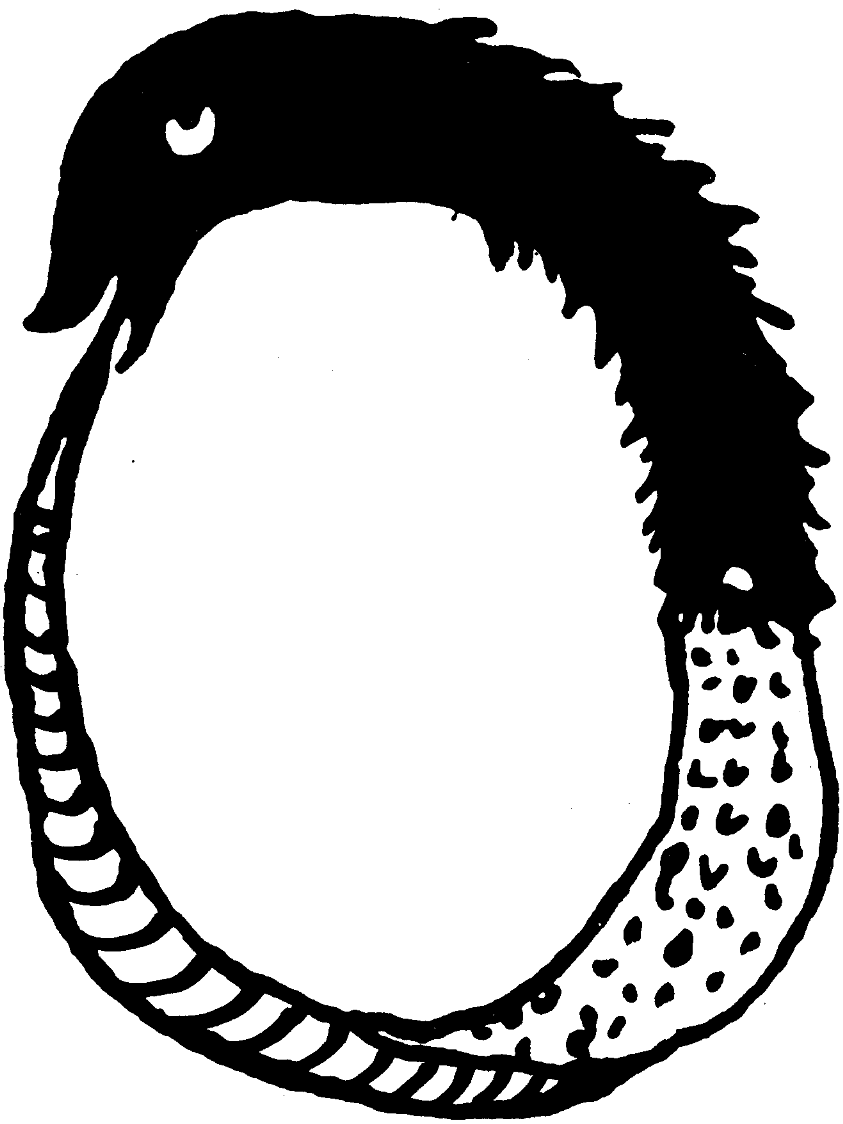
A Cybernetics offers access to and interaction with complex systems in order that they may appear simple; to and with apparently simple systems in order that their complexity may be revealed.

I would like to call this book the "Cybernetics of Cybernetics" because it offers access to and interaction with cybernetics that are simple in their complexity and complex in their simplicity.

B. Rebitzer

Should it be desired to establish connections between concepts whose links lie in dimensions different from the one suggested by the sequential arrangement of topics in this collection, punch holes into pages according to the schedule (small, open circles ◯) indicated on the right outer margin of each page.

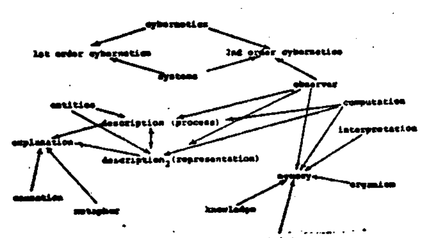
● Large, solid black circles indicate target pages. These circles should not be punched. To reach a target page, insert a stylus (pencil, pen, etc.) into holes, flip pages until target page is reached.



FIRST ORDER CYBERNETICS

The cybernetics of observed systems.

[H.V.F.]



SECOND ORDER CYBERNETICS

The cybernetics of observing systems.

[H.V.F.]

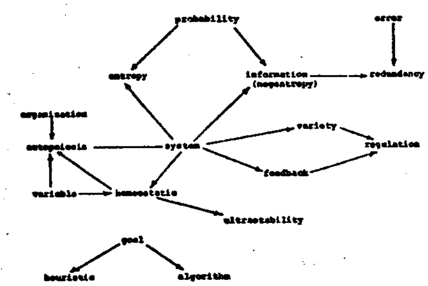
CYBERNETICS

Cybernetics dates from 1942 and was named in 1947 by the late Norbert Wiener and the late Arturo Rosenbleuth, distinguished mathematician and physician respectively. It was then defined as 'the science of control and communication in the animal and the machine'. This definition indicated (a) that a state of 'in-control' depends upon a flow of information, and (b) that the laws governing control are universal, i.e. do not depend on the classical dichotomy between organic and inorganic systems. The name cybernetics derives from the Greek word meaning 'steersman', and was chosen to show that adaptive control is more like steersmanship than dictatorship. Today, a more general definition of cybernetics might be preferred: <u>the science of effective organization</u>.

Always an interdisciplinary subject, cybernetics was seen by its founding fathers moreover as <u>trans</u>disciplinary. This perception was followed by the original United States workers, and by cyberneticians in the United Kingdom, who looked to the science as linking organizational notions in every field, and as specifying quite general principles. Elsewhere in the United States, and in some other countries, notably France, early discoveries about the importance of feedback and the role of entropy focussed the subject on its engineering aspects, at the expense of its biology, its economics, its ecology, and so on. In the USSR, cybernetics was officially treated as an 'imperialist device' until the mid-fifties. At this time, Soviet work in the field, heavily dependent on mathematics, achieved such importance internationally that the Soviet authorities admitted the science officially.

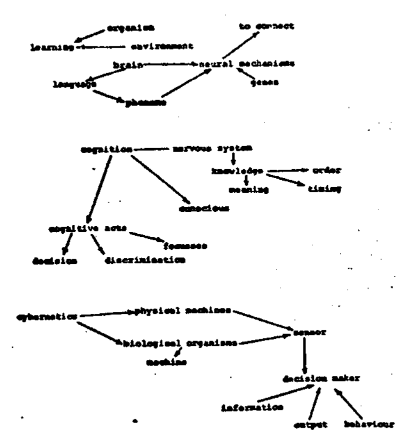
There remains disagreement about the generality of the science, especially in relation to General Systems Theory which has identical objectives to those expressed by the founders of cybernetics. Thus for some, cybernetics and GST are co-extensive, while those could be found who regard each as a branch of the other. In their origins, at least, they express the same intentions.

Thanks to the academic forces that will always seek to classify in a reductionist way, one may hear of engineering cybernetics (as mentioned above), of neurocybernetics (which deals especially with the brain), of bio-cybernetics (sometimes called bionics), of computer cybernetics, of management cybernetics, and so on. A clear perception of cybernetics must accept these distinctions by areas of application, but will not take them as undermining the transdisciplinary unity of cybernetics itself. [S.B.]



CYBERNETICS

Cybernetics is a word used to convey the idea of comparing physical machines with biological organisms in regard to how their behavior is controlled. Both possess a sensor that feeds information into a decision-maker which then regulates the output, or behavior, up or down. Since 1751, when Robert Whytt (pronounced White) clearly described the pupillary reflex (light in the eye, pupil gets smaller) biologists have conceived organisms to be "machines" wherein the motor output can be controlled by the sensory input through a central processor whose rules of operation would be fascinating to know. When Norbert Weiner invented the word cybernetics in order to reify his idea, only the word, not the idea, was new to these biologists. Whether the intellectual ferment generated by Weiner's new word has made much difference to biologists as they make experiments upon their system is debatable. His word, however, has generated a lot of thinking, talking and writing, by non- and quasi-biologists. [R.G.]

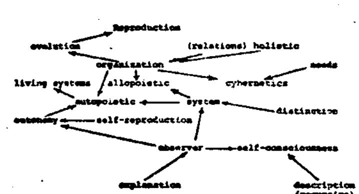


CYBERNETICS

It is demonstrated that information flow in scientific or aesthetic inquiry can be modelled via conceptual communication and conscious cognitive control of information. In The Human Use of Human Beings, Norbert Wiener defines "cybernetics" as "the science of communication and control". Traditionally, conceptual modelling of problems in cybernetics have employed an electronic data processing paradigm: for example, neural activity in cognition has been modelled via digital and analog computer perspectives. In problem solving, such an approach is exemplified by Newell Simon's Human Problem Solving. This grasp of cybernetics is too narrow: cybernetics is most generally, an heuristic by which one conceptually notes a problem through parameters of communication (or relation) and control (or effect). The second-order heuristic presented earlier is such a cybernetic model of problem-solving. Information can be input into such a cybernetic heuristic, processed, and subsequently output. Considering cybernetics as a heuristic expands the scope of the "science of communication and control" to relevantly encompass nearly all epistemological domains. Make cybernetics an heuristic, and apply it to nearly any problem. [D.S.]

CYBERNETICS

The science of effective organization or the art of relating things together so that it happens what is desired, in brief, the discipline of human action. Cybernetic notions and products are designed to satisfy human needs and expectations from where it draws its source and inspiration. As a science Cybernetics belongs to the more inclusive domain of a Science of Organization at large. (Thus there is no cybernetics of a cell; there is cell organization from where cybernetic notions can draw). [F.V.]



Cybernetics

by Norbert Wiener

introduction

1948 was a successful and stimulating year for Norbert Wiener. Two papers close to his heart appeared now in print, one reporting the results of his and his student's Walter Pitts enjoyable stay in Mexico with his long time friend Arthuro Rosenblueth (Rosenblueth, A., N. Wiener, W. Pitts and J. Garcia Ramos with the assistance of F. Weber: "An Account of the Spike Potential of Axons." J. Cell. and Comp. Physiol. 32, 275-318 (1948)), the other one was his ambitious address to the New York Academy of Science on teleological mechanisms (Wiener, N.: "Time, Communication, and the Nervous System." N.Y. Acad. Sci. 50 (4) 197-220 (1948)). The highlight of this year, however, was the publication in mid-summer of his favorite brainchild "Cybernetics" that became a similar unexpected public bombshell as Alfred C. Kinsey's report on the sexual behavior of the human male, published in the same year.

In anticipation of such a success, the allert publishers of the recently streamlined Scientific American approached Norbert Wiener with the request to write a short account of his newly established science for their November issue. The following article is the result. It is scientific journalism at its best: relaxed, clear, informative and deeply concerned. A "Norbert Wiener" as he wished to be seen by his contemporaries, the "scientific humanist" or the "humanistic scientist", emerges here with clarity and touching persuasion.

The article gives first the etymology of the term "Cybernetics", and then defines with well chosen examples the core of the subject matter. After a concise biographical account of his collaboration with others during the evolution of this topic, he turns to a brief, but delightfully written, history of thoughts -- from Daedalus to I. B. M. -- that led to their modern formulation in cybernetics. He recognizes biomimetics -- the desire to imitate nature -- to be the motivating power for this intellectual activity, and keenly observes that with a new understanding of the once esoteric concepts of information and control the apparently trivial problem of accurately duplicating electric signals will take priority over the problem of generating electric power.

A quick comparison of curricula offered in departments of electrical engineering in the early fifties with today's will convince even the sceptic of the significance of ideas: while then almost all that was taught was "power", today almost all that is taught is "communication".

The article goes on to discuss the problem of informational fallibility in large systems, artificial or organic. The effects of error accumulation in cascaded signal processors, and of size of these processors on the corruption of signal fidelity, is lucidly pursued. It is here where Norbert Wiener's deeply felt humane concern becomes most clearly articulated. More than half of this article is devoted to an attempt of utilizing his new insights for the betterment of the fate of the sensory deprived and the mentally disordered. While many of his theorized parallelisms between malfunctions of machines and brains did not survive the experimental scrutiny of the last two decades, his important distinction between functional and anatomical anomalies is a fruitful concept in today's psychotherapy.

Noting correctly from geometrical considerations that an increase in the volume of the brain will result in a proportionate increase in the number of neurons but in a disproportionately lower increase of connections, and thus will result in a corruption of the higher mental functions, he concludes with detachment that "the human brain may be as far along on its road to destructive specialization as the great nose horns of the last of the titanotheres."

It appears today that Norbert Wiener might have been correct again.

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CYBERNETICS is a word invented to define a new field in science. It combines under one heading the study of what in a human context is sometimes loosely described as thinking and in engineering is known as control and communication. In other words, cybernetics attempts to find the common elements in the functioning of automatic machines and of the human nervous system, and to develop a theory which will cover the entire field of control and communication in machines and in living organisms.

It is well known that between the most complex activities of the human brain and the operations of a simple adding machine there is a wide area where brain and machine overlap. In their more elaborate forms, modern computing machines are capable of memory, association, choice and many other brain functions. Indeed, the experts have gone so far in the elaboration of such machines that we can say the human brain behaves very much like the machines. The construction of more and more complex mechanisms actually is bringing us closer to an understanding of how the brain itself operates.

The word cybernetics is taken from the Greek *kybernetes*, meaning steersman. From the same Greek word, through the Latin corruption *gubernator*, came the term governor, which has been used for a long time to designate a certain type of control mechanism, and was the title of a brilliant study written by the Scottish physicist James Clerk Maxwell 80 years ago. The basic concept which both Maxwell and the investigators of cybernetics mean to describe by the choice of this term is that of a feedback mechanism, which is especially well represented by the steering engine of a ship. Its meaning is made clear by the following example.

Suppose that I pick up a pencil. To do this I have to move certain muscles. Only an expert anatomist knows what all these muscles are, and even an anatomist could hardly perform the act by a conscious exertion of the will to contract each muscle concerned in succession. Actually what we will is not to move individual muscles but to pick up the pencil. Once we have determined on this, the motion of the arm and hand proceeds in such a way that we may say that the amount by which the pencil is not yet picked up is decreased at each stage. This part of the action is not in full consciousness.

To perform an action in such a manner, there must be a report to the nervous system, conscious or unconscious, of the amount by which we have failed to pick up the pencil at each instant. The report may be visual, at least in part, but it is more generally kinesthetic, or to use a term now in vogue, proprioceptive. If the proprioceptive sensations are wanting, and we do not replace them by a visual or other substitute, we are unable to perform the act of picking up the pencil, and find ourselves in a state known as ataxia. On the other hand, an excessive feedback is likely to be just as serious a handicap. In the latter case the muscles overshoot the mark and go into an uncontrollable oscillation. This condition, often associated with injury to the cerebellum, is known as purpose tremor.

Here, then, is a significant parallel between the workings of the nervous system and of certain machines. The feedback principle introduces an important new idea in nerve physiology. The central nervous system no longer appears to be a self-contained organ receiving signals from the senses and discharging into the muscles. On the contrary, some of its most characteristic activities are explainable only as circular processes, traveling from the nervous system into the muscles and re-entering the nervous system through the sense organs. This finding seems to mark a step forward in the study of the nervous system as an integrated whole.

The new approach represented by cybernetics—an integration of studies which is not strictly biological or strictly physical, but a combination of the two—has already given evidence that it may help to solve many problems in engineering, in physiology and very likely in psychiatry.

This work represents the outcome of a program undertaken jointly several years ago by the writer and Arturo Rosenblueth, then of the Harvard Medical School and now of the National Institute of Cardiology of Mexico. Dr. Rosenblueth is a physiologist; I am a mathematician. For many years Dr. Rosenblueth and I had shared the conviction that the most fruitful areas for the growth of the sciences were those which had been neglected as no-man's lands between the various established fields. Dr. Rosenblueth always insisted that a proper exploration of these blank spaces on the map of science could be made only by a team of scientists, each a specialist but each possessing a thoroughly sound acquaintance with the fields of his fellows.

OUR collaboration began as the result of a wartime project. I had been assigned, with a partner, Julian H. Bigelow, to the problem of working out a fire-control apparatus for anti-aircraft artillery which would be capable of tracking the curving course of a plane and predicting its future position. We soon came to the conclusion that any solution of the problem must depend heavily on the feedback principle, as it operated not only in the apparatus but in the human operators of the gun and of the plane. We approached Dr. Rosenblueth with a specific question concerning oscillations in the nervous system, and his reply, which cited the phenomenon of purpose tremor, confirmed our hypothesis about the importance of feedback in voluntary activity.

The ideas suggested by this discussion led to several joint experiments, one of which was a study of feedback in the muscles of cats. The scope of our investigations steadily widened, and as it did so scientists from widely diverse fields joined our group. Among them were the mathematicians John Von Neumann of the Institute for Advanced Study and Walter Pitts of Massachusetts Institute of Technology; the physiologists Warren McCulloch of the University of Pennsylvania and Lorente de No of the Rockefeller Institute; the late Kurt Lewin, psychologist, of M. I. T.; the anthropologists Gregory Bateson and Margaret Mead; the economist Oskar Morgenstern of the Institute for Advanced Study; and others in psychology, sociology, engineering, anatomy, neurophysiology, physics, and so on.

The study of cybernetics is likely to have fruitful applications in many fields, from the design of control mechanisms for artificial limbs to the almost complete mechanization of industry. But in our view it encompasses much wider horizons. If the 17th and early 18th centuries were the age of clocks, and the latter 18th and 19th centuries the age of steam engines, the present time is the age of communication and control. There is in electrical engineering a division which is known as the split between the technique of strong currents and the technique of weak currents; it is this split which separates the age just passed from that in which we are living. What distinguishes communication engineering from power engineering is that the main interest of the former is not the economy of energy but the accurate reproduction of a signal.

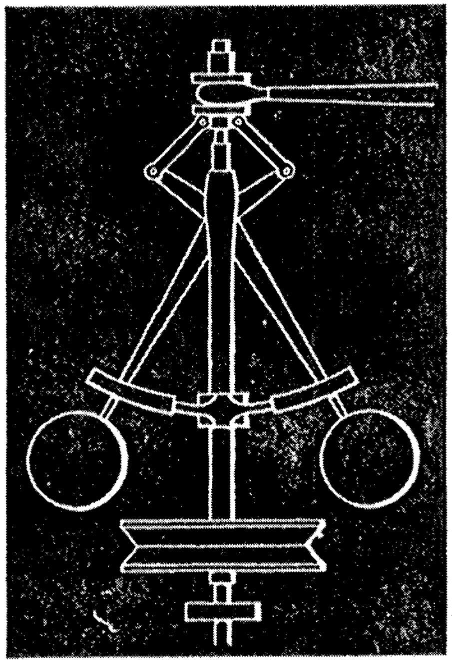
At every stage of technique since Daedalus, the ability of the artificer to produce a working simulacrum of a living organism has always intrigued people. In the days of magic, there was the bizarre and sinister concept of the Golem, that figure of clay into which the rabbi of Prague breathed life. In Isaac Newton's time the automaton became the clockwork music box. In the 19th century, the automaton was a glorified heat engine, burning a combustible fuel instead of the glycogen of human muscles. The automaton of our day opens doors by means of photocells, or points guns to the place at which a radar beam picks up a hostile airplane, or computes the solution of a differential equation.

Under the influence of the prevailing view in the science of the 19th century, the engineering of the body was naturally considered to be a branch of power engineering. Even today this is the predominant point of view among classically minded, conservative physiologists. But we are now coming to realize that the body is very far from a conservative system, and that the power available to it is much less limited than was formerly believed. We are beginning to see that such important elements as the neurones—the units of the nervous complex of our bodies—do their work under much the same conditions as vacuum tubes, their relatively small power being supplied from outside by the body's circulation, and that the bookkeeping which is most essential to describe their function is not one of energy.

In short, the newer study of automata, whether in the metal or in the flesh, is a branch of communications engineering, and its cardinal ideas are those of the message, of the amount of disturbance or "noise" (a term taken from the telephone engineer), of the quantity of information to be transmitted, of coding technique, and so on.

This view obviously has implications which affect many branches of science. Let us consider here the application of cybernetics to the problem of mental disorders. The realization that the brain and computing machines have much in common may suggest new and valid approaches to psychopathology, and even to psychiatry.

These begin with perhaps the simplest question of all: how the brain avoids gross blunders or gross miscarriages of activity due to the malfunction of individual parts. Similar questions referring to the computing machine are of great practical importance, for here a chain of operations, each of which covers only a fraction of a millionth of a second, may last a matter of hours or days. It is quite possible for a chain of computational operations to involve a billion separate steps. Under these circumstances, the chance that at least one operation will go amiss is far from negligible, even though the reliability of modern electronic apparatus has exceeded the most sanguine expectations.



GOVERNOR of a steam engine is an example of feedback, one of the most important basic ideas in cybernetics.

IN ordinary computational practice by hand or by desk machines, it is the custom to check every step of the computation and, when an error is found, to localize it by a backward process starting from the first point where the error is noted. To do this with a high-speed machine, the check must proceed at the pace of the original machine, or the whole effective order of speed of the machine will conform to that of the slower process of checking.

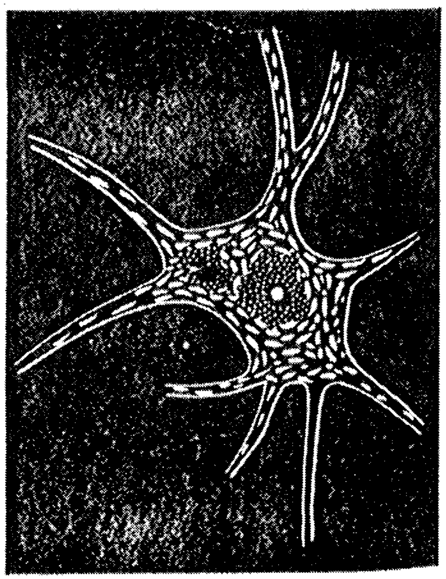
A much better method of checking, and in fact the one generally used in practice, is to refer every operation simultaneously to two or three separate mechanisms. When two such mechanisms are used, their answers are automatically collated against each other; and if there is a discrepancy, all data are transferred to permanent storage, the machine stops and a signal is sent to the operator that something is wrong. The operator then compares the results, and is guided by them in his search for the malfunctioning part, perhaps a tube which has burned out and needs replacement. If three separate mechanisms are used for each stage, there will practically always be agreement between two of the three mechanisms, and this agreement will give the required result. In this case the collation mechanism accepts the majority report, and the machine need not stop. There is a signal, however, indicating where and how the minority report differs from the majority report. If this occurs at the first moment of discrepancy, the indication of the position of the error may be very precise.

It is conceivable, and not implausible, that at least two of the elements of this process are also represented in the nervous system. It is hardly to be expected that any important message is entrusted for transmission to a single neurone, or that an important operation is entrusted to a single neuronal mechanism. Like the computing machine, the brain probably works on a variant of the famous principle expounded by Lewis Carroll in *The Hunting of the Snark:* "What I tell you three times is true."

It is also improbable that the various channels available for the transfer of information generally go from one end of their course to the other without connecting with one another. It is much more probable that when a message reaches a certain level of the nervous system, it may leave that point and proceed to the next by one or more alternative routes. There may be parts of the nervous system, especially in the cortex, where this interchangeability is much limited or abolished. Still, the principle holds, and it probably holds most clearly for the relatively unspecialized cortical areas which serve the purpose of association and of what we call the higher mental functions.

So far we have been considering errors in performance that are normal, and pathological only in an extended sense. Let us now turn to those that are much more clearly pathological. Psychopathology has been rather a disappointment to the instinctive materialism of the doctors, who have taken the view that every disorder must be accompanied by actual lesions of some specific tissue involved. It is true that specific brain lesions, such as injuries, tumors, clots and the like, may be accompanied by psychic symptoms, and that certain mental diseases, such as paresis, are the sequelae of general bodily disease and show a pathological condition of the brain tissue. But there is no way of identifying the brain of a schizophrenic of one of the strict Kraepelin types, nor of a manic-depressive patient, nor of a paranoiac. These we call functional disorders.

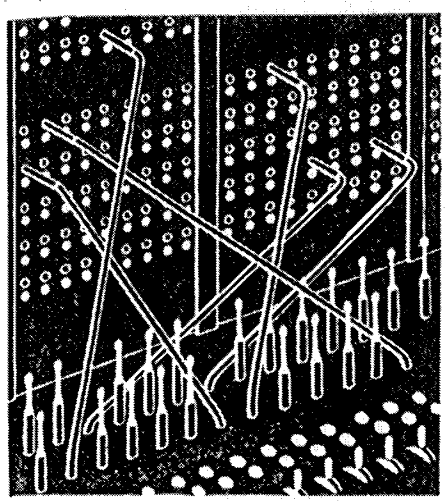
This distinction between functional and organic disorders is illuminated by the consideration of the computing machine. It is not the empty physical structure of the computing machine that corresponds to the brain—to the adult brain, at least—but the combination of this structure with the instructions given it at the beginning of a chain of operations and with all the additional information stored and gained from outside in the course of its operation.



NERVE CELL performs functions in much the same situation as a vacuum tube, obtaining power from outside.

This information is stored in some physical form—in the form of memory. But part of it is in the form of circulating memories, with a physical basis that vanishes when the machine is shut down or the brain dies, and part is in the form of long-time memories, which are stored in a way at which we can only guess, but probably also in a form with a physical basis that vanishes at death.

There is therefore nothing surprising in considering the functional mental disorders fundamentally as diseases of memory, of the circulating information kept by the brain in active state and of the long-time permeability of synapses. Even the grosser disorders such as paresis may produce a large part of their effects not so much by the destruction of tissue which they involve and the alteration of synaptic thresholds as by the secondary disturbances of traffic, the overload of what remains of the nervous system and the rerouting of messages which must follow such primary injuries.



TELEPHONE EXCHANGE, when it is overloaded, has breakdowns rather similar to the kind in human beings.

In a system containing a large number of neurones, circular processes can hardly be stable for long periods of time. Either they run their course, dissipate themselves and die out, as in the case of memories belonging to the specious present, or they embrace more and more neurones in their system, until they occupy an inordinate part of the neurone pool. This is what we should expect to be the case in the malignant worry that accompanies anxiety neuroses. In such a case, it is possible that the patient simply does not have the room —*i.e.*, a sufficient number of neurones— to carry out his normal processes of thought. Under such conditions, there may be less going on in the brain to occupy the neurones not yet affected, so that they are all the more readily involved in the expanding process. Furthermore, the permanent memory becomes more and more deeply involved, and the pathological process which began at the level of the circulating memories may repeat itself in a more intractable form at the level of the permanent memories. Thus what started as a relatively trivial and accidental disturbance of stability may build itself up into a process totally destructive to the normal mental life.

Pathological processes of a somewhat similar nature are not unknown in the case of mechanical or electrical computing machines. A tooth of a wheel may slip under such conditions that no tooth with which it engages can pull it back into its normal relations, or a high-speed electrical computing machine may go into a circular process that seems impossible to stop.

HOW do we deal with these accidents in the case of the machine? We first try to clear the machine of all information, in the hope that when it starts again with different data the difficulty will not recur. If this fails and the difficulty is inaccessible to the clearing mechanism, we shake the machine or, if it is electrical, subject it to an abnormally large electrical impulse in the hope that we may jolt the inaccessible part into a position where the false cycle of its activities will be interrupted. If even this fails, we may disconnect an erring part of the apparatus, for it is possible that what remains may be adequate for our purpose.

In the case of the brain, there is no normal process, except death, that can clear it of all past impressions. Of the normal non-fatal processes, sleep comes closest to clearing the brain. How often we find that the best way to handle a complicated worry or an intellectual muddle is to sleep on it! Sleep, however, does not clear away the deeper memories, nor indeed is a malignant state of worry compatible with adequate sleep.

Thus we are often forced to resort to more violent types of intervention in the memory cycle. The most violent of these involve surgery on the brain, leaving behind permanent damage, mutilation and the abridgement of the powers of the victim, for the mammalian central nervous system seems to possess no power of regeneration. The principal type of surgical intervention that has been practiced is known as prefrontal lobotomy, or leucotomy. It consists in the removal or isolation of a portion of the prefrontal lobe of the cortex. It is currently having a certain vogue, probably not unconnected with the fact that it makes the custodial care of many patients easier. (Let me remark in passing that killing them makes their custodial care still easier.) Prefrontal lobotomy does seem to have a genuine effect on malignant worry, not by bringing the patient nearer to a solution of his problem, but by damaging or destroying the capacity for maintained worry, known in the terminology of another profession as the conscience. It appears to impair the circulating memory, *i.e.*, the ability to keep in mind a situation not actually presented.

The various forms of shock treatment—electric, insulin, metrazol—are less drastic methods of doing a very similar thing. They do not destroy brain tissue, or at least are not intended to destroy it, but they do have a decidedly damaging effect on the memory. In so far as the shock treatment affects recent disordered memories, which are probably scarcely worth preserving anyhow, it has something to recommend it as against lobotomy, but it is sometimes followed by deleterious effects on the permanent memory and the personality. As it is used at present, it is another violent, imperfectly understood, imperfectly controlled method to interrupt a mental vicious circle.

In long-established cases of mental disorder, the permanent memory is as badly deranged as the circulating memory. We do not seem to possess any purely pharmaceutical or surgical weapon for intervening selectively in the permanent memory. This is where psychoanalysis and the other psychotherapeutic measures come in.

Whether psychoanalysis is taken in the orthodox Freudian sense or in the modified senses of Jung and of Adler, or whether the psychotherapy is not strictly psychoanalytic at all, the treatment is clearly based on the concept that the stored information of the mind lies on many levels of accessibility. The effect and accessibility of this stored information are vitally conditioned by affective experiences that we cannot always uncover by introspection. The technique of the psychoanalyst consists in a series of means to discover and interpret these hidden memories, to make the patient accept them for what they are, and thus to modify, if not their content, at least the affective tone they carry, and make them less harmful.

All this is perfectly consistent with the cybernetic point of view. Our theory perhaps explains, too, why there are circumstances in which a joint use of shock treatment and psychotherapy is indicated, combining a physical or pharmacological therapy for the malignant reverberations in the nervous system and a psychological therapy for the damaging long-time memories which might re-establish the vicious circle broken up by the shock treatments.

AUTOMATON of the 15th century was one of a long series of attempts to assign human functions to machinery.

We have already mentioned the traffic problem of the nervous system. It has been noted by many writers that each form of organization has an upper limit of size beyond which it will not function. Thus insect organization is limited by the length of tubing over which the spiracle method of bringing air by diffusion directly to the breathing tissues will function; a land animal cannot be so big that the legs or other portions in contact with the ground will be crushed by its weight (*see page 52*), and so on. The same sort of thing is observed in engineering structures. Skyscrapers are limited in size by the fact that when they exceed a certain height, the elevator space needed for the upper stories consumes an excessive part of the cross section of the lower floors. Beyond a certain span, the best possible suspension bridge will collapse under its own weight. Similarly, the size of a single telephone exchange is limited.

In a telephone system, the important limiting factor is the fraction of the time during which a subscriber will find it impossible to put a call through. A 90 per cent chance of completing calls is probably good enough to permit business to be carried on with reasonable facility. A success of 75 per cent is annoying but will permit business to be carried on after a fashion; if half the calls are not completed, subscribers will begin to ask to have their telephones taken out. Now, these represent all-over figures. If the calls go through a number of distinct stages of switching, and the probability of failure is independent and equal for each stage, in order to get a high probability of final success the probability of success at each stage must be higher than the final one. Thus to obtain a 75 per cent chance for the completion of the call after five stages, we must have about 95 per cent chance of success at each stage. The more stages there are, the more rapidly the service becomes extremely bad when a critical level of failure for the individual call is exceeded, and extremely good when this critical level of failure is not quite reached. Thus a switching service involving many stages and designed for a certain level of failure shows no obvious signs of failure until the traffic comes up to the edge of the critical point, when it goes completely to pieces and we have a catastrophic traffic jam.

So man, with the best developed nervous system of all the animals, probably involving the longest chains of effectively operated neurones, is likely to perform a complicated type of behavior efficiently very close to the edge of an overload, when he will give way in a serious and catastrophic manner. This overload may take place in several ways: by an excess in the amount of traffic to be carried; by a physical removal of channels for the carrying of traffic; or by the excessive occupation of such channels by undesirable systems of traffic, such as circulating memories that have accumulated to the extent of becoming pathological worries. In all these cases, a point is reached—quite suddenly—when the normal traffic does not have space enough allotted to it, and we have a form of mental breakdown, very possibly amounting to insanity.

This will first affect the faculties or operations involving the longest chains of neurones. There is appreciable evidence, of various kinds, that these are precisely the processes recognized as the highest in our ordinary scale of valuation.

If we compare the human brain with

that of a lower mammal, we find that it is much more convoluted. The relative thickness of the gray matter is much the same, but it is spread over a far more involved system of grooves and ridges. The effect of this is to increase the amount of gray matter at the expense of the amount of white matter. Within a ridge, this decrease of the white matter is largely a decrease in length rather than in number of fibers, as the opposing folds are nearer together than the same areas would be on a smooth-surfaced brain of the same size. On the other hand, when it comes to the connectors between different ridges, the distance they have to run is increased by the convolution of the brain.

Thus the human brain would seem to be fairly efficient in the matter of the short-distance connectors, but defective in the matter of long-distance trunk lines. This means that in the case of a traffic jam, the processes involving parts of the brain quite remote from one another should suffer first. That is, processes involving several centers, a number of different motor processes and a considerable number of association areas should be among the least stable in cases of insanity. These are precisely the processes which we should normally class as higher, thereby confirming our theory, as experience does also, that the higher processes deteriorate first in insanity.

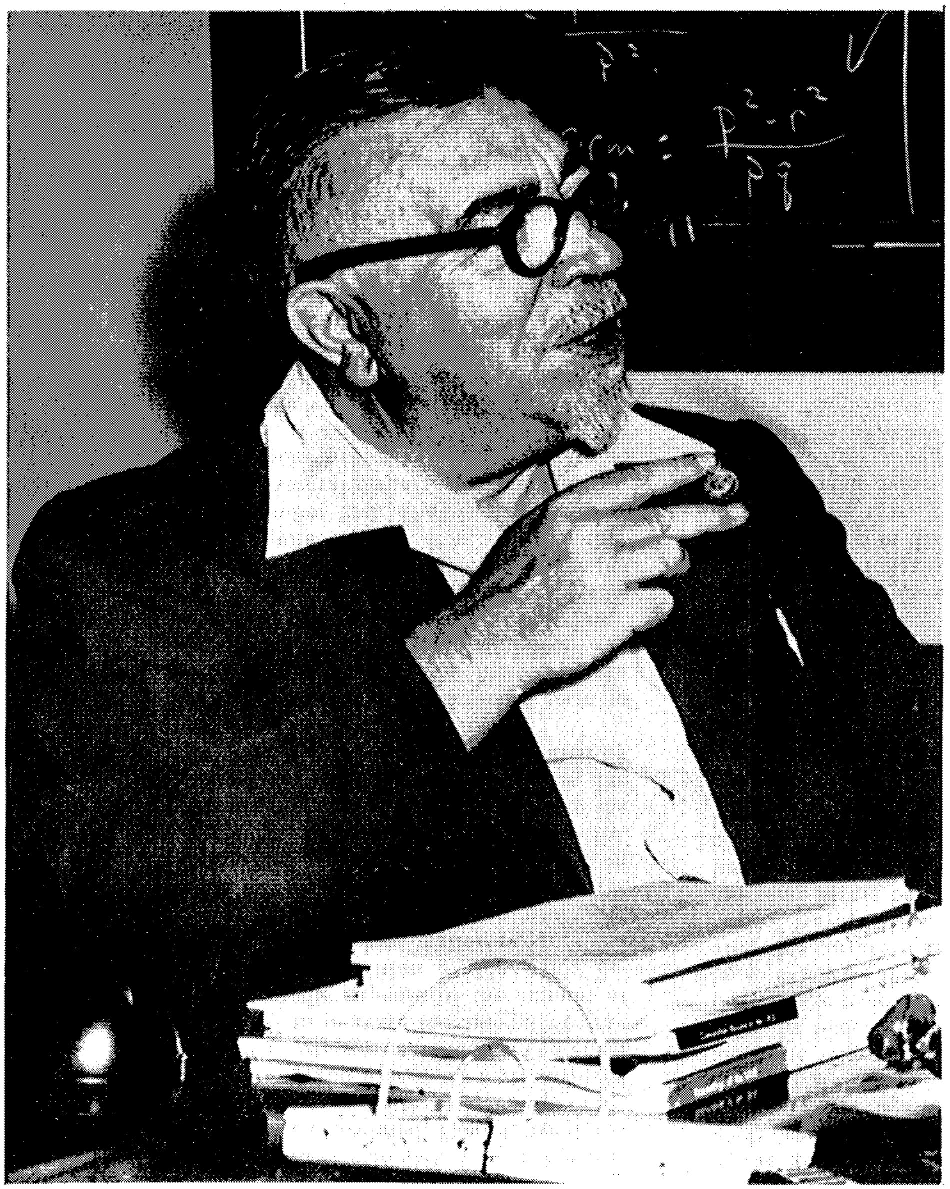
THE phenomena of handedness and of hemispheric dominance suggest other interesting speculations. Right-handedness, as is well known, is generally associated with left-brainedness, and left-handedness with right-brainedness. The dominant hemisphere has the lion's share of the higher cerebral functions. In the adult, the effect of an extensive injury in the secondary hemisphere is far less serious than the effect of a similar injury in the dominant hemisphere. At a relatively early stage in his career, Louis Pasteur suffered a cerebral hemorrhage on the right side which left him with a moderate degree of one-sided paralysis. When he died, his brain was examined and the damage to its right side was found to be so extensive that it has been said that after his injury "he had only half a brain." Nevertheless, after this injury he did some of his best work. A similar injury to the left side of the brain in a right-handed adult would almost certainly have been fatal; at the least it would have reduced the patient to an animal condition.

In the first six months of life, an extensive injury to the dominant hemisphere may compel the normally secondary hemisphere to take its place, so that the patient appears far more nearly normal than he would have been had the injury occurred at a later stage. This is quite in accordance with the great flexibility shown by the nervous system in the early weeks of life. It is possible that, short of very serious injuries, handedness is reasonably flexible in the very young child. Long before the child is of school age, however, the natural handedness and cerebral dominance are established for life. Many people have changed the handedness of their children by education, though of course they could not change its physiological basis in hemispheric dominance. These hemispheric changelings often become stutterers and develop other defects of speech, reading and writing.

We now see at least one possible explanation for this phenomenon. With the education of the secondary hand, there has been a partial education of that part of the secondary hemisphere which deals with skilled motions such as writing. Since these motions are carried out in the closest possible association with reading, and with speech and other activities which are inseparably connected with the dominant hemisphere, the neurone chains involved in these processes must cross over from hemisphere to hemisphere, and in any complex activity they must do this again and again. But the direct connectors between the hemispheres in a brain as large as that of man are so few in number that they are of very little help. Consequently the interhemispheric traffic must go by roundabout routes through the brain stem. We know little about these routes, but they are certainly long, scanty and subject to interruption. As a consequence, the processes associated with speech and writing are very likely to be involved in a traffic jam, and stuttering is the most natural thing in the world.

The human brain is probably too large already to use in an efficient manner all the facilities which seem to be present. In a cat, the destruction of the dominant hemisphere seems to produce relatively less damage than in man, while the destruction of the secondary hemisphere probably produces more damage. At any rate, the apportionment of function in the two hemispheres is more nearly equal. In man, the gain achieved by the increase in the size and complexity of the brain is partly nullified by the fact that less of the organ can be used effectively at one time.

It is interesting to reflect that we may be facing one of those limitations of nature in which highly specialized organs reach a level of declining efficiency and ultimately lead to the extinction of the species. The human brain may be as far along on its road to destructive specialization as the great nose horns of the last of the titanotheres.



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Pask

1 The Background of Cybernetics

Introduction

CYBERNETICS is a young discipline which, like applied mathematics, cuts across the entrenched departments of natural science; the sky, the earth, the animals and the plants. Its interdisciplinary character emerges when it considers economy not as an economist, biology not as a biologist, engines not as an engineer. In each case its theme remains the same, namely, how systems regulate themselves, reproduce themselves, evolve and learn. Its high spot is the question of how they organize themselves.

A cybernetic laboratory has a varied worksheet – concept formation in organized groups, teaching machines, brain models, and chemical computers for use in a cybernetic factory. As pure scientists we are concerned with brain-like artifacts, with evolution, growth and development; with the process of thinking and getting to know about the world. Wearing the hat of applied science, we aim to create what Boulanger,[1] in his presidential address to the International Association of Cybernetics, called the instruments of a new industrial revolution – control mechanisms that lay their own plans.

The crux of organization is stability, for 'that which is stable' can be described; either as the organization itself, or some characteristic which the organization preserves intact. 'That which is stable' may be a dog, a population, an aeroplane, Jim Jones, Jim Jones's body temperature, the speed of a ship, or indeed, a host of other things.

In chemistry, for example, Le Chatellier's Principle is a statement that the equilibrial concentration of reactants in a closed vessel is stable, for it asserts that the assembly will react so as to nullify thermal or chemical disturbances. But the equilibrium, which is always implied by the word stability, is rarely of this simple kind. Jim Jones is in dynamic equilibrium with his environment. He is not energetically isolated and his constituent material is being continually built up and broken down and interchanged. When we say 'Jim Jones is stable', we mean the form, the organization that we recognize as Jim Jones, is invariant. Again, if Jim Jones drives his motor car his behaviour is (statistically speaking) stable, and (in the sense that a destination is reached and no collision occurs) Jim Jones and his automobile are in equilibrium with their world.

Origins of Cybernetics

A great deal of cybernetics is concerned with how stability is maintained with 'control mechanisms'. One of the first of these to be treated explicitly was Watt's invention of the governor (a theoretical analysis was offered by Maxwell in 1865). The device illustrates a principle called *negative feedback*. A signal, indicating the speed of a steam engine, is conveyed to a power amplifying device (in this case, a steam throttle) in such a way that when the engine accelerates the steam supply is reduced. Hence, the speed is kept stable. The signalling arrangement is independent of energetic considerations, and it is legitimate to envisage the governor as a device which feeds back *information* in order to effect speed control.

Physiological Sources

Perhaps the earliest cybernetic thinking comes within the compass of physiology, where the key notions of information feedback and control appear as the ideas of reflex and homeostasis. In 1817 Magendie defined a reflex as an activity produced by a disturbance of some part of the body which travelled (over the dorsal nerve roots) to the central nervous system, and was reflected (through the ventral nerve roots) to the point of origin where it modified, stopped or reversed the original disturbance. The basic idea of signalling and directed activity is apparent (the common misinterpretation of a reflex as a mere relay action should be avoided). The elaboration of this idea in the early part of the present century, and the experiemental study of reflexes up to and beyond Pavlov, is well known.

Whereas reflexis preserves the organism against the flux of its environment, homeostasis counters the internally generated changes which are prone to disrupt the proper structure and disposition of parts in the organism. Homeostatic mechanisms maintain the *milieu internale* of Claude Bernard, the proper values of acidity, water balance and metabolites – a body temperature which the cells of the body can tolerate. The first comprehensive study was published by Cannon in 1932[2] and there is a vast amount of recent work (to cite a few representative papers; Stanford Goldman[3] treating blood sugar control as a feedback mechanism, T. H. Benzinger[4] for a discussion of the thermal regulator in the hypothalamus, and Magoun, Peterson, Lindsley, and McCulloch[5] for a study of feedback in postural tremor).

In much, though not all, physiological control the brain is chief controller, and in effecting control, chief recognizer, rationalizer and arbiter. Hence cybernetic thinking stems also from psychology and in turn makes comment. Studying the brain we meet a feature common to most cybernetic investigations – the assembly is so large that its details always, and its general outline sometimes, remain necessarily obscure. Here the mathematical models of our science are particularly valuable. One kind of model is a network of formal neurones (a formal neurone is a construct, depicting the least set of properties which a real neurone, a constituent active cell of the brain, could possibly possess). McCulloch, who pioneered this field has reached a number of conclusions. In particular he and Pitts showed some years ago[69, 70] that plausible networks of these formal neurones were automata capable of many gambits, such as learning, the elaboration of gestalten and the embodiment of universals. Hence, the corresponding modes of mentality are neither surprising nor adventitious when they appear in the far more elaborate real brain.

Finally there is the question of 'purpose'. All the homeostatic and reflexive mechanisms are goal-directed and self-regulating. There is no magic about this and, whilst we can discern the goal, no mystery either. But when, as often happens, a goal is sought by several interacting mechanisms, or several goals appear to be sought by one, we might apply the term 'purposive' to the resulting behaviour. There is no suggestion of a vital force (and though we rightly marvel at the organization, there is no need to introduce teleological concepts). In particular we are likely to find purposive behaviour in assemblies like brains, which are large and incompletely observed. But I do not wish to give the impression that the generation of purposive or any other behaviour is enlodged within a particular assembly. In cybernetics we are thinking of an organization. Citing McCulloch's 1946 lecture, 'Finality and Form' '... some re-entrant paths lie within the central nervous system, others pass through remote parts of the body and still others, leaving the body by effectors, returning by receptors, traverse the external world. The functions of the first are, at present, ill defined, the second constitute the majority of our reflexes, the last our appetites and purposes ...' Their totality is the organism we study in cybernetics.

Other Sources

In zoology and in embryology there used to be a problem equivalent to the teleological dilemma of purposive behaviour. Here it took the name equifinality. Driesch, for example, was led to believe in a vital force, because the development of sea urchin embryos seemed to be pre-determined 'from outside' since they reached the same final form even though crassly mutilated. By the early 1920's biologists were thinking in terms of organization (there is a classic paper of Paul Weiss,[6] which bears this out) and it became obvious that in a wholly pedestrian manner the whole of an organization is more than the sum of its parts. The mystique behind equifinality (which lay there because, from a circumscribed point of view, the parts *should* add up to the whole) evaporated like the apparent magic of purposiveness. Von Bertalanffy's thinking in this direction exerted considerable influence, not only in biology but also in the social sciences, and he gave the name *system* to the organization which is recognized and studied (we speculate about the system which is the organization of a leopard and not about the leopard itself). Further, von Bertalanffy realized that when we look at systems (which cyberneticians always do) many apparently dissimilar assemblies and processes show features in common.[7] He called the search for unifying principles which relate different systems, General Systems Theory.

General Systems Theory found little acceptance in engineering and had little relation to the physiological developments until the mid-1940's. About then, engineers had to make computing and control devices elaborate enough to exhibit the troublesome kinds of purposiveness already familiar in biology. Also it was in the 1940's that Julian Bigelow, then Rosenblueth and Wiener realized the significance of the organizational viewpoint, and had the insight to wed together the developments we have discussed and the rigorous mathematics of communication engineering.

Definitions of Cybernetics

Thus, cybernetics was born. Since then it has been variously defined. At one extreme, there is the original definition, 'the *science* of control and communication in the animal and the machine,' advanced by Norbert Wiener[8] when he adopted the word* in 1948 in the book *Cybernetics* which is the first complete statement of the discipline (a paper[9] anticipates a part of the argument). At the other extreme is Louis Couffignal's[10] proposal, put forward as an expansion in 1956, 'La Cybernetique est l'art d'assurer l'efficacite de l'action.' The gap between *science* and *art* is filled by a continuum of interpretations. Thus, Stafford Beer[11] looks upon cybernetics as the science of proper control within any assembly that is treated as an organic whole. In industry, for example, this could be the science of management. Also he regards Operational Research, in its widest sense, as the principal experimental method of cybernetics, the science. Ross Ashby,[12] on the other hand, gives emphasis to abstracting a controllable system from the flux of a real world (for abstraction is a prerequisite of talk about control), and he is concerned with the entirely general synthetic operations which can be performed upon the abstract image. He points out that cybernetics is no more restricted to the control of observable assemblies and the abstract systems that correspond with them, than geometry is restricted to describing figures in the Euclidean space which models our environment.

For my own part,[13] I subscribe to both Ashby's and Beer's view, finding them compatible. Their definitions are both included by Wiener's global dictum.

The cybernetician has a well specified, though gigantic, field of interest. His object of study is a system, either constructed, or so abstracted from a physical assembly, that it exhibits interaction between the parts, whereby one controls another, unclouded by the physical character of the parts themselves. He manipulates and modifies his systems often using mathematical techniques, but, because in practical affairs cybernetics is most usefully

* The world 'Cybernetics' was first used by Ampère as the title of a sociological study. It is derived from the Greek word for steersman.

applied to a very large system, he may also build mechanical artifacts to model them. Simply because the particulars are irrelevant, he can legitimately examine such diverse assemblies as genes in a chromosome, the contents of books in a library (with respect to information storage), ideas in brains, government and computing machines (with respect to the learning process).

Common Misconceptions

It is easy to misinterpret the whole idea and conclude that cybernetics is a trivial or even meaningless pursuit. We have to answer the kind of criticism offered by Buck[14] – that anything whatever can be a system – according to most cybernetic definitions of the word. But I believe an answer can be given, providing we do not confuse the strict identity of principle between the workings of several assemblies, which the cybernetician tries to embody in his abstract system, with mere facile analogy. The confusion does occur when people over-simplify the supposed activities of a cybernetician, perhaps, for a popular account of them, by expressing these activities in terms of a single experiment.

Let us suppose, for example, that Mr X is building a cybernetic model of some region of the brain. Mr X is approached by Mr Y who asks his profession. 'Cybernetician,' says Mr X. 'Such nonsense,' says Y, 'I've never heard of it, but,' he adds, 'I can see you're making a model of the brain. Be sensible and tell me whether you are a psychologist, or an electronic engineer.' If Mr X insists that he is neither, but a cybernetician, Y will make some private reservations and humour the man, pressing Mr X to describe his activity 'as though he were a psychologist' or 'as though he were an electronic engineer', because he can 'understand that sort of language'. For Y is convinced that X is making some electrical imitation of the brain. But if the device *is* a cybernetic model, then it is almost certainly a *very* poor imitation. In consonance with Beer[8] I submit that the workings of a cybernetic model are identical with some feature in the workings of a brain which is relevant to the control within a brain. Most likely, this feature is *not* readily describable in terms of psychology *or* electronics. So, having missed the point, Y is apt to depart under the impression that X is bad at psychology and bad at electronics and a little demented.

It is easy to cite brain models which are merely imitations; most well-behaved robots, most of the tidy automata that imitate a naughts and crosses player, nearly all of the maze solving machines (though there are some, like Deutsch's Rat,[15] which are used explicitly to illustrate an organizational principle rather than to imitate a response). There are not so many cybernetic models to choose from, but one of them, made by Ashby[16] and called the Homeostat, admirably illustrates the distinction. It is made up of four interacting regulators and an independent switching mechanism which changes the interconnections between these elements until a stable arrangement is reached. It can (from the viewpoint of psychology and engineering respectively) be dubbed a 'brain-like analogue' and a 'device for solving differential equations', for it does, rather imperfectly, display a brain-like behaviour and it will, rather eccentrically, solve differential equations. Its imperfections as an equation solver (which it is not meant to be) are obvious from its construction and have met with a good deal of heavy-handed criticism. Its imperfections as a brain-like analogue (which, once again, it is not meant to be) occur because at the level of functional analogy the organization of a homeostat is not particularly brainlike. It is only when we come to the level intended in the cybernetic abstraction that the self-regulation in a homeostat is *identical* with the self-regulation in a brain, and with reference to this feature the homeostat *is a* cybernetic model of all brains.

Summary

To summarize, a cybernetician adopts, so far as possible, an attitude which lays emphasis upon those characteristics of a physical assembly which are common to each discipline and 'abstracts' them into his 'system'.

This is not a prudent methodology, for it runs the risk of seeming to be impertinent. It is justified in so far as it *does* lead to effective control procedures, efficient predictions, and acceptable unifying theories (and whilst this is true of *any* science, the sanctions are rightly enough weighted against a Jack of all trades). But the risk, on balance, is worth while, for the cybernetic approach *can* achieve generality and yield rigorous comments upon *organization*.

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ASHBY

WHAT IS NEW

1/1. Cybernetics was defined by Wiener as "the science of control and communication, in the animal and the machine"—in a word, as the art of *steermanship*, and it is to this aspect that the book will be addressed. Co-ordination, regulation and control will be its themes, for these are of the greatest biological and practical interest.

We must, therefore, make a study of mechanism; but some introduction is advisable, for cybernetics treats the subject from a new, and therefore unusual, angle. Without introduction, Chapter 2 might well seem to be seriously at fault. The new point of view should be clearly understood, for any unconscious vacillation between the old and the new is apt to lead to confusion.

1/2. *The peculiarities of cybernetics.* Many a book has borne the title "Theory of Machines", but it usually contains information about *mechanical* things, about levers and cogs. Cybernetics, too, is a "theory of machines", but it treats, not things but *ways of behaving*. It does not ask "what *is* this thing?" but "*what does it do?*" Thus it is very interested in such a statement as "this variable is undergoing a simple harmonic oscillation", and is much less concerned with whether the variable is the position of a point on a wheel, or a potential in an electric circuit. It is thus essentially functional and behaviouristic.

Cybernetics started by being closely associated in many ways with physics, but it depends in no essential way on the laws of physics or on the properties of matter. Cybernetics deals with all forms of behaviour in so far as they are regular, or determinate, or reproducible. The materiality is irrelevant, and so is the holding or not of the ordinary laws of physics. (The example given in S.4/15 will make this statement clear.) *The truths of cybernetics are not conditional on their being derived from some other branch of science.* Cybernetics has its own foundations. It is partly the aim of this book to display them clearly.

1/3. Cybernetics stands to the real machine—electronic, mechanical, neural, or economic—much as geometry stands to a real object in our terrestrial space. There was a time when "geometry" meant such relationships as could be demonstrated on three-dimensional objects or in two-dimensional diagrams. The forms provided by the earth—animal, vegetable, and mineral—were larger in number and richer in properties than could be provided by elementary geometry. In those days a form which was suggested by geometry but which could not be demonstrated in ordinary space was suspect or inacceptable. Ordinary space *dominated* geometry.

Today the position is quite different. Geometry exists in its own right, and by its own strength. It can now treat accurately and coherently a range of forms and spaces that far exceeds anything that terrestrial space can provide. Today it is geometry that contains the terrestrial forms, and not vice versa, for the terrestrial forms are merely special cases in an all-embracing geometry.

The gain achieved by geometry's development hardly needs to be pointed out. Geometry now acts as a framework on which all terrestrial forms can find their natural place, with the relations between the various forms readily appreciable. With this increased understanding goes a correspondingly increased power of control.

Cybernetics is similar in its relation to the actual machine. It takes as its subject-matter the domain of "all possible machines", and is only secondarily interested if informed that some of them have not yet been made, either by Man or by Nature. What cybernetics offers is the framework on which all individual machines may be ordered, related and understood.

1/4. Cybernetics, then, is indifferent to the criticism that some of the machines it considers are not represented among the machines found among us. In this it follows the path already followed with obvious success by mathematical physics. This science has long given prominence to the study of systems that are well known to be non-existent—springs without mass, particles that have mass but no volume, gases that behave perfectly, and so on. To say that these entities do not exist is true; but their non-existence does not mean that mathematical physics is mere fantasy; nor does it make the physicist throw away his treatise on the Theory of the Massless Spring, for this theory is invaluable to him in his practical work. The fact is that the massless spring, though it has no physical representation, has certain properties that make it of the highest importance to him if he is to understand a system even as simple as a watch.

The biologist knows and uses the same principle when he gives to *Amphioxus*, or to some extinct form, a detailed study quite out of proportion to its present-day ecological or economic importance. In the same way, cybernetics marks out certain types of mechanism (S.3/3) as being of particular importance in the general theory; and it does this with no regard for whether terrestrial machines happen to make this form common. Only after the study has surveyed adequately the *possible* relations between machine and machine does it turn to consider the forms actually found in some particular branch of science.

1/5. In keeping with this method, which works primarily with the comprehensive and general, cybernetics typically treats any given, particular, machine by asking not "what individual act will it produce here and now?" but "what are *all* the possible behaviours that it can produce?"

It is in this way that information theory comes to play an essential part in the subject; for information theory is characterised essentially by its dealing always with a *set* of possibilities; both its primary data and its final statements are almost always about the set as such, and not about some individual element in the set.

This new point of view leads to the consideration of new types of problem. The older point of view saw, say, an ovum grow into a rabbit and asked "why does it do this?—why does it not just stay an ovum?" The attempts to answer this question led to the study of energetics and to the discovery of many reasons why the ovum should change—it can oxidise its fat, and fat provides free energy; it has phosphorylating enzymes, and can pass its metabolites around a Krebs' cycle; and so on. In these studies the concept of energy was fundamental.

Quite different, though equally valid, is the point of view of cybernetics. It takes for granted that the ovum has abundant free energy, and that it is so delicately poised metabolically as to be, in a sense, explosive. Growth of some form there will be; cybernetics asks "why should the changes be to the rabbit-form, and not to a dog-form, a fish-form, or even to a teratoma-form?" Cybernetics envisages a set of possibilities much wider than the actual, and then asks why the particular case should conform to its usual particular restriction. In this discussion, questions of energy play almost no part—the energy is simply taken for granted. Even whether the system is closed to energy or open is often irrelevant; what *is* important is the extent to which the system is subject to determining and controlling factors. So no information or signal or determining factor may pass from part to part without its being recorded as a significant event. Cybernetics might, in fact, be defined as *the study of systems that are open to energy but closed to information and control*—systems that are "information-tight" (S.9/19.).

1/6. *The uses of cybernetics.* After this bird's-eye view of cybernetics we can turn to consider some of the ways in which it promises to be of assistance. I shall confine my attention to the applications that promise most in the biological sciences. The review can only be brief and very general. Many applications have already been made and are too well known to need description here; more will doubtless be developed in the future. There are, however, two peculiar scientific virtues of cybernetics that are worth explicit mention.

One is that it offers a single vocabulary and a single set of concepts suitable for representing the most diverse types of system. Until recently, any attempt to relate the many facts known about, say, servo-mechanisms to what was known about the cerebellum was made unnecessarily difficult by the fact that the properties of servo-mechanisms were described in words redolent of the automatic pilot, or the radio set, or the hydraulic brake, while those of the cerebellum were described in words redolent of the dissecting room and the bedside—aspects that are irrelevant to the *similarities* between a servo-mechanism and a cerebellar reflex. Cybernetics offers one set of concepts that, by having exact correspondences with each branch of science, can thereby bring them into exact relation with one other.

It has been found repeatedly in science that the discovery that two branches are related leads to each branch helping in the development of the other. (Compare S.6/8.) The result is often a markedly accelerated growth of both. The infinitesimal calculus and astronomy, the virus and the protein molecule, the chromosomes and heredity are examples that come to mind. Neither, of course, can give *proofs* about the laws of the other, but each can give suggestions that may be of the greatest assistance and fruitfulness. The subject is returned to in S.6/8. Here I need only mention the fact that cybernetics is likely to reveal a great number of interesting and suggestive parallelisms between machine and brain and society. And it can provide the common language by which discoveries in one branch can readily be made use of in the others.

1/7. *The complex system.* The second peculiar virtue of cybernetics is that it offers a method for the scientific treatment of the system in which complexity is outstanding and too important to be ignored. Such systems are, as we well know, only too common in the biological world!

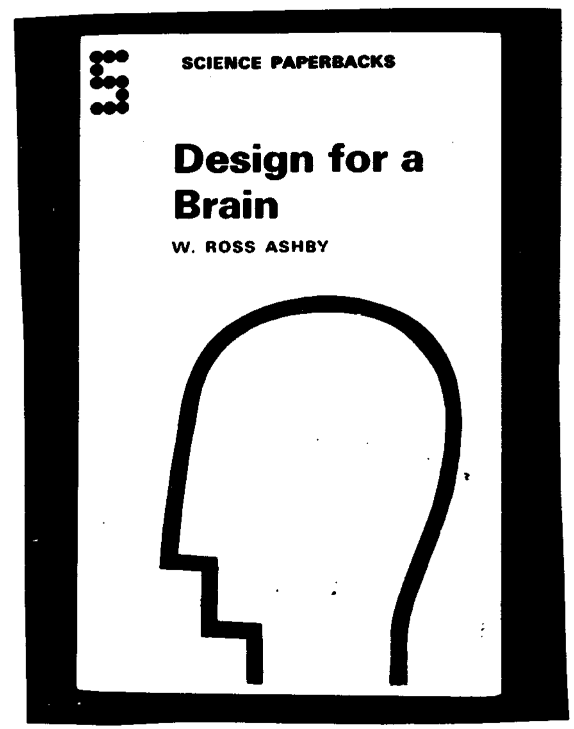
In the simpler systems, the methods of cybernetics sometimes show no obvious advantage over those that have long been known. It is chiefly when the systems become complex that the new methods reveal their power.

Science stands today on something of a divide. For two centuries it has been exploring systems that are either intrinsically simple or that are capable of being analysed into simple components. The fact that such a dogma as "vary the factors one at a time" could be accepted for a century, shows that scientists were largely concerned in investigating such systems as *allowed* this method; for this method is often fundamentally impossible in the complex systems. Not until Sir Ronald Fisher's work in the '20s, with experiments conducted on agricultural soils, did it become clearly recognised that there are complex systems that just do not allow the varying of only one factor at a time—they are so dynamic and interconnected that the alteration of one factor immediately acts as cause to evoke alterations in others, perhaps in a great many others. Until recently, science tended to evade the study of such systems, focusing its attention on those that were simple and, especially, reducible (S.4/14).

In the study of some systems, however, the complexity could not be wholly evaded. The cerebral cortex of the free-living organism, the ant-hill as a functioning society, and the human economic system were outstanding both in their practical importance and in their intractability by the older methods. So today we see psychoses untreated, societies declining, and economic systems faltering, the scientist being able to do little more than to appreciate the full complexity of the subject he is studying. But science today is also taking the first steps towards studying "complexity" as a subject in its own right.

Prominent among the methods for dealing with complexity is cybernetics. It rejects the vaguely intuitive ideas that we pick up from handling such simple machines as the alarm clock and the bicycle, and sets to work to build up a rigorous discipline of the subject. For a time (as the first few chapters of this book will show) it seems rather to deal with truisms and platitudes, but this is merely because the foundations are built to be broad and strong. They are built so that cybernetics can be developed vigorously, without the primary vagueness that has infected most past attempts to grapple with, in particular, the complexities of the brain in action.

Cybernetics offers the hope of providing effective methods for the study, and control, of systems that are intrinsically extremely complex. It will do this by first marking out what is achievable (for probably many of the investigations of the past attempted the impossible), and then providing generalised strategies, of demonstrable value, that can be used uniformly in a variety of special cases. In this way it offers the hope of providing the essential methods by which to attack the ills—psychological, social, economic—which at present are defeating us by their intrinsic complexity. Part III of this book does not pretend to offer such methods perfected, but it attempts to offer a foundation on which such methods can be constructed, and a start in the right direction.



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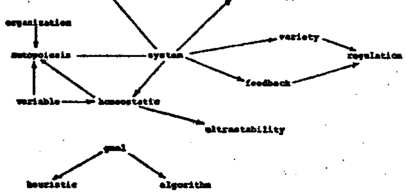
GENERAL SYSTEM THEORY

General System(s) Theory (GST) is a general science of organization and wholeness. It is generally agreed to have been founded by the late Ludwig von Bertalanffy, and he dated its inception from 1940. However, he acknowledged the same debts to precursors as did the founders of cybernetics, and denied the identity of GST and cybernetics only by delimiting the definition of the latter in a way which is probably too restrictive. The objectives of the Society for General Systems Research, founded in 1954, would certainly have had the agreement of the early cyberneticians in 1942. On the other hand, they may be more general than some scientists (notably in the USA and France) would allow to cybernetics today.



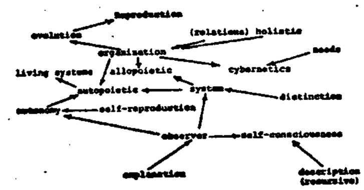
[S.B.]

SYSTEM

A system is the set of elements and relations, or operations on these elements, that is specified by an observer. Alternatively, a system is a set of variables specified by an observer. See the paper "System versus Collection". [K.L.W.]

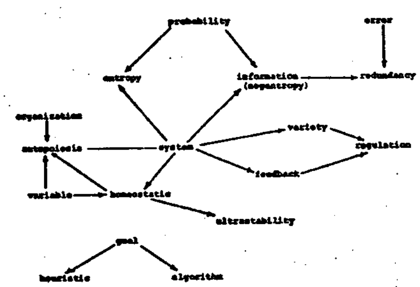
SYSTEM

Any distinction done by an observer, with the intention of further explaining in a consensual network the distinction done and its content. [F.V.]



FEEDBACK

The return of part of a system's output to change its input. Positive feedback increases the input, negative feedback decreases it. Hence if feedback is used (as it is in all regulatory systems) in comparing output with some standard to be approached, negative feedback is inherently stabilizing (because it decreases the error) while positive feedback is inherently destabilizing (and the error gains explosively in magnitude). The casual use of 'feedback' to mean 'response to a stimulus' is incorrect. [S.B.]



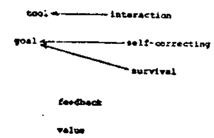
FEEDBACK

Information about the results of a process which is used to change the process itself. [S.U.]

FEEDBACK

An unpoetic inexpressive word that shrieks for replacement. Correct use of the term would refer to eating your own vomit. 'Positive feedback' and 'negative feedback' would signify whether you like the vomit or not.

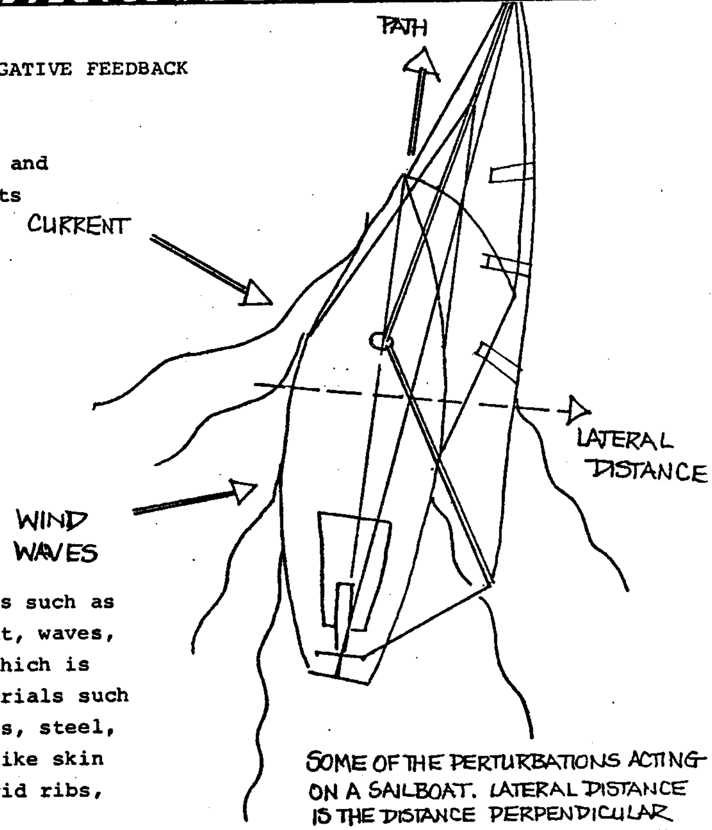
I'd prefer a term like 'circuit' to indicate any system or subsystem that responds to its own action - and something like 'convergent' or 'divergent' to indicate the nature of the response ('divergent' would cover the two unstable forms - anti-corrective 'positive feedback' and over-corrective hunting oscillation.)



[S.Br.]

TWO EXAMPLES OF NEGATIVE FEEDBACK

Rodney Clough

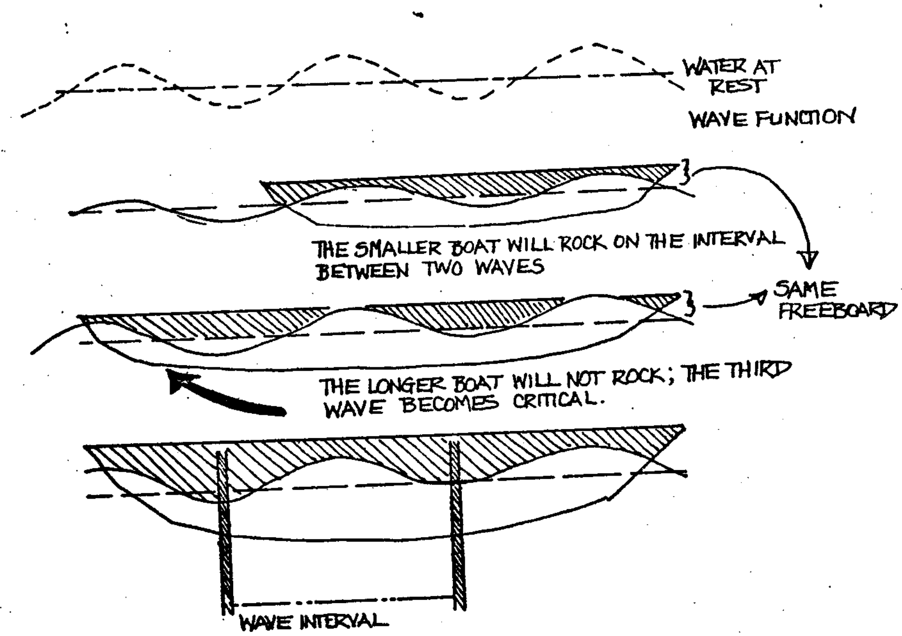


SOME OF THE PERTURBATIONS ACTING ON A SAILBOAT. LATERAL DISTANCE IS THE DISTANCE PERPENDICULAR TO THE PATH OR DIRECTION OF THE BOAT.

In the design and fabrication of boats or vessels which can be navigated in water, the origin of the keel is one example of negative feedback. We want to navigate a vessel in water. We know that to hold us in an environment which is easily perturbed by forces such as wind, tide, current, waves, we need a vessel which is made of rigid materials such as wood, fibreglass, steel, concrete, rubber-like skin stretched over rigid ribs, birchbark.

We also know that the larger a vessel we build, the more surface we create which is perpendicular to our path or to the direction we wish to go in at a given time. This surface is called 'lateral surface'.

By experimentation and process we know that the longer a vessel we build, the more height we need from the surface of the water. This height is called both 'freeboard' or the amount of hull exposed when the vessel is in the water and 'draft' or vertical distance of the hull



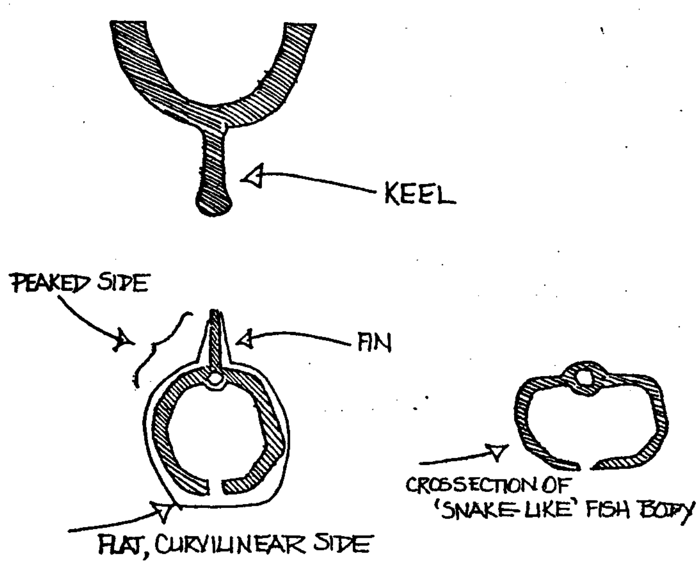
THERE EXISTS A RATIO BETWEEN THE LENGTH OF A BOAT AND THE AREA OF THE EXPOSED HULL OR FREEBOARD, AND DRAFT

from top to bottom.

By navigating a boat--one which we have either built ourselves or which we have traveled on--we observe that the amount of lateral surface and freeboard retards the speed of a boat. Fast boats are associated with low profile, sleek shapes similar to the bodies of fish.

If we watch fish swimming, we observe that the faster fish are very thin and are able to pilot themselves by a very complicated actior of twisting the body and fluttering a side appendage or fin. Some fish do not have any fins and navigate by twisting their bodies snake-like through the water. Other fish, which appear larger and more 'evolved', twist less and propel themselves by sweeping very large fins, very like a bird's wings. Their motion seems more effortless and smooth. We notice that they are equipped with two highly differentiated sides:

a top which is peaked, and a bottom which is curvilinear--nearly flat. These fish are very different from the snake-like cousins, whose bodies, if we were to cut them up, are circular.



CROSSECTION OF SAILBOAT AND CROSSECTION OF FISH BODY. FOR COMPARISON, NOTE CROSSECTION OF 'SNAKE-LIKE' FISH BODY.

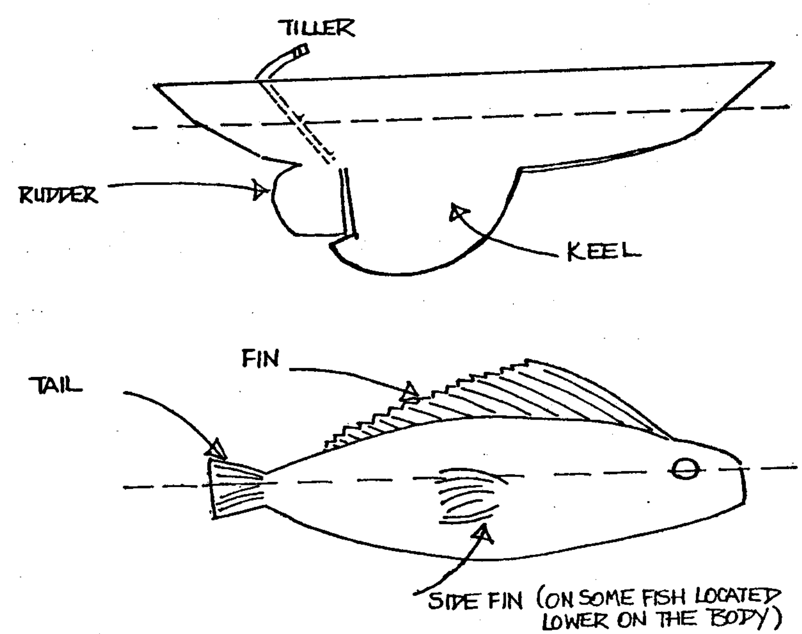
We turn our attention to the larger family of fish, which propel themselves by sweeping fins. The snake-like family of fish, which twist, seem to have a motion which is unlikely for our purposes of navigating a boat built of rigid materials--something which will hold us as we travel through the water.

Looking closely at how these fish do this--we could also look closely at different kinds of vessels--we see that the shape of the fish body tapers at one end where the activity of propulsion seems to be concentrated. More complicated movements and agility at performing different movements--swimming, darting, cruising, diving--are associated with this taper and how the peaked side of the fish follows this taper.

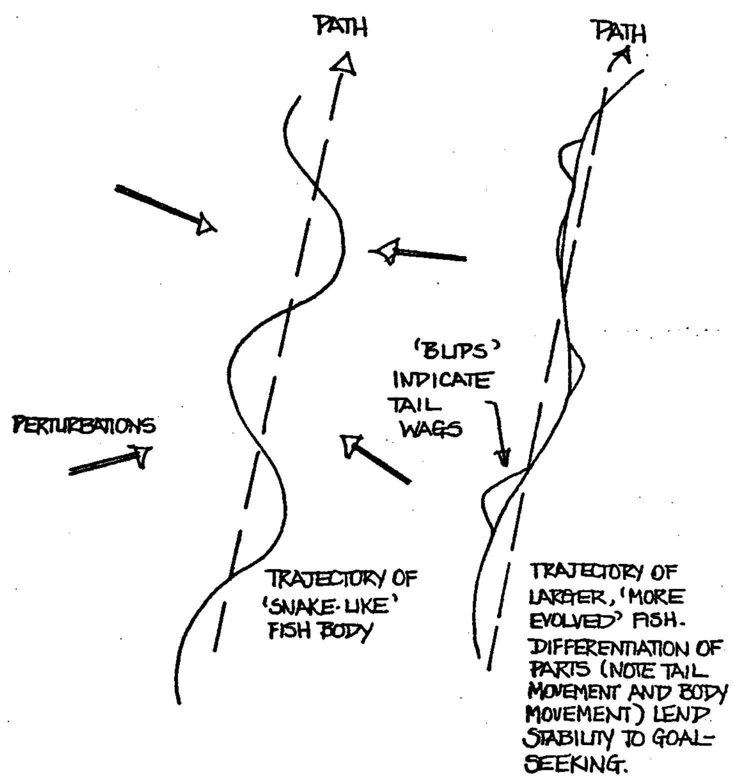
The larger the fish, proportionately, the larger the peaked side and the smoother the taper of the body shape.

Can there be a relationship between the length, freeboard, lateral surface of our vessel and the relationships we have observed between the peaked side, body taper and volume of the fish?

By experimenting with various representations or models of vessels--some which we borrow from ones that have been built, others which we build ourselves--we notice that this peaked side of a shape moving in water plays a large role. It keeps the fish 'up'; it keeps the fish straight on its path, without drifting from side to side; and it keeps the fish stable when it is not moving. In



SIDE PROFILE OF BOAT WITH KEEL AND FISH BODY ENLARGED FOR COMPARISON. NOTE HOW FORM TAPERS TO AREA OF STEERAGE (CONTROL) AND PROPULSION theory it plays the same role as the twisting to and fro of the snake-like fish, for the constant movement of the twisting keeps the snake-like fish stable without drifting from side to side.



For our purpose of navigating a rigid structure with a minimum of movable parts through a fluid environment, the form of the keel acts to maintain the stability of the system at rest and while moving.

<u>For discussion in class</u>: Assuming our purpose, demonstrate how the hydroplane and the Roman Galley are two examples of positive feedback.

Another example of negative feedback is the function a jury performs in the adversary or 'trial' form of justice.

The 'adversary form of justice' assumes that in a society governed by law and not by force, an injustice is defined as the infringement of rights by one party on another. Both parties re-enact the injustice in a public forum before an assemblage of peers, called a jury. Advocates for each party defend their position by constructing evidence or the string of events which comprise the interaction. The jury, meeting outside of the forum, re-constructs the events and decides which party is responsible for the infringement of rights and therefore must pay the other party for any loss, damage, or hurt which has been inflicted. The judge, or presiding officer of the court, weighs the loss incurred and demands the responsible party to pay a penalty to theother party or likewise suffer a loss of rights, or both.

Which function helps to maintain stability in the system governed by law: that of the jury or the judge? We must rule out the judge, for the function of a judge is to analyze the loss incurred, irrespective of who is responsible for the loss.

We are left with the jury, whose function is to reconstruct the events and decide which party is responsible, irrespective of the loss incurred.

Imagine we selected the judge as an example of negative feedback. In the role of the judge would be concentrated the task of deliberation: the judge would be privy to one of both sides and suspect. Centuries ago, this was the case. 'The concept of justice resided in one man--usually, born of nobility. If we would be fortunate to live in the tenure of a 'good lord' we might have justice. However, if we were not so lucky, rule by force would be the case.

Our peers, represented by a jury, resolves the breach of credibility caused when two parties participate in an injustice. The jury maintains stability of the system and, as well, stability of the adversary form.