EXISTING CYBERNETICS FOUNDATIONS

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Keywords: Cybernetics, system, control, black box, entropy, information theory, mathematical modeling, feedback, homeostasis, hierarchy.

Contents

Summary

Cybernetics is a science that studies systems of any nature that are capable of perceiving, storing, and processing information, as well as of using it for control and regulation.

The second title of the Norbert Wiener’s book “Cybernetics” reads “Control and Communication in the Animal and the Machine”. However, it is not recognition of the external similarity between the functions of animals and machines that Norbert Wiener is credited with. That had been done well before and can be traced back to La Mettrie and Descartes. Nor is it his contribution that he introduced the notion of feedback; that has been known since the times of the creation of the first irrigation systems in ancient Babylon. His distinctive contribution lies in demonstrating that both animals and machines can be combined into a new, wider class of objects which is characterized by the presence of control systems; furthermore, living organisms, including humans and machines, can be talked about in the same language that is suitable for a description of any teleological (goal-directed) systems. This epistemological assumption has determined to a great extent the specific means and methods that are used in

cybernetics.

An analysis of the existing paradigms and views on the subject, and the content of this area of knowledge, shows that the foundations of cybernetics are formed from the principles of organization of complex systems, the processes of information transfer, storage, and processing, and the mechanisms of goal-directed control. It is precisely these principles, processes, and mechanisms that are used in the study of the specific properties of control and communication which provide for the synthesis or simulation of the behavior of living organisms and automatic systems, and that constitute the essence of cybernetic research.

To obtain concrete results, various mathematical methods that allow the construction of effective dynamical models are widely used in cybernetics.

1. Introduction

Cybernetics is a science that studies systems of any nature which are capable of perceiving, storing, and processing information, as well as of using it for control and regulation. This is one of the many definitions of cybernetics. Some others are:

- Cybernetics studies systems that are open with respect to energy, but closed under information and control.
- Cybernetics studies various informable, informing, and information systems.
- Cybernetics studies how to create, reveal the design of, and identically transform algorithms describing control processes.
- Cybernetics studies the optimal, goal-directed control of complex developing systems.

Despite the seemingly apparent differences in these definitions, an analysis of their specific content shows that the difference lies not in the subject itself, but rather in the varying approaches to phenomena under study. It becomes especially clear if we consider the main notions and principles of cybernetics.

The second title of Norbert Wiener’s book “Cybernetics” is “Control and Communication in the Animal and the Machine”. However, cybernetics, as a science, is not credited with placing emphasis on the apparent kinship between human and animal functions. That had been noticed long before cybernetics was born, and dates back to La Mettrie and Descartes. Nor is cybernetics credited with the introduction of the notion of feedback—an adjustment of controlling actions on the basis of information about their results. The idea of feedback itself was known as early as ancient Babylon with its creation of irrigation systems. However, cybernetics has been crucially important in noticing that any feedback system is automatically goal-directed. The difference between an automatically directed system and a system that attempts to reach its goal as a result of will power impulses is purely implicit, “internal”, and cannot be established with certainty by application of any external criterion.

Therefore, the achievement of cybernetics can actually be seen in the demonstration of the fact that both animals and machines fall into a new, wider class of objects that is characterized by the possession of control systems. In other words, cybernetics not only draws analogies between animals and machines, but also studies the questions of system development at such an abstract level that, in context, both animals and machines merely represent special cases that can be approximated by modeling. The significance of cybernetics also lies in that it makes it possible to talk about living organisms, including humans, and machines, in the same language that is equally suitable for a description of any teleological (goal-directed) systems. This last assumption, which is inherently epistemological, has essentially determined the specific means and methods used in cybernetics.

An analysis of the existing views on the subject and content of this area of knowledge shows that the foundations of cybernetics are the principles of complex systems organization; the processes of information transfer, storage and processing; and the mechanisms of goal-directed control. It is precisely these principles, processes, and mechanisms that are used to study the specific properties of control and communication, which provide for a synthesis or simulation of the behavior of living organisms and automatic systems, and that shape the core of cybernetic research.

One of the basic ideas introduced by cybernetics into modern philosophy is a new view on the components of the world around us. The classical notion of the world consisting of matter and energy has been changed to that of a world which has the three components of matter, energy, and information, since an organized system without information is unthinkable.

It has also become apparent that complex systems are not entirely determined by their physical descriptions. Their information content and control structures must be described as well. For example, the "gene" system is not wholly determined by the description of the DNA molecules; the gene also contains the information encoded by the configuration of the molecules as well as by the control chains that synthesize proteins. It is in that context that the gene becomes a unit of heredity.

Another principal question posed by cybernetics is the relationship between the abilities of computers and thinking, which represent extreme types of control systems, fully formalized in case of the computer and not formalized at all in case of human thinking.

As cybernetics developed, the approach to this basic question transformed, and cybernetics and artificial intelligence became separated. In the field of artificial intelligence, models of systems implementing various aspects of knowledge-seeking activities are developed; however, the methods used are not required to be the same as the ones used by humans and animals. On the other hand, in cybernetics we always talk about "resemblance" to live prototypes.

Cybernetics possesses two aspects: syntactic and semantic, if both terms are used as in linguistics. The former is related to the study of the principles that determine how the set of all possible systems functions; the latter is concerned with interrelationships between these principles and actual systems belonging to various knowledge areas. Furthermore, the main emphasis is on the very complex probabilistic self-adjusting systems which are studied in cybernetics.

Research on these systems is conducted at the level of organization and information. The properties of the material from which a system is composed are considered only to the extent that they affect the organization. To obtain specific results, various mathematical methods are used. These methods must enable us to design effective dynamical models; this constitutes the main methodological technique in cybernetic research.

It has become absolutely clear that many of the conceptual schemes that determine the behavior of living organisms when solving specific problems are virtually identical to the schemes that characterize control processes in complex man-made systems. Furthermore, there is no doubt that both social and economic control models can be analyzed on the basis of the same general assumptions and notions that have been developed in cybernetics.

When studying general rules and laws that are possessed by systems very different in their nature and specific activity mechanisms, it is necessary to apply far-reaching abstraction processes, based on a number of mathematical disciplines such as probability theory, mathematical statistics, set theory, functional analysis, topology, etc. Being based on mathematics, cybernetics in turn propels the development of the mentioned branches of the mathematical sciences and the creation of new ones. As a matter of fact, such areas of mathematics as information theory, game theory, automata theory, and several others were invented and took shape as a direct consequence of research in cybernetics.

2. Organization

Among the core three components—organization, information, and control—organization can be arguably positioned as the most important, since it is the very basis for all the subsequent analyses of cybernetic systems. It was John von Neumann who first emphasized that, when complex systems are studied, the question of how the elements of a system function presents just one part of the problem. The second part is concerned with the way in which these elements are connected to form the whole. It is exactly this part that is properly cybernetic because it is related to system organization, and to the evaluation of the degree of that organization.

2.1 Systems and Complexity

Usually, organization is defined as a set of elements united as a whole in such a way that their various activities are put into a common order that determines the specific properties of the system thereby formed.

In its turn, a system is a set of interacting elements or processes united as a whole by the realization of a common function that is irreducible to a function of the system's components. Hence, the notions of system and organization are closely intertwined.

Some of the system's features are as follows: when interacting with the environment, the system acts as a whole entity; every element of the system cannot be decomposed further; when external conditions and the internal state change, the general structure of interactions among the system's elements remains the same.

The common property, shared by all systems, is the presence of some input variables which are transformed into output variables according to a function realized by the system. The most complete characteristic of any system is a description of the entire set of values of the variables that determine its behavior. Such a set is a state space of the system and consists of the sets of input variables, output variables, internal states, state-to-state transfer functions, and output functions.

As a rule, the state space is n-dimensional where n is the number of independent variables, or, in other words, coordinates. In the state space of a system, the number of independent variables is the number of its degrees of freedom.

The presence of a large number of nontrivially interacting elements leads to the conclusion that, in cybernetic systems, the whole is more than a sum of its components. It is not possible to draw correct inferences about the properties of the system as a whole if only the properties of the components and their interactions are given.

The organization of cybernetic systems also reveals itself in the process of control. For organized systems, it is typical that at each moment of time their dynamics are determined by a relatively small number of parameters. This feature allows one to rationally design the control process, and to seek the most important properties of such systems.

The complexity of cybernetic systems is usually imparted in a hierarchy; all hierarchical systems share common properties that are independent of the specific content of those systems, but are determined by the intensities and the interaction structures of their subsystems.

Therefore, a hierarchical system is defined to be a system consisting of interrelated subsystems, each of which, in its turn, is hierarchical in structure, etc., until some lowest level of the elementary subsystems is reached. Hence, the special property of hierarchical structures is the successive separation of the system into co-directed subsystems.

It is widely recognized that biological systems are hierarchically organized. If the cell is to be considered an elementary subsystem, then cells are organized into tissues; tissues are organized into organs; organs are organized into the systems of organs; the systems of organs are organized into the organism, etc.

The notion of hierarchical organization is closely related to the ideas of organizational levels, i.e. levels of description, abstraction, and decision-making complexity for cybernetic systems. According to these ideas, it only makes sense to study living organisms at levels higher than the chemical and physical ones; furthermore, it is precisely at these levels that principally new phenomena, which are essential to self-organizing systems, but not observable at the lower levels, occur.

In terms of their functional organization, all systems can be classified as either deterministic or probabilistic. A deterministic system is a system that can be studied without any uncertainty. For such a system, if a current state, input signal, and input transformation rules are specified, the next state can be predicted with 100% accuracy. However, if under the same conditions the prediction can only be made with some probability, such a system is called probabilistic. It has been mentioned above that the probability is one of the properties of systems studied in cybernetics.

2.2 Organizability

An essential property of any complex system is the degree of its organization, which depends on how varied the elements and their connections are, as well as on the multiplicity of connections. Hence, the degree of organization is determined by the sufficient structural and functional complexity of the system. Organizability, i.e. the presence of a certain structure that manifests itself in the expediency of the system's elements and their connections, is a necessary condition for the existence in the system of at least potential possibilities for control.

It is difficult to define the notion of organizability, but it seems intuitively conceivable that organized systems possess, to a greater or lesser degree, some ordering, as a measure of which we can accept the degree of deviation of the system from the thermal equilibrium.

It seems reasonable to assume that organization occurs when a relation between two variables depends on the value or state of a third variable. This can be illustrated by the following simplest example ("chassis of the tent"). Let a be necessary for b and c, b be necessary for a and c, and c be necessary for a and b. Any two of those elements cannot exist without the third; therefore, any attempt at building such a system by successive addition of the elements would fail at the very start. In other words, a system of that type can only exist as a whole, where the interaction between any two elements depends on the third one.

One of the special features of an organized system is its ability to extract order to sustain or even increase the degree of its own ordering. This case is of particular interest since it can serve as a justification of the assumption that there is a universal principle that, for example, enables biological systems to increase the degree of their structural and functional ordering in the processes of growth, development, and adaptation to the environment. Cybernetic systems that implement this principle are called self-organizing.

A special property of self-organizing systems is their ability to adapt their behavior in response to changes in the environment in which they function. Such behavior incorporates both a simple feedback adaptation and its more complex analog, adaptation by learning. In the process, two classes of control tasks are performed: control of the internal organization of the system; and functional control.

The term "self-organization" has at least two meanings. The first one refers to the case where we have a system in which all of its parts had initially been independent from each other, but have developed connections in the process of functioning. The second meaning concerns the case where the transition from a “badly-organized” to a “well-organized” system occurs.

In cybernetics, a “good” organization is one that provides, in each specific case, for interaction of the parts of the system to achieve a prescribed state (goal function). However, generally speaking, the notion of “good” organization is relative. For example, the wide variety of functional connections among different areas of the animal brain is good inasmuch as the environment is rich in connections. On the other hand, if the parts of the environment are not very strongly connected (independent), the adaptation will accelerate if the parts of the brain are likewise weakly connected (independent).

Another peculiarity of organized systems is the presence of functionally different, interconnected parts that permit the distinction of the structure and purpose of various elements of the system, and the establishment of the nature of their interaction amongst themselves, and with the environment.

2.3 Black Box

When organization is studied formally, an auxiliary concept of the “black box” is often used. It formalizes the standard research strategy in which a newly studied object is treated as having an unknown internal structure, but is assumed to be able to perceive some set of input signals, generate some set of output signals, and associate the input with the output according to one of a set of admissible rules.

Therefore, a black box is a system that only avails its input and output variables to an external observer; its internal workings remain unknown. It turns out that a series of important conclusions about a system’s behavior can be drawn by observing the reactions of the output variables to changes in the input variables. Such an approach opens a possibility for objective study of systems whose internal structure is either unknown or too complex to deduce their behavior from the properties of their constituent parts and the structure of their connections.

To study a black box, it is necessary to study the information streams and choose an algorithm that would transform the input information to match the output state. When using the black box concept, there is a limit on the information that can be obtained. A black box can only be studied up to an isomorphism. In other words, if, based on the given data, it is possible to design a mechanism that fully imitates the behavior of the black box, the problem can be considered solved. However, the generation of a black box analog, i.e., a device isomorphic to the black box, does not mean that we understand the black box completely. It is necessary to keep in mind that any black-box research of a system cannot principally lead to a unilateral conclusion concerning the internal structure of the system because its behavior cannot be distinguished from the behavior of all systems isomorphic to it.

Whenever a relatively simple system corresponds to the properties of a more complex system, i.e., whenever a one-to-one mapping from the simple to the complex exists (but not vice versa), the systems are homomorphic. Therefore, it should be said that actual black boxes can only be homomorphically mapped to models, devices, and algorithms.

It is always possible to decompose any complex system into several black boxes and focus on the study of the organization and functional principles of just one or some of these black boxes; this is precisely what makes the black box concept so meaningful. When studying a black box, the following problems are solved:

- Determination of the inputs and outputs of the system (homomorphic approach).
- Revelation of the information streams (successive trials aimed at the limitation of the variety of the system's responses).
- Disclosure of the information code, i.e., determination of the necessary dichotomies, the rules according to which an input state is mapped onto an output state.
- Design of a model homomorphic to the black box under study.

Advances in the analysis and synthesis of cybernetic systems can be symbolically presented as the replacement of black boxes by white boxes where a white box is understood to be a system that is built from well-known elements that are connected in such a well-known way that the given dependence between the inputs and the outputs is implemented.

The black box concept is, to a certain extent, a realization of the epistemological assumption in cybernetics, which states that any clear (rule-based) description of behavior can be formalized. Hence it is possible, at least in principle, to represent the behavior of a human by a set of independent statements that describe the "inputs" of the organism and are correlated with the statements that describe its "outputs". (See *General Systems Theory*.)

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Biographical Sketch

Boris M. Vladimirski was born in Tiraspol, Moldova, (former Soviet Union) in 1939. In 1965, he graduated from Novocherkassk Polytechnic Institute having majored in mathematical and computing devices. From 1965–1969, Boris Vladimirski studied bionics as a graduate student at Rostov State University, Russia. In 1970, he defended a Candidate of Science (the approximate equivalent of Ph.D.) dissertation entitled “On some Properties of Spatial Organization of Various Functional States of a Neural Cell and a Neuronal Network”. Immediately after the defense, he began to teach and conduct research at Rostov University as an Assistant Professor, then later as Associate Professor, Professor of the Department of Human and Animal Physiology, Head of the High-performance Computing Laboratory, and from 1995-present, as both Director of the A. B. Kogan Research Institute for Neurocybernetics and Chair of the Department of Biophysics and Biocybernetics.

In 1993, Boris M. Vladimirski defended a Doctor of Science (a research degree awarded only for outstanding original contributions; a step up from a Ph.D. degree as major as that from a Bachelor to a Ph.D.) dissertation entitled “The functional state of the human operator: Prognosis and control” at Moscow State University. His research interests include diagnostics of the functional state of human and animal brain; and methods of analysis of bioelectrical activity. In 1998, he was conferred upon the Order of Honor of the Russian Federation for the development and realization of a method for identification of visually unidentifiable persons. Boris M. Vladimirski is the author of nearly one hundred publications, including two monographs and two textbooks recommended formerly for use over the entire territory of the Soviet Union by the Department of Education of the Soviet Union, and latterly for use nationwide by the Russian Department of Higher Education. He is also a member and the Chair of the Organizing Committees of international conferences on neuroinformatics and neurocomputers.