Departmental Papers (ASC)   Annenberg School for Communication

1989

Cybernetics

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Disciplines
Communication | Social and Behavioral Sciences

that contain and process their own information or are informationally closed. For management consultant Stafford Beer, cybernetics became the science of effective organization. U.S. neurophysiologist Warren S. McCulloch saw in cybernetics an experimental epistemology that enabled him to study communication within the brain and between observers and their environments. Late in his life JEAN PIAGET recognized cybernetics as an approach to modeling the cognitive processes underlying the human mind (see COGNITION). And GREGORY BATESON stressed that whereas the subject matter of science previously had been matter and energy, cybernetics, as a branch of MATHEMATICS dealing with problems of control, recursiveness, and information, focuses on forms and "the patterns that connect."

Circularity and Purpose

Probably the single most fertile idea in cybernetics is that of circularity. When A causes B and B causes C but C causes A, then A essentially causes itself, and the whole—consisting of A, B, and C—somewhat defies external manipulation. The cybernetic notion of circular reasoning has expanded scientific explanation and has yielded extraordinarily important constructions.

Traditional machines, culminating in the Industrial Revolution of the nineteenth century, replaced human physical labor in many areas, but humans still had to control the machines. For example, cars contain engines for locomotion, but drivers have to keep them on course. Early control theory aimed at the design of servomechanisms, that is, machines that could control other machines. Thermostats for temperature regulation, automatic pilots, industrial robots, wholly automated chemical plants, and, unfortunately, goal-seeking missiles are the results. In all of these examples the purpose is imposed from the outside by a human user or designer. When this theory is applied to human behavior, the negative feedback implied requires internal representations of desired states of affairs against which perceived deviations are measured and counteracted. For example, William T. Powers linked actions to perceptions and developed a psychology from the insight that all human behavior controls PERCEPTION.

During the seminal Macy Foundation conferences on cybernetics between 1946 and 1953 the multidisciplinary participants came to realize that circular causalities—such as a steersman who acts on the observed consequences of his actions, a speaker who continuously modifies her presentation while monitoring audience reactions to what she says, or the homeostatic mechanisms by which a living organism keeps important physiological variables in balance—underlie all purposive actions and that systems that embody them are fundamentally different from those

CYBERNETICS

The word *cybernetics* was derived by mathematician and social philosopher NORBERT WIENER from the Greek word for the art of steering, *kybernētēs*. He defined it as "the science of control and communication," and to emphasize that the material embodiments of these processes were not central to its concern he added "in the animal and the machine." Before its modern meaning, André-Marie Ampère had used the word in 1838 and 1843, and ideas of cybernetics have been traced to Hero of Alexandria, who lived in the first century C.E.

Cybernetics is fundamentally concerned with organization, how organization emerges and becomes constituted by networks of communication processes, and how wholes behave as a consequence of the interaction among the parts. Cybernetics surfaced in a series of interdisciplinary meetings that began in the 1940s at a time when machines were envisioned that could do intellectual work; when communication and control became an increasingly important feature of society; when organizational challenges, especially during World War II, revealed scientific limitations; and when overarching organizing principles such as religion, IDEOLOGY, and imperialism seemed to give way to notions of autonomy, self-government, and, last but not least, information.

Wiener's book *Cybernetics,* first published in 1948, summarized the interdisciplinary collaboration and set forth the accomplishments and visions of the new field. In 1956 British psychiatrist W. Ross Ashby wrote an influential introduction to the field and suggested that cybernetics be concerned with systems

that do not. As a consequence of circular causalities within their organization the initial conditions and actual trajectories of behavior of such systems are insignificant in view of the final state to which they converge or the goal that they maintain in spite of outside disturbances. This recognition gave rise to a new teleology in which circular forms of organization (processes) and final conditions (states or structures) mutually define each other without reference to an origin or external purpose. Finding such circularities everywhere in the human nervous system suggested scientific research into questions of mind, consciousness, the notion of self (as in self-organization, self-identification, self-awareness), and an approach to human behavior without recourse to inside representations of outside events, controllers, or values. Such research is distinct from a search for linear causalities that either remains incomplete or ends in ultimate causes (theology). The early study of circular causalities helped to identify pathologies of the nervous system and aided the design of artificial organs. To social scientists it meant that purpose and mind may be seen as distributed (not centralized) and imminent in the way people interact or communicate with one another regardless of whether participants are fully aware of them. Examples of applications of this principle range from the maintenance of homeostasis in families to the working of checks and balances in an economy. Here cybernetics shifted attention from control *of* to control *within*.

Stability and Morphogenesis

Control theory is conservative in the double sense of motivating systems capable of stabilizing some of its variables and of requiring that such systems remain organizationally invariant during the process (morphostasis). Consequently, the modeling of social phenomena in terms of negative feedback control theory tends to promote the status quo. But circular causalities also can lead to runaways, such as arms races, explosions, meltdowns, or cancerous growths. These appear "uncontrolled" for fear of the unknown destruction they may cause. However, Japanese anthropologist Magoroh Maruyama has shown that deviation-amplifying circular causalities need not always be destructive. They may lead, through temporary instabilities, to new forms (morphogenesis), and in fact may account for many processes of social change. For example, above a certain threshold, organizational success breeds more success and initiates growth until new constraints are encountered; or an originally insignificant dissatisfaction may mushroom into widespread dissent until the whole social system is ready to undergo structural changes, reorganize itself, or assume a new identity. Managers, politicians, and therapists do not hesitate to initiate such "vicious cycles" for creating new systems. Ash-

by's concept of ultrastability, French mathematician René Thom's catastrophe theory, and Belgian physicist and Nobel laureate Ilya Prigogine's work on dissipative structures all concern such forms of morphogenesis.

Communication

Modern communication theory arose out of the cybernetic marriage of statistics and control theory. The idea that messages could be distorted by unpredictable perturbations ("noise") and recovered within limits by a receiver led to a concept of communication as the variation that senders and receivers share, or of information as the pattern that is invariant throughout the noisy transmission of messages from one place or medium to another. CLAUDE SHANNON's 1948 monograph "A Mathematical Theory of Communication" was a milestone for understanding communication quantitatively (*see* INFORMATION THEORY). Since its publication, explanations in terms of information processing, encoding-decoding functions, channels of communication, pattern recognition, uncertainty, redundancy, noise, equivocation, entropy, and the like have come to be used in nearly all fields of science. The theory reflects a shift in emphasis from isolated objects to organized wholes or from the separate study of senders, receivers, and messages to an inquiry into how they are related dynamically and quantitatively. Ashby's extension of the originally bivariate notion of communication to one embracing many variables renders information theory a statistical tool for tracing information flows in complex systems. The theory also provides measures of diversity, memory capacity, intelligence, and organization, plus a new way of conceptualizing cultural functions of art.

Computation and Algorithms

The development in cybernetics of an algorithmic logic that incorporates circularities in the form of recursive functions (functions that contain themselves in their arguments, like the square root of the square root of the square root . . .) and time profoundly changed scientific thinking. Against the background of Kurt Gödel's famous incompleteness theorem, whose proof involved recursive functions, British mathematician Alan M. Turing's work on a theory of computation, McCulloch and Walter H. Pitts's logic of neuronal networks containing loops, and, after experiences with ENIAC (the first operational vacuum-tube-based "ultra-rapid calculating machine"), JOHN VON NEUMANN presented a landmark proposal to an international symposium on Cerebral Mechanisms of Behavior (the 1948 Hixon Symposium) that became the foundation of the theory of finite-state automata and a blueprint for modern programmable digital computers (*see* COMPUTER:

HISTORY). These ideas not only gave birth to computer science, the field of ARTIFICIAL INTELLIGENCE, and the computerization of society but also shifted scientific attention from existing structures (ontology) to the operations that bring about particular phenomena (ontogenesis). In addition, they challenged the verification theory of truth, on which traditional science could heretofore rely, by positing instead a computability/decidability criterion. The notion of computation has since been generalized to a great many processes—technological, mental, and social—and theory constructions in the form of algorithms, which are a prerequisite of computer and mathematical modeling, are increasingly common. *See also* COMPUTER: IMPACT.

Contributions to Biology

Research in biology, by U.S. physiologist Walter B. Cannon on homeostasis and continued by Ashby on adaptation, ultrastability, information, and intelligence, revealed the enormous "wisdom" in the human nervous system. Work by McCulloch on neuronal communication nets, by von Neumann on self-reproduction, and by Austrian-born biophysicist Heinz von Foerster on learning and self-organization led to a view of the human brain as a model of sophisticated computing machinery and expanded greatly the conception of computers as an aid to human intelligence. (In the field of artificial intelligence this relationship is often reversed, taking computers as models of human cognition.)

Chilean biologists Humberto R. Maturana and Francisco G. Varela, along with others, suggested autopoiesis, a recursive process of self-production, as the fundamental process characterizing all living systems. Varela proposed various principles of biology, based on the autopoietic organization of living systems, relating especially to the concepts of autonomy and closure, that aim to overcome the previous preoccupation with control. In Maturana's work on the biology of cognition he challenged the epistemological foundations of all sciences that claim to study nature without acknowledging that all scientists are constitutionally tied to their own biology of cognition and that their universe is thus confined to computations in their own nervous systems. These ideas originated in biology, but the theories and computational models they inform are generalizable to other disciplines.

Contributions to the Social Sciences

Wiener, quoting Bateson and MARGARET MEAD, recognized that the social sciences are fundamentally concerned with organization, that communication systems and circular flows of messages in particular are the "glue" that holds social organizations together, and that cybernetics therefore is essential for understanding the ontogenesis of society. Von Neumann and Oskar Morgenstern's game theory was an early cybernetic contribution to social interaction. It formalizes the coordination of action by players who have to consider their own behavior and the behavior of others. Extended to many players—so-called n-person game theory—to longer strategic commitments—so-called meta-game theory—and to different levels of information available, the theory is now a standard approach in economics and political decision making.

The idea that purpose could be structurally manifest in social organization proved attractive to anthropologists, sociologists, political scientists, and management scientists. With its emphasis on organization, variety, teleology, autonomy, and epistemology, cybernetics offered attractive alternatives to the usual theological, hierarchical, and linear causal constructions of social reality. Beer derived cybernetic principles of decision making, social learning, and adaptation and successfully applied them to business organizations and governments. Political scientist Karl W. Deutsch explored teleological models in the social sciences and developed a cybernetic approach to government. For some sociologists, cybernetics has lent mathematical substance to KARL MARX's idea of "structural purpose." Polish economist Oskar Lange used cybernetics to model the economics of production. Bateson suggested "messages in circuit" as a unit of analysis and applied cybernetics in his explorations of art as communication, of human reasoning, and later of family therapy. Taking seriously the fundamental circularity in human interactive communication, Bateson saw the therapist as a participant in a system in which the family could develop its own autonomy, much as British educational theorist Gordon Pask viewed education as a mutual process in which teachers and learners adapt to and learn from each other. U.S. anthropologist Roy A. Rappaport employed cybernetics to demonstrate the regulative function of RITUAL and sanctity in human ecology. And in a related analysis Bateson showed convincingly how planning, as a supreme manifestation of human conscious purpose, will destroy the environment and thereby humans as well unless this received mode of action is replaced by a cybernetic understanding of the human role in an ecology of mind.

Contributions to Epistemology

Since Mead suggested in 1968 that cybernetics apply its insights about circular communication and organization to itself, the cybernetics of cybernetics, or second-order cybernetics as von Foerster called it, has become an increasingly fascinating subject. In this pursuit cybernetics not only relativizes itself but also challenges the traditional paradigm of scientific

inquiry at its base. Whereas the latter insists that scientific observers not enter their domain of observation, the cybernetics of cybernetics suggests instead that observers cannot escape participation in the very phenomena they observe. This necessarily self-referential involvement converges to world constructions that reflect more the recursivity of observing than the (unknowable) perturbations that may enter the process from outside. Austrian-born psychologist and philosopher Ernst von Glasersfeld, who calls himself a radical constructivist, therefore insists that all realities are, within experiential constraints, cognitively constructed. Von Foerster worked on the role of LANGUAGE and logic in such constructions. Austrian-born family therapist Paul Watzlawick points to the interactional grounding of such constructions. With this shift in ground, cybernetics leaves ontology (the branch of philosophy concerned with the nature of reality or what exists independent of its observation) in favor of an epistemology (the branch of philosophy concerned with processes by which we come to know) and lays the foundation for a new approach to human social cognition and self-understanding.

For the scientific study of communication the methodological consequences of this development are enormous. Theories of communication in systems that include their observers must be constructed within the very object they claim to describe, and the act of formulating such theories is also an act of changing the object while it is being described. Knowledge so obtained can no longer be evaluated as representative of an independently existing reality but as recursively embedded in actions that realize (construct or compute) its claims. Scientists—or any cognitively involved being, for that matter—can then no longer blame an objective reality for their "findings" but must assume responsibility for their own constructions. This responsibility has become the basis for ethical considerations of a cybernetic epistemology.

Cybernetics is not a mere collection of facts but a scientific approach to communication, knowledge, and reality construction with all of its cognitive and social consequences. True to its interdisciplinary origin, it provides a language for scientists to talk to one another across disciplinary boundaries. Cybernetics has been a continuous source of revolutionary ideas, has given rise to numerous specialized disciplines, and is providing a theoretical foundation for understanding the paths toward an information society. Its implicitly humanistic aim is wholly emancipatory.

See also MODELS OF COMMUNICATION.

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International Encyclopedia of Communications

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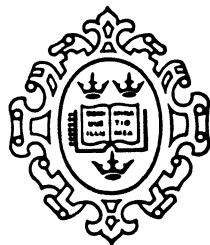Editor in Chief

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