Jakob von Uexküll and the origins of cybernetics

KARI Y. H. LAGERSPETZ

Norbert Wiener launches cybernetics

Mathematician Norbert Wiener introduced in 1948 the word 'cybernetics' to designate the study of 'control and communication in the animal and the machine'. Wiener had studied philosophy as a student of Bertrand Russell (Wiener 1948: 13), but his main interest was the study of non-linear systems. For this there was in the 1940s an urgent practical need: to develop anti-aircraft techniques. The importance of this work for neurophysiology and general biology was recognized already in 1943 (Rosenblueth et al. 1943). Wiener wrote:

> The present age is truly the age of servomechanisms as the nineteenth century was the age of the steam engine or the eighteenth century was the age of the clock. — To sum up: the many automata of the present age are coupled to the outside world both for the reception of impressions and the performance of actions. They contain sense organs, effectors, and the equivalent of a nervous system to integrate the transfer of information from the one to the other. They lend themselves very well to description in physiological terms. It is scarcely a miracle that they can be subsumed under one theory with the mechanisms of physiology. (1948: 43)

Wiener came from mathematics and technology, and considered the explanation of functions of human-made automata as a case of physiology. The converse, but not opposite idea, to subsume the explanation of the functions of living organisms to the theory of automata, was with certain reservations expressed by some biologists and physiologists already much earlier. Jakob von Uexküll was one of the first.

Early ideas of cybernetics in biology and medicine

The health-restoring forces inherent in organisms have been known since antiquity as *vis medicatrix naturae*. The importance of self-regulatory

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systems in the function of animals and humans was stressed by philosophers with medical knowledge, like René Descartes (1596–1650) and Julien de La Mettrie (1709–1751). Descartes described animals and the human body as machines; in his work he drew on clockworks and the automata known at his time — hydraulically operated toys — as models for physiology. Descartes' description of reflexes became later a research program for the gradually developing neurophysiology.

Claude Bernard (1813–1878) started his scientific work with a study on the anatomical basis of spinal reflexes in the frog. However, his most important result is summarized in his celebrated aphorism: 'La fixité du milieu intérieur est la condition de la vie libre'. The constancy of the internal environment, in which the cells of higher animals live, is the condition of their freedom. This constancy is a result of the function of numerous physiological regulation mechanisms.

Bernard's Russian pupil I. M. Sechenov (1829–1905) was the first to compare the function of regulation systems of organisms with the function of fly-ball governors of steam engines devised by James Watt in 1788. Sechenov did this in his inaugural lecture as a professor of physiology at Moscow University in 1899:

> In most machines the regulation is done by the operator whose hand brings a particular device in action. But there are some regulators which replace the operator's hand: they come into action, so to speak, automatically, but actually under the influence of certain changes in the functioning of the machine. The safety-valve of Watt's steam engine is the best known example of such a regulator. As the pressure of the steam in the boiler exceeds a definite limit, the valve automatically widens the exhaust outlet, and vice versa. The numerous devices of this kind are called automatic regulators. In the animal, which is a kind of self-acting machine, the regulators are also automatic, being brought into action by the changes in the state of the machine or in its functioning. As the work of these regulators is expedient, they replace the hand of the operator which is guided by his mind. (Quoted by Rosenblith 1965: 144)

Already in his book *Reflexes of the Brain* (1863) Sechenov had come to the conclusion that inhibition is an active function of the nervous system. He became the founder of the Russian school of reflexology. Sechenov already in 1861 formulated the postulate:

> The organism cannot exist without its supporting external environment; hence a scientific definition of the organisms should include also the environment which influences it. (Koshtoyants 1965: 122)

One of the first indisputable discoveries of a feedback regulation system in humans was made in 1868 by Joseph Breuer (1842–1925) when studying the effect of lung distension on vagal activity (Ullmann 1970). Breuer's chief, Ewald Hering (1834–1918) published a preliminary account of this work (Hering 1868). This was followed the same year by Breuer's own paper. An interesting conclusion of this work was expressed already by Hering:

> Every inspiration, therefore, in that it distends the lung *brings about its own end* by means of this distension, and thus initiates expiration. (Hering 1868: 361; italics by the present author)

For a long time, the Hering-Breuer reflex did not arouse much interest, and its neurophysiological mechanism was found out much later, in 1933 by Edgar (Lord) Adrian (Ullmann 1970: 13–14).

C. S. Sherrington (1857–1952) knew the works of Bernard, Sechenov, and of Hering and Breuer. Sherrington wrote in 1906: 'The nervous system is in a certain sense the highest expression of that which French physiologists term the milieu interne' (Sherrington 1906: 3–4). '*The unit reaction in nervous integration is the reflex*, because every reflex is an integrative reaction and no nervous action short of a reflex is a complete act of integration' (Sherrington 1906: 71). As we shall see later, Sherrington's work on reflexes became later the neurophysiological basis of computer science and technology.

At this time cell theory was generally accepted, but not as the structural basis of the nervous system. Camillo Golgi (1844–1926) and Santiago Ramón y Cajal (1852–1934) in 1906 shared the Nobel Prize in physiology and medicine, although their conclusions from their work were the opposite: Golgi, like most biologists of his time, considered the nervous system to be a protoplasmic non-cellular continuum, while Cajal, with excellent evidence, found it to consist of limited cells, the neurons. For the contacts of neurons with each other and with other cells, Sherrington had already in 1897 coined the term synapse (Sherrington 1906: 17).

It is against this setting we should consider Jakob von Uexküll's work as a forerunner of cybernetics.

From reflexes to control: The idea of feedback

Jakob von Uexküll (1864–1944) was born in Estonia and studied zoology first at the University of Tartu (Dorpat), but moved soon to Germany, first to Heidelberg, later to Hamburg. He did much of his experimental work in Italy at the Zoological Station of Naples. In those years when it was still possible, he spent his summers with his family in Estonia, did his writing in Germany, and retired from time to time to Italy, where his tomb is near his house on Capri (G. von Uexküll 1964). Jakob von Uexküll was a true European cosmopolite. He also crossed many boundaries of science in his work: from zoology to physiology, from philosophy to ethology.

Uexküll's early interest in the physiology of marine animals led to the work on muscular movements and reflexes of sea-urchins, brittle-stars, and octopuses (1892–1905). Based on his knowledge of mammalian physiology and on his own work on sea-urchins, Uexküll formulated a law relating nervous excitation to muscle stretch: nervous excitation always flows towards the stretched muscles. This means that the activity of the nervous system tends to shorten a stretched muscle; it counteracts the muscle stretch. This is a case of negative feedback caused in part by the activity of the nervous system. Uexküll writes in 1905:

> Nun sind alle Tiere so gebaut, dass ihre Körpermuskeln bei ihrer Verkürzung stets gegen einen Antagonisten wirken. Dieser mag in einem anderen Muskel oder in einem elastischen Widerstand irgend welcher Art bestehen. *Durch diese Anordnung der Muskeln wird das Entstehen einer jeden Muskelaktion zugleich zur Ursache ihres vergehens*. Durch jede Muskelkontraktion wird entweder einen Gegenkraft im elastischen Widerstand geweckt oder eine Dehnung der Antagonisten-Muskeln veranlasst. Die gedehnten Muskeln aber saugen den Tonus an sich, während die kontrahierten Muskeln ihn in das zentrale Netz zurückwerfen. (Uexküll 1905: 53; italics by the present author)

Uexküll's law is one of the first formulations of the principle of negative feedback which occurs inside an organism. It offers an explanation for muscular tone and position maintenance in animals by referring it to the activity of the nervous centers. This has been later analyzed much further. Work by Gellhorn, Granit, and others has shown that there are stretch receptors in the muscles. When stretched these send sensory impulses to the centers, which in turn, excite the stretched muscles. Sherrington referred frequently to Uexküll's work (Sherrington 1906).

Uexküll met Sherrington at the Fourth International Congress of Physiology in Cambridge 1898 (G. von Uexküll 1964: 41–42), in which Sherrington gave a demonstration on the reciprocal innervation of antagonist muscles: he showed that inhibition of the tonus of a voluntary muscle was produced by excitation of its antagonist (Franklin 1938: 260). This seems at first sight to be an effect opposite to what is predicted by Uexküll's law, but this did not bother Sherrington and Uexküll. Although the contraction of a muscle is made possible by a simultaneous neuromotor inhibition and passive stretching of the antagonist muscles, the stretched muscles become at the same time gradually more liable to contraction through nervous feedback via nervous centers, as predicted by Uexküll. This is the basis of breathing, walking, and of numerous other activities in most animals.

Reflexes are usually described as reflex arcs, loops carrying information from receptors via afferent nerves to nervous centers and from them via efferent nerves to effectors. In some cases, like in the avoidance reactions, reflex arcs can through their action on the environment be completed as cycles, two-way interactions between organism and its environment, but they then present *actions* rather than reflexes of the organism.

The function cycle — *Der Funktionskreis*

In the short Preface to the second edition (1921) of *Umwelt und Innenwelt der Tiere*, Uexküll says that he has now replaced the chapter on reflexes, included in the first edition in 1909, with a chapter on the function cycle (Uexküll 1921). The chapter 'Die Funktionskreise' was already included in the first edition of *Theoretische Biologie* (1920: 97ff.), with first schemes of functional cycles (1920: 116–117, Figures 3 and 4). This indicated an important change in the thought of Uexküll. He had become more deeply committed to the ideas of the philosophical master of his youth, Immanuel Kant.

The idea of the function cycle clearly had its origin in the concept of the reflex arc. However, instead of the immense environment to which the animals reacted, the main emphasis was now on the subjective, internal environment ('Innenwelt') which encounters and selects parts of the external world, the objects which it comprises as parts of its own content. The objective environment is there, but it can be approached only as parts of the subjectively perceived environment ('Umwelt'). In this view the internal relations of organisms are important, as the organisms grasp the objects both by receptors and effectors (cf. the figure of function cycle in Uexküll 1928: 105; also 1921: 43 and 1920: 116–117).[1] The object becomes through its representations ('Repräsentanten') inside the organism a part of the 'Merkwelt' and the 'Wirkwelt' of the organism. In this refinement of Kant's philosophy Uexküll moves from cybernetic analysis to semiotic analysis, and to what is now called cognitive psychology. However, the original cybernetic idea is also retained.

The function cycles are multiple and of many different kinds: related to prey organisms, to enemies, to sexual partners, to the medium (Uexküll 1921: 46). These ideas on the multiplicity and typology of function cycles, or rather of *function spheres* of animals are important in current ethology and zoosemiotics.

Cybernetic diagrams and other new approaches

When writing his *Theoretische Biologie* Uexküll developed his cybernetic ideas and presented them also as diagrams of the type which has later become more familiar (Figure 1, from Uexküll 1920: 201; the same in 1928: 209). This shows his continuing interest in the physiological analysis of animal functions and actions within the then non-existent but developing framework of cybernetics. Some biological functions, especially some internal functions of multicellular and higher developed animals could be explained as new types of machines.

There were other independent developments. Arturo Rosenblueth, Wiener's physiologist collaborator in the launching of cybernetics in 1943, studied and worked with Walter Bradford Cannon (1871–1945) on the internal, especially neuro-endocrine regulation of body activity (Cannon 1932). In 1930 Cannon coined the term *homeostasis* to designate the relative constancy of the internal environment. Cannon's earlier term was 'homeostatics' (Granit 1977: 230).

Sherrington's conclusions on the action of the nervous system (Sherrington 1906) were the basis of the work of the mathematical logician Walter Pitts and the physiologist Warren S. McCulloch. They described in 1943 the 'neural net' model, which combined earlier knowledge on nervous systems with Boolean algebra and with the basic operations of classical logics (Pitts and McCulloch 1943). Their model was also easily reproducible in hardware by using electric circuits as analogous elements. This was the starting point of computer science and technology.

Wiener considered cybernetics as a branch of physiology; Pitts and McCulloch modeled computers to match physiology — all this in 1943. The converse but not opposite problem, posed by Uexküll and others — to what extent the functions of organisms can be explained by cybernetics and computer science — has been settled so far that many complicated

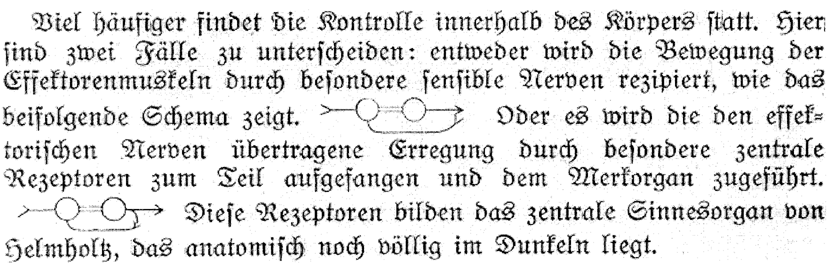
Viel häufiger findet die Kontrolle innerhalb des Körpers statt. Hier sind zwei Fälle zu unterscheiden: entweder wird die Bewegung der Effektorenmuskeln durch besondere sensible Nerven rezipiert, wie das beifolgende Schema zeigt. Oder es wird die den effektorischen Nerven übertragene Erregung durch besondere zentrale Rezeptoren zum Teil aufgefangen und dem Merkorgan zugeführt. Diese Rezeptoren bilden das zentrale Sinnesorgan von Helmholtz, das anatomisch noch völlig im Dunkeln liegt.

Figure 1. *Feedback diagrams within the original text (from Uexküll 1920: 201)*

regulatory functions of organisms have been reasonably well explained and modeled as cybernetic control systems. However, to be cautious:

> By the time the physiologist has reached the stage of fitting the elements of the transfer function to the structure of his biological system, he is beyond the point where feedback theory can help him. A knowledge of current engineering techniques may guide analogistic thinking, and some ideas of what is not possible may prevent wrong guesses. (Machin 1964: 444)

Pattern recognition

> 'Artificial neural networks' are massively parallel interconnected networks of simple (usually parallel) elements and their hierarchical organizations which are intended to interact with the objects of the world in the same way as biological nervous systems do. (Kohonen 1988: 4)

This definition by one of the leaders of current computer research on pattern recognition recalls the earlier attempts to present the necessary and sufficient conditions of pattern recognition in biological systems. Jakob von Uexküll's attempt was probably the first. It is given in Figure 2 (from Uexküll 1928: 106, Figure 4), and shows clearly the idea of parallel elements with interconnections.

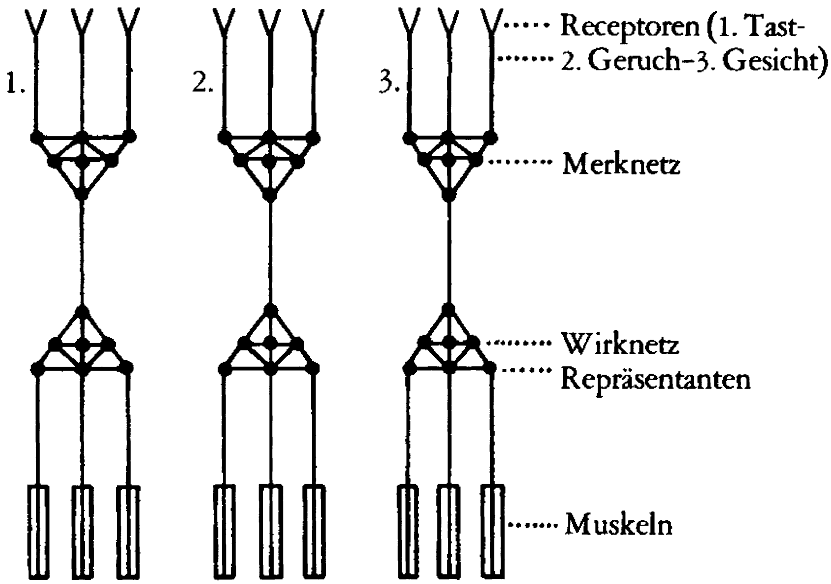

Figure 2. *The nervous mechanism of pattern recognition (from Uexküll 1928: 106, figure 4)*

It took thirty years before Rosenblatt (1958) used the same idea in his design of '*perceptron*', which has been useful in throwing light on the problem of pattern recognition. Perceptron is a practical example of the use of cybernetics in the modeling of mechanisms used by living organisms (Gérardin 1968). It took yet another thirty years before these ideas were used in computers in the 1980s.

Summary

Jakob von Uexküll studied muscle and nerve physiology of marine invertebrate animals, and before 1905 found the concept of causally efficient cycles and the importance of negative feedback in the control mechanisms within organisms. He developed this concept further in the 1920s, and in 1921, influenced by Kant's philosophy, he introduced the concept of the function cycle which has later become a basis of animal ethology and semiotics. His idea of pattern recognition by parallel but interconnected nervous elements is similar to those later used as the basis of artificial neural networks for pattern recognition. Jakob von Uexküll's work as a pioneer of cybernetics has not received attention previously, except for an occasional remark (Lagerspetz 1959: 33).

Note

1. See Uexküll's figure of the functional cycle in the beginning of this volume.

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Kari Y. H. Lagerspetz (b. 1931) is Professor Emeritus of Animal Physiology at the University of Turku, Finland ⟨kari.lagerspetz@utu.fi⟩. His research interests include thermal biology and the physiology of behavior. His major publications include *Teleological Explanations and Terms in Biology* (1959), 'Temperature acclimation and the nervous system' (1974), 'Comparative psychopharmacology' (1981), and *From Chance to Control* (1983).