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■ *Research Paper*

Systemics and Cybernetics in a Historical Perspective

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Systemics and cybernetics can be viewed as a metalanguage of concepts and models for transdisciplinarian use, still now evolving and far from being stabilized. This is the result of a slow process of accretion through inclusion and interconnection of many notions, which came and are still coming from very different disciplines. The process started more than a century ago, but has gathered momentum since 1948 through the pioneering work of Wiener, von Neumann, von Bertalanffy, von Förster and Ashby, among many others. This paper tries to retrace the history of the accretion process and to show that our systemic and cybernetic language is an evolving conceptual network. This is of course only a first and quite incomplete attempt, merely destined to give the 'feel' of the process. Systemic concepts and models are underlined in order to enhance the perception of the process, as well as its systemic significance. Copyright © 1999 John Wiley & Sons, Ltd.

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PRECURSORS (BEFORE 1948)

Prehistory of Systemic–Cybernetic Language

Some systemic–cybernetic terms have remote origins. Hereafter they are traced back in time, but connections with more recent developments are signalled.

The Greek word 'sustema' stood for reunion, conjunction or assembly. 'Kubernetes' (helmsman) was used by Plato, already in the abstract sense of 'pilot' of a political entity.

The concept of system resurfaced during the seventeenth century, meaning a collection of organized concepts, e.g. principally in a philosophical sense. Descartes' *'Discours de la Méthode'* introduced a coordinated set of rules to be used to reach coherent certainty, i.e. an epistemic methodology of systematic and even possibly in some sense systemic character. After Descartes, practically all important philosophers did

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construct their philosophical system, starting from some basic interrelated postulates. Leibnitz, for example, stated his 'principle of pre-established harmony' between substances, according to which any change in one substance is necessarily correlated with every other. This is coherence in complexity through reciprocal constraints. It would already be a kind of conceptual homeostat, in Ashby's twentieth century terms! Moreover these Leibnitzian correlations could be eventually formulated in scientific laws. Thus are scientific theories heralded, as conceptual systems.

At the end of the eighteenth century, the philosophical notion of system was firmly established as a constructed set of practices and methods usable to study the real world.

Much later, the unavoidable necessity of correlations and mutual interdependence, associated with a complex causality, and leading naturally to the concept of system, reappeared in N. Hartmann's reconsideration of ontology (1912). Hartmann also developed a theory of stratification, i.e. hierarchy of levels of reality through his theory of categories. His ideas were quoted more than once by Bertalanffy (1949, 1950) and seem to have filtered, directly or indirectly, for example, into the works of Miller on living systems (1978), those of Mesarovic *et al.* (1970) and other authors on hierarchies, and possibly van Gigch's concept of metasystems (1987b).

Again the concept of correlation is a very basic one. Indeed, as natural entities undoubtedly show numerous interrelations between their parts, the notion of 'system' also starts to make sense as descriptive of these natural entities. This meaning of 'system' seems to have slowly seeped into the English and French languages during the eighteenth century, and became more frequent throughout the next one, as shown hereafter.

As to 'cybernetics', the term appeared in 1843 in French with Ampère, 'to represent the art of government' in his classification of sciences (*Essai sur la Philosophie des Sciences*, 1843) (Vallée, 1993). Vallée also notes that this very same year 'Trentowski used the word 'kibernetiki' in a book on management written in Polish'.

From 1854–1878, the French physiologist Bernard (see 1952) in a series of works established the existence of the 'internal milieu' in the living being, thus making clear the difference between what happens 'inside' and what is now called the 'environment' Vendryes, 1942). In his *Introduction a la Médecine Expérimentale* (1865), Bernard states: 'In the living being's organism, an harmonic set of phenomena must be considered.' 'Harmonic' obviously implies the notion of balanced interrelations, in this case physicochemical ones related to 'water, temperature, air, pressure and chemical composition' in the internal milieu. Obviously, the general concepts of 'living system' and 'regulation' are already latent at that time.

Indeed, in 1866 the brothers de Cyon discovered in France the first example of a biological regulator: the countervailing action of the accelerator and the moderator nerves of the heart, a discovery which elicited the following comment by Bernard on 'the marvellous mechanism, hitherto without precedent in physiology, of a nervous self-regulator, able to determine the heart's work and the strength of the resistances that it must overcome' (French Academy of Sciences, 1867).

While some previous technical devices, as for example Watt's regulator, were already well known, this seems to have been the first time that the concept of regulation was formulated in an implicit systemic context. It also heralds Cannon's *Wisdom of the Body* (1932). Shortly before, at the end of the nineteenth century, systemics and cybernetics were already potentially rooted in biology.

At the same time, and in a completely independent way, a first inkling of the concept of chaos emerged, even if not under that name at the time. The French mathematician Poincaré enounced the three-bodies problem concerning the dynamics of the interactions of three celestial bodies and proved that no precise solution could be calculated if no arbitrary simplification was introduced (1892–99). He produced a mathematical method, the so-called Poincaré section, showing the vagaries of any specific trajectory. He thus opened the whole field of instability studies. And, of course, systems can be, and frequently are, unstable. This work was to lead to a wide-ranging research on the various types of stability and on ergodic systems.

Poincaré also introduced a new type of mathematical study, christened by him 'Analysis Situs', which was the original form of topology, as the science of forms — and deformations. Among his conceptual heirs we must count Thompson (*On Growth and Form*, 1916). Laville, with his dynamics based on whorls (1950), and quite recently McNeil (1993), who considers any system as a torus or toroid resulting from interacting fields. Obviously, equivalent concepts and models are independently rediscovered generation after generation by researchers unaware of former formulations. This is quite an interesting feature from an epistemologic viewpoint: dynamic systemic models clearly allow for significant descriptions of nature, whatever their ontological value.

As to Poincaré's work, it is one of the very first steps towards the establishment of a new type of qualitative mathematics appropriate for the study of complex systems.

A second important advance in topology was the publication in 1936 by Konig in Germany of his *Theorie der endlichen und unendlichen Graphen*, i.e. theory of graphs, which was in fact the first elaborated mathematical theory of topological interrelations — exactly two centuries after Euler's problem of the bridges of Königsberg. It would have been, for example, much more difficult for Forrester (1973) to develop his 'Systems Dynamics' without this important tool.

From another viewpoint, as shown later on by von Förster (*The Second Order Cybernetics of Observing Systems*, in 1981), cybernetics was also in need of a non-contradictory logic of sets. This was provided by Russell and Whitehead who, in their *Principia Mathematica* of 1925, definitively put paid to the innumerable contradictions and paradoxes in the logics related to self-referring systems, from Epimenides the liar up to the Cantor set and the Peano curve.

At the beginning of twentieth century, the concept of system surfaced in linguistics. This was mainly the work of Saussure, the Swiss linguist. Saussure (*Cours de Linguistique Générale*, 1906–1911) describes the set of sounds used in a language as its 'phonologic system', containing a 'determined number of well-differentiated phonemes'. The way any language interconnects these phonemes to construct words is in effect quite strictly defined through precise rules. These are not initially stated formally in the spoken language. However, they become finally explicated by grammarians. In cybernetic terms these rules are phonetic constraints. The same is true when the language is used to express meanings. Saussure speaks of 'articulated language' and specifies that 'in Latin, articulus means member, part, subdivision in a series of things'. He adds that, in this way, 'we observe the subdivision of the chain of meanings into significative units'. These articulations imply that the language is made of permanently constructed and reconstructed interrelations between words, whose meaning depends on context, in a sense analogous to the 'meaning' of a hydrogen atom in H_2O, HCl or NH_3.

That is, words are elements that can combine in semantic nets. And, like any elements, once combined they lose some characteristics or significance and acquire some other ones.

Obviously, this is one of the roots of constructivism. It also offers a good preview of all types of combinatorics in systems.

As to Saussure's 'articulus', we find it again 30 years later in Vendryes' very general concept of the articular relation (1942), which allows for the choice among different possible relationships between elements — until a choice is effectively made, selecting one and only one of the virtual relationships. It also curiously reminds one of Heisenberg's indeterminacy, of wave collapse in microphysics and even of the hapless Schrödinger's cat. This again is giving defined significance to a relationship through the introduction of a constraint. Once more, we are led to Ashby.

In the realm of physics, another forgotten precursor was the French physicist Bénard, who made in 1908 a curious observation of hexagonal convective cells forming in a jar of boiling water. These 'dissipative structures' were at the time considered merely an oddity. However, Prigogine was to discover their deep thermodynamic significance in systems brought far away from energetic equilibrium, with an ever-growing number of examples from chemistry of what could be called 'social physics' (Prigogine, since 1947, numerous others more recently). However, much longer ago the German geographer Christaller (1933, 1937) and Losch in Switzerland (1944) had discovered hexagonal structures in land occupation. Until now such structures — which could still be observed in a somewhat different form around 1950 in the cyclical moves of semi-nomadic Central African groups — have not been widely understood as a general feature of the dynamics of systems!

This same line also led to an original and deeper understanding of the interrelations between structures, energy overload and emergence. As early as 1922, Lotka was investigating in a closely related sense the 'energetics of evolution' and proposed (1924) his 'world engine' model, based on the cascade of energy from the sunlight, through the whole of the correlated world of living systems into final heat sinks. This was of course creating a firm grounding for global systemic ecology in thermodynamic terms.

Psychology also was in want of more global views. After Brentano's research on the relation of the subject with the object (*Psychology from an empirical viewpoint*, 1874, 1911), Wertheimer's research on the principles of perceptual organization (1923) led to the formulation of Gestalt psychology, i.e. psychology of perception of forms, widely developed by Kohler (1929) and Koffka (1935).

It became obvious that perception must start by picking up static structures and dynamic interrelations between elements, i.e. is systemic. We have here yet another root of various systemic–cybernetic interpretations of reality.

Again, von Förster's observer, and probably Maturana's autopoiesis (1980), as well as von Glasersfeld's constructivism (1995), Piaget's version of structuralism (1967) and possibly Gibson's concept of affordance (1986) owe a debt to the Gestalt psychologists.

Another early precursor of the systemic view in human sciences was the Romanian historian Xenopol, according to whom history is a science 'which possesses the general elements of a system of classificational truths', while admitting, however, that series of phenomena or events are always unique and characteristic. Xenopol offered 'a whole system of principles relative to historical science' (1899, 1911). The Portuguese historian Salazar introduced (1942) the concept of 'historic systems' with a surprising grasp of systemic concepts — before their official appearance: 'Europe is the first historic system whose area of influence covers the whole world'. Somewhat later on, the French biologist Prat (1964) offered interesting insights into the dynamics of historic systems through the concept of 'aura', i.e. the traces they leave after their destruction (this concept should be definitively incorporated into the systemic language, in view of its great generality).

However, while historians like Toynbee and Braudel, and even Sorokin in his theories about the growth and decay of cultures, have worked more or less implicitly along systemic lines, it remains that the use of systemic and cybernetic concepts and models in history is still largely nowadays a no-man's land.

Four other precursors should yet be mentioned, who are unfortunately quite unknown from most systemists.

One is Bogdanov, whose essay on 'Tektology' (in Russian, 1921), which developed clearly cybernetic concepts, was translated into English only in 1980.

Another early, and quite improbable, systemist was the South African general and statesman Smuts, who published (1926) his book on *Holism and Evolution*, introducing the term 'holon' and developing the corresponding concept, much later rediscovered by Koestler and Smythies (1969).

In 1932, Cannon introduced into biology the concept of homeostasis, an important extension of Bernard's idea of the stability of the 'internal milieu'. This was in effect the birth of biological cybernetics, but 20 years later the concept of homeostasis was to be considerably generalized by Ashby, as a feature of all types of systems in dynamic equilibrium.

Cannon's work was paralleled from 1942 on by the French biologist Vendryes (to whom the author of this paper revealed Cannon's ideas in 1972!). Vendryes made an exhaustive study of regulation first in living systems and, later on in history, in social systems and in psychology. He also extensively developed the concept of autonomy (nearly 20 years before Maturana and Varela — while in a different, but compatible meaning). It was unfortunately impossible to organize a debate between them all before Vendryes' death in 1989. Vendryes was undoubtedly an early cybernetician, even if he himself became aware of it only in the 1970's.

In 1938, the Romanian Odobleja published in Paris his *Psychologie Consonantiste*, a first step leading to the birth of the lively Romanian school of cybernetics.

Biology, on the other hand, was still to contribute more to systemics.

Driesch's famous experiences with embryos of sea urchins (see Bertalanffy, 1949) brought him to the conclusion that 'physical laws of nature were transgressed' in living systems and led developmental biology astray into a fierce controversy between mechanistic and vitalistic views for more than 40 years. However, in Bertalanffy's terms 'The strange result of his sea urchin experiment is indicated by the notion of equifinality', i.e. 'the same goal is reached from different starting points and in different ways'. Until Woodger (1929) and Bertalanffy, it appeared practically impossible to escape from some more or less metaphysical explanation.

However, it dawned on these authors that the basic difference between non-living and living systems was dynamic and adaptive organization of the latter as wholes — a concept also developed by the Belgian physiologist Dalcq (1941).

So, finally, vitalism gave way to organismic biology, and led Bertalanffy to the formulation of his original systemic views (1950). In his paper he significantly signals the then very recent works of Hartmann (1942), Korzybski (1933, 1950), Wiener (1948) and Prigogine (1947), which shows that he was already keenly aware of the close connections between his systems concept and general semantics, cybernetics and thermodynamics, in the light of a renovated very general epistemological perspective.

Another important work was Selye's on stress and the 'general adaptation syndrome' (GAS) in strained biological systems (from 1950 on). It is impressive to find in the glossary of his main book (1956, 1976) entries on adaptation energy, developmental adaptation, heterostasis, homeostasis, involution, metabolism, internal milieu and resistance, whose meaning has been or could be generalized to many kinds of systems. Moreover, stress and the GAS are related to the general conditions of stability and instability.

Still another biologist, McCulloch, concerned himself in his outstanding paper 'Recollections of the many sources of cybernetics' (1969, published in 1974) with how the study of nervous nets, and particularly of the brain, from Ramon y Cajal on, led himself and Pitts to the discovery of 'A logical calculus of the ideas immanent in nervous activity'. This 1943 paper is as much a root of cybernetics as Wiener's and von Neumann's works. Moreover it neatly covers the logical as well as epistemological aspects of cybernetics. This is part of the conceptual thread which runs from Fibonacci's numbers to Russell and Whitehead's *Principia*, through Leibnitz's 'parts which work one upon another', Boole's binary logic and Peirce's notion that 'given a stochastic world, order will evolve'. Moreover, McCulloch and Pitts' (1943) work also introduced the basics of neurophysiological cybernetics, which started von Förster on his road to 'observing systems' and Maturana towards autopoiesis.

A substantial synthesis on biology in its relations to knowledge was published in 1967 by Piaget.

Going back to logics, semiotics and semantics, it is obvious that Peirce's work on symbols, signals and the basic conditions of communication (of meanings) (see Peirce, 1961), the beginning of this century, has been widely influential on later systemists, as for example Churchman, Ackoff, Warfield and their followers.

After more than 60 years, any conceptual construction, including of course cybernetics and systemics, still remains under the pall of Gödel's incompleteness theorem (1931), whose most general implication is that any formal system contains statements that cannot be proved within that formal system. The lesson for systemics is that models can be constructed and used, but that they never offer an absolute value of truth. This seems in accordance with Russell and Whitehead's reformulation of logics and could be seen as an interesting fundament for Poppers's falsifiability. It can also be considered as the bedrock for van Gigch's concept of metasystem. However, it leads to what the author of this paper calls ontological skepticism — which, while in any case is not too dramatic for practical purposes, should always be remembered as a psychological and conceptual background.

Another very important precursor was the Polish logician, psychologist and semanticist Korzybski, who published in 1933 (in the United States) his seminal work on *Science and Sanity*, wherein he developed a 'Non-Aristotelian' logic, with very significant implications in psychology and psychiatry. While his work is frequently ignored by systemic psychologists, he explained psycho-semantic pathologies in an obvious systemic way. Bateson and probably most of his direct intellectual heirs have had knowledge of Korzybski's work. It is obvious that no satisfactory conversation nor consensus can be reached if psycho-semantic pathologies are not understood.

The following section of this historical research will consider the specific role of the pioneers or 'founding fathers' and some significant sidelines (1947–1960). The final one will cover as much as possible the basic advances after 1960 due to the most prominent recent innovators.

FROM PRECURSORS TO PIONEERS (1948–1960)

It would be quite redundant to insist on the fundamental role of Wiener (1948) as the creator of cybernetics (he himself duly acknowledged the role of his co-workers, among them Bigelow and Rosenblueth). Let us only briefly take stock of the basic concepts he introduced, once and for all.

His original goal was to address the problems of prediction and control (in anti-aircraft artillery) and, more generally, of steering. He found that the basic condition for correct steering and control was regulation by corrective feedback, a term already used by control engineers. But the basic problem of control was 'centered not around the technique of electrical engineering but around the much more fundamental notion of the message' (1948) — and thus of information to be transmitted. He adds that 'the amount of information in a system is a measure of its degree of organization, so the entropy of a system is a measure of its degree of disorganization'. Wiener already had knowledge of Shannon's work on communication, coding and disturbances by noise.

Thus the whole of the original cybernetics notions was to become neatly organized in a coordinated bundle of concepts — something that is still not always perceived nowadays. Indeed, Wiener also at the time, informed about McCulloch and Pitts' work on nervous connections, clearly understood — and stated — that the new cybernetic viewpoint was to be useful in many different disciplines, from physiology to social sciences.

He also saw the necessary connections with mathematics, logics and thermodynamics. In short, this encyclopaedic mind opened avenues and horizons so wide that they will possibly never be totally explored.

In 1949, Shannon and Weaver published their seminal *Mathematical Theory of Communication*, frequently referred to as *Theory of Information*, which is at least partly a confusing misnomer, as their concept of information is not related to meanings, but merely with quantitative and entropic aspects. Here, in their own words: 'information should not be confused with significance', — a warning still widely ignored, even after MacKay's research and the distinction he introduced between 'metron' and 'logon' in information (1969).

The authors clarified the concept of communication by introducing the sequential concepts of source, code, message, transmitter, signal, channel and receptor (necessarily a decoder).

Shannon, as a Bell Telephone engineer, was interested in solving the technical problem of the satisfactory transmission of messages. Accordingly, he researched the noise problem, i.e. the distortions of messages by external disturbances in channels. This led him to quantify the limits of a channel's capacity and the use of redundancy.

All these notions are of utmost importance for any class of systems, since all are made of elements that must communicate in an efficient manner. This branch of cybernetics thus also became by necessity an indispensable part of systemics.

Weaver, on the other side, emphasized the connections of the theory with stochastic processes, Markoff chains and ergodic Markovian processes. This feature was shortly to be reconsidered and developed by Ashby (1956). Shannon and Weaver also established a relation between the probability of a message and a new interpretation of entropy, as related to information content. This subject was widely researched by Brillouin during the late 1950s (e.g. 1959, 1962).

Obviously, Wiener's control, regulation and feedbacks could never take place without messages and efficient channels. Shannon and Weaver's work is thus directly complementary to Wiener's.

And again, systemics would not have been possible without those very basic conceptual tools.

Von Bertalanffy's main contribution was neatly stated in his 1950 paper, in the *British Journal for the Philosophy of Science*. However, equally important was his role as a catalyst of the systems view. This is so in at least two different senses.

In the first place he clearly stated the central concept of systems. The same could be said of him that is said about Christopher Colombus and America: after him there was never anymore need to discover systems. On the other hand, he strongly insisted on the existence of 'isomorphic laws in science', giving convincing examples. From this fact he deduced the possibility of a new multidisciplinary approach and proposed a 'general system theory', by generalizing some widely significant principles.

He presented the so-called theory as 'an important regulative device in science' which should lead to the 'unity of science'. However, he merely discussed some specific subjects as competition between parts, finality and equifinality, closed and open systems, and anamorphosis and catamorphosis.

Later on, he brought few significant contributions and his role seems to have been more of a communicator and a leader.

Boulding, an economist who remained all his life somewhat sceptical about the ways in which economics were theorized and practised, proposed some interesting principles about the phenomenon of growth in general (1956). He was interested in topics that are generally ignored by economists as, for example, nucleation (confirmed in a different way by Prigogine), form as related to size, self-closure in growth (a subject also explored by Maruyama and later on, in a different perspective, by the Club of Rome) and different types of growth rates, particularly in relation to scale. All these aspects can be translated into economics but correspond in fact to basic principles applicable to the dynamics of any evolving system. Unfortunately Boulding's programme has never been translated into a systematic research, leaving a gaping hole in systemics.

Boulding was also one of the first to understand the nature of man's global relation with his planet: he christened our man–planet system the 'Spaceship Earth' and was acutely conscious that the whole planet is the commons of mankind as a whole, and in danger of being promptly destroyed by human universal and unrestrained greed and spendthrift. More than 40 years later, the lesson seems farther than ever from having been learned.

Another very original line was developed in the early 1950s by von Neumann, i.e. his theory of automata, resumed in his 1956 and posthumous 1966 works. The root of the modern idea of automaton seems to be in Turing's theoretical model for a computer (1950). Von Neumann's ideas spawned a considerable number of models of sets of potentially interactive elements, distributed in configurations that should be dynamized by appropriate rules of transformation.

Von Neumann's automata, even if made of unreliable components, may offer a coherent and reliable behaviour. Automata are somehow on the border (and crossing the border) between collections of unorganized elements and true complex systems, thus helping to bridge one of the most gaping conceptual chiasms in systemics.

Construction rules were proposed by Maruyama (1963) and by Conway in his *Game of Life*, popularized by Gardner since 1972 in his column in *Scientific American*, even before the appearance of the book.

These models have been used, for example, in genetics (Kauffman, 1969 on) and for models of the brain (Dubois, 1986 on). The latter may be considered an extension of the McCulloch and Pitts models. They are also related to properties of composite (or quasi) systems, i.e. not strongly integrated ones. Such properties are, for instance avalanches, percolation, power laws and runaway processes, all of which are now integrated in the more general theory of self-criticality.

The field of automata is presently undergoing an explosive development related to self-organizing automata and so-called artificial life, whose future could be awesome.

Von Neumann was also seeking the grail of the self-reproducing automation, in fact a kind of cyclical cybernetics. He may thus be considered as one of the forefathers of autopoiesis (Maturana and Varela, 1980) and hypercycles (Eigen and Winkler, 1975; Eigen and Schuster, 1979).

Automata research is now a whole field in itself. Interesting classifications of the various types of automata have been proposed by Klir (1965) and Bunge (1979).

Von Förster is yet another of that peculiar brand of humanist scientists (among them Wiener, Bertalanffy, McCulloch, Pask, Miller, etc.) who have illustrated systemics and cybernetics. The key to his contribution is in the following comment: 'the cybernetician must apply his competence to himself lest he will lose all scientific credibility'. This was his programme at the Biological Computer Laboratory at the University of Illinois (Urbana) from 1957–1976, with collaborators like Ashby, Löfgren, Pask and Maturana. The basic password for his work is probably the German word *Eigen*, i.e. self-, now incorporated into the systemic language as in eigenbehaviour, eigenelement, eigenfunction, eigenprocess, eigenvalue, and the like, not to mention the numerous expressions beginning with 'self-'. No system could survive without the capacity to maintain and reproduce its own behaviour and organization. This idea led to enormous developments in systemics. It has been at the root of von Förster's own second-order cybernetics (how systems observe and what implies the deliberately ambiguous expression observing systems), of Maturana's autopoiesis through organizational closure, of the systemic psychology school, and of any systemic epistemology. His work influenced numerous other fields, and still undoubtedly will influence them in the future.

The next great cybernetist was Ashby, whose basic works appeared from 1951 to 1960. However, he was also a great systemist and probably the one who did most to connect the two sets of concepts. His friendship with von Förster may have been a crucial factor in this sense. One of his most significant contributions was the understanding that a system should be 'richly joined', but not overly so. He clearly explained that no system could operate, nor even exist, without 'constraints', but altogether that sufficient leeway was an absolute necessity for the system to be adaptive. His homeostat model showed how a system made of interacting components may oscillate and settle within progressively self-defined limits of stability, throwing a new light on the nature of ergodicity. Another of his basic contributions was the famous 'law of requisite variety', which defined the general conditions of adaptiveness of a system to the range of variability of its environment. The law is one of the most general systemic–cybernetic principles, as it is useful for the understanding of any type of system. An important corollary was the Conant–Ashby principle according to which 'every good regulator of a system must be a model of that system'. This is a kind of original side glance on the independently developed concept of autopoiesis. Ashby also expanded the meaning of redundancy, in relation to variety.

One of the most notable polymaths in cybernetics and systemics was Pask. He had that very rare blend of talents which allowed him (apart from his interest in architecture, theatre and art in general) to create a number of practical devices, to be a successful consultant and, at the same time, an outstanding theorist, who investigated the implications of cybernetics for a wide range of subjects. He explored the general self-organization conditions for learning, the meaning of recursivity, the conditions of conversation and its relation to cognition — and much more. He was one of those who 'humanized' cybernetics (Pask, 1975, 1993).

It is not possible to situate the long-lasting influence of Prigogine on systemics at a specific moment. His first works on the thermodynamics of irreversible systems appeared in 1940 and 1947 and at the time did not escape the watchful mind of Bertalanffy. Prigogine was one of the first (after De Donder) to try to escape from the yoke of the initial thermodynamic models inspired from Clausius and Boltzmann — in fact, models of ideally isolated systems, i.e. purely conceptual ones. These views precluded any satisfactory explanation of life and evolution in the general direction of complexity and seemed to justify the vitalist argument in biology — and the need for Maxwell's demons (already 'exorcized', however, by Szilard in 1929, who showed the practical inapplicability of the 'isolated system' model).

The pieces of the thermodynamic puzzle were to be collected by Prigogine (and his co-workers in Brussels Free University and in Texas University at Austin) all along from the 1950s on, in a constant flow of papers and books.

He was the first to understand clearly the compensation of energy degradation in terms of structuration. He thus recuperated Bénard's structuration through dissipation of energy, which proved to be the key to the emergence of more complex systems.

Moreover, he understood that energized systems are practically at the same time accelerators of entropy since they can construct their structures and maintain them only by extracting a more important energy allowance from their environment and by increasing their production of entropy until they reach a stable level of energy dissipation, close to equilibrium, and in accordance with their acquired degree of structural organization. This was Prigogine's theorem of minimum entropy production (1945).

Later on, Prigogine came to explain what happened when a system was pushed far from equilibrium due to a massive absorption of energy. He showed that such a process produced increasingly wide oscillations in the dynamics of the system until a critical threshold of instability was crossed. At such a point, bifurcations became possible towards higher complexity through stabilized dissipative structures and a correspondingly higher level of minimum entropy production. He also introduced the concept of nucleation, showing that, at the bifurcation point, any random event can become decisive in the selection of the type of higher level of organization. These are ponderous contributions to the general understanding of evolution, applicable to any class of evolving systems, at least from chemistry and biochemistry to biological and social evolution.

In synthesis, Prigogine reinstated irreversible time in science and described understandable dynamics in systems. His work is exerting a powerful influence on the wider understanding of systems (as shown by the great variety of his collaborators and students works).

A lonely voice during the 1950s was Rosenblatt's, the developer of the perceptron (1962), an electromechanical device able to recognize some patterns among a number of stimuli it is able to register. Truly, such a device could not be satisfactorily programmed, as observed by Minsky, whose preference went to top-down programmed artificial intelligence based on the manipulation through algorithmic transformation rules of symbols representing knowledge. It has now become clear, however, that parallel self-transforming natural systems do exist. Minsky's own *Society of the Mind* (1986) (would it not be better called *The Social Brain*?) seems to be an example. Moreover Hillis's connection machine, Langton *et al.*'s *Artificial Life* and Rumelhart and McClelland's work on parallel distributed processing show that Rosenblatt's proposal, after all, did not lead into a dead end. Of course, so-called artificial life (AL) is in no way exclusive of our classical artificial intelligence. AL is, however, a much more difficult proposal because it is much less strictly deterministic: ergodicity, chaos, sensibility to initial conditions, stability conditions, stability margins and many other topics will have to be considered.

Some ethologists, not necessarily closely connected with the systems movement, made interesting contributions to the pool of transdisciplinary concepts. Already in 1934, von Uexkull had developed an understanding of the environment as a percept, different from species to species and even from individual to individual. Other ethologists, as for example Bonner (1955), investigated the general social aspects of animal life. Bonner explored, for instance, colonies of cells and microorganisms or, at a higher level of complexity, coordination and cooperation in animal societies (ants, termites, beavers, deer, monkeys, seals). As these studies widely expanded and are still going on nowadays, it seems possible that a very general systemic theory of sociality and its ways could finally emerge, possibly connected to the recent research in AL. Bonner also studied other systemic topics such as differentiation, morphogenesis, patterns and limits of growth, and symmetry.

INNOVATORS (AFTER 1960)

After 1960, it becomes quite difficult to spot every innovator and to place her or him within the general landscape of systemics and cybernetics.

An interesting contribution was that of Maruyama, who introduced in 1963 his 'deviation-amplifying mutual causal processes', describing the role of positive feedback, particularly in the structuration of growing and competing systems. The subject is close to von Neumann's automata and Conway's game of life. However, it highlights another interesting angle, i.e. the antagonism between growth and limiting factors, already considered during the nineteenth century in a different way by Verhulst and his logistic equation and developed by Lotka and Volterra during the 1920s.

A limitless positive feedback, supposing a considerable — but limited — source to feed on, would indeed quickly turn absolutely destructive. So, it is important to study limits to such a growth. Even today, it seems that positive feedbacks without any adequate braking process (a characteristic and dangerous feature of our economies in relation to environment factors) are still insufficiently researched. Maruyama called this type of process 'second cybernetics', which should not be confused with the very different 'cybernetics of second order' of von Förster.

In his 1962 paper on 'The architecture of complexity', Simon successfully tried to throw more light on the concept of complexity, until then merely a not very clear password. Of course, systems, as made of numerous interacting components, and more generally identifiable sets of specifically interacting components, are to be clearly differentiated from simple unorganized collections of elements. Simon gave a variety of examples in his paper, but most of all made the difference crystal clear with his famous Hora and Tempus parable of two watchmakers, one of them working in a systemic way, and the other merely in a linear sequential way.

The discovery of criticality, as a characteristic of quasi-systems, made clear quite recently that complexity, i.e. structured organization, generally in levels, is a cardinal feature of systems: complexity and systemicity are near synonyms, both concepts corresponding to a wide embracing way to describe many entities as perceived by observers.

Miller started to publish his papers on living systems in *Behavioral Science* in 1965, while his book came out in 1978. His descriptive classification was a milestone for systemics. It covers the whole universe of systems from the cell to the man–planet system, leaving out only physicochemical and ecological ones. Moreover it creates at the same time a taxonomy of parts, or subsystems (originally 19 of them; 20 in the most recent version) and of levels of complexity (now eight of them, from seven originally). He added a method for the discovery of cross-level isomorphies, thus giving systemics a significant and workable research tool. While many other interesting systems classifications have been proposed, none is as satisfactorily horizontally and vertically structured, nor by far, as widely embracing.

Miller's taxonomy largely implies systemics in the same sense that Mendeleev's table of chemical elements implied chemistry and part of physics and became a guideline for future research. Both contain implicit principles of order which had never been clearly stated before.

Living Systems surely enhanced the rational and scientific status of systemics and led it closer to experimental research by defining much more clearly the areas that could be covered, in a transdisciplinary way.

Haken proposed and developed his 'synergetics' during the 1970s and 1980s (Haken, 1983). It amounts to a different and significant formulation of systemics. Ashby's notion of constraints is given here a considerable extension under the so-called slaving principle, the final synthesis of multiple constraints between numerous elements (Leibnitz!) in growing confinement. In this way, systemic correlations and cooperation result in an order parameter, a very general feature, that can be observed from laser light, solitons, hexagonal dissipation, etc, to territorial occupation and fashion fads.

Synergetics creates conceptual bridges between chaos theory and thermodynamics of irreversible systems. It also helps to understand the genesis of complex systems, the general conditions of stability and synchronization phenomena (as for instance implosion, phase locking and stigmergy — see below).

Also in Germany, Eigen together with his coworkers Winkler (1973, 1975) and Schuster (1978) investigated in a very synthetic way the cyclical behaviour of many systems processes, a subject closely related to autopoiesis. They developed the important connective concept of hypercycle, a hierarchy describing the second-level circularity of a series of linked cycles. They showed its relation to attractors, automata, boundary conditions, dissipation, catalysis and self-catalysis, eigenvalues, thermodynamics of irreversible systems, morphogenesis (understood as competitive stabilization), structural stability, constrained growth, thresholds, and of course self-reproduction, i.e. autopoiesis.

Steinbuch introduced in 1961 his matrix models of learning, in German 'Lernmatrix'. He proposed a 'Lernphase', in which meanings become connected with signals or symbols, and a habilitated 'Kennphase', when the constructed connections are used to retrieve meanings from signals or symbols, or conversely. Unfortunately this research line, akin to Bateson's second- and third-order learning, seems to have been abandoned.

All of the aforementioned German cybernetists and systemists very much deserve a wider audience.

Maturana's considerable contribution has been the discovery and elaboration of the concept of autopoiesis, i.e. self-production, which emerged from his research on the neurophysiology of perception with Lettvin, McCulloch and Pitts. Autopoiesis, enounced in 1973 in collaboration with Varela (both Chileans, see Maturana *et al.*, 1980), is a multi-connected concept: it is significant for problems of cognition, but also for the self-reproduction of living systems (von Förster's eigenbehaviour, eigenvalue, etc,). Associated with autopoiesis are the significant concepts of self-closure, self-reference, self-production process, these latter also researched by Eigen. Autopoiesis moreover is a cornerstone for autonomy.

Autopoiesis is equally significant for systemic epistemology because it shows that which is observed cannot be neatly abstracted and separated from the observer's own condition. It has changed the whole perspective of systemics and cybernetics (von Förster's second-order cybernetics).

Klir elaborated from 1965 on his 'reconstructability analysis', whose aim is the establishment of a suitable strategy to reconstruct an ill-understood system from fragmentary data, mainly in order to solve systems problems. Klir situates his reconstructability analysis as 'an offspring of Ashby's constraint analysis' (Klir, 1991).

As many constraints are cross-level, Miller's methodology of creation of cross-level hypothesis could possibly be correlated with Klir's methodology. In turn, it would be interesting to apply it, for instance, to the construction of the basic models of systems used in Forrester's 'systems dynamics'.

We surely need better connections between so many interesting systemic and cybernetic concepts, models and tools.

The topic of hierarchy was widely explored by Mesarovic and collaborators during the 1960s (Mesarovic *et al.*, 1970). Their work, quite formalized, included multi-level structures, interactions, conflict resolution, optimization and generally coordinability and coordination with an eye on decision-making.

Hierarchies have also been investigated from an ecological complexity perspective by Allen and Starr (1982). A particularly interesting feature of their book is a critical glossary of many systemic terms.

Apart from his timely proposals for the practical use of systemics in management (1987a), van Gigch introduced into systemics the very important translevel concept, generically characterized by the prefix 'meta-': metasystem, metacontrol, metadecision-making, etc. He thus translated to systemics — in cybernetic terms of regulation and control — a much clearer understanding of the deeper nature of hierarchic levels. The parallel with Russell and Whitehead's reformulation of logics and with Gödel's 'incompleteness' is striking. But he translated these high-level abstractions to the practical world of real hierarchical organizations.

Curiously enough, some relationship of van Gigch's ideas with Mandelbrot's fractals (1977) could be less far-fetched than supposed at first glance. The basic concept in Mandelbrot's work, more than the fractal model itself, could be self-similarity between levels of complexity. This feature is obvious in every example of fractals and this was so even a long time before the computer produced fractal images. Self-similarity is already visible for instance in Koch curves, or in Sierpinski's sieves. Moreover, the concept seems very close to Weierstrass's renormalization equation (showing self-similarity through a superposition of harmonic terms at different scales in a curve — see West and Goldberger (1987) — and generally to the notion of scaling. And more or less hidden self-similarity can be observed in graphical representation of also more or less complex cyclical processes. A deeper exploration of the concept in different disciplines would possibly bring rich rewards.

Still other new and important mathematical and formal tools and models appeared between 1960 and 1985.

Zadeh proposed his fuzzy sets and fuzzy logic in 1965, thus starting a lively special interest group in systemics. Fuzzy sets are useful in studies of classes with unsharp boundaries, which are numerous and very difficult to model. Correlatively fuzzy algorithms, fuzzy categories, fuzzy functions, fuzzy structures, fuzzy subsets and fuzzy topological spaces have been introduced.

The French mathematician Thom described in 1972 his models of structural stability, of morphogenesis and of general morphology, later to be known as theory of catastrophes, i.e. sudden discontinuous changes. His table of archetypal morphologies, however, covers probably all of the possible changes that may occur in a process. Among the topics considered we find attractors, bifurcations, chreods, epigenesis, forms, gradients, Hamiltonian systems, information, morphogenetic fields, various types of processes, singularities, symmetry-breaking, topological complexity and waves (see Thom, 1975).

Thom's models have sometimes been put to dubious uses by enthusiasts, but this does not detract from their importance for a deeper understanding of many systemic and cybernetic features.

Chaos theory as the study of the irregular, unpredictable behaviour of deterministic non-linear systems is one of the most recent and important innovations in systemics. Complex systems are by nature non-linear, and accordingly they cannot be perfectly reduced to linear simplifications. Notwithstanding, a good concept of the complexities of non-linearity was lacking until the mid-1970s. Chaos theory, whose original preview was introduced by Poincaré, is a collective construction of a number of mainly American, French and German researchers and mathematicians. It has renewed our views on determinism and randomness, now closely intertwined. It is significant for many systemic processes, for instance irregular periodic behaviour, bifurcations, instabilities and threshold crossings. It also helps in reconsidering the problems of forecasting and predictability in relation to initial conditions.

Another void in the formal scaffolding of systemics has been covered recently by the theory of self-organized criticality (Bak, Wiesenfeld and Chen, among others, 1988 on, and in France by de Gennes). This theory studies quasi-systems, or composite systems, made of millions of elements interacting only over a short range and intermittently, with no discernible organized subsystems. Examples, some of them quite unexpected, are snow fields, sand heaps, stock markets, ecosystems, geological faults and earthquakes, forest fires, traffic on highways and panics in crowds. It could seemingly also be applied to studying social behaviour in animal societies (locust swarms, lemming mass migrations). This listing shows that criticality is obviously a transdisciplinarian tool. It introduces new aspects of the notions of instability, instability thresholds, power laws and turbulence, as well as new concepts and models as avalanches, chain reactions and flicker noise. Self-organized criticality is closely related to chaos, fractals, transition matrices and vortices.

Conway's *game of life* has been used to model critical situations in systems.

Another outstanding French cybernetician and systemist, active since 1950, Vallée has constructed during the last 40 years under the general name of 'epistemo-praxeology' an elaborate mathematical and logical theory of cognition as related to systems (1993, 1995). This work, based on a very wide knowledge of the relevant authors in the field (as for instance von Förster, Maturana, McCulloch, Pitts and Wiener), introduces the notions of observation operator, inverse transfer and epistemo-praxeologic loop in order to clarify the deeper nature of the interrelations between the observer and that which is observed.

In 1977, Le Moigne, also French, published his first edition of his *Théorie du Systeme Général*, which is in fact an attempt to establish a general theory of modelization of complex systems of any kind, i.e. a general systemography ('le systeme, en général' in Le Moigne's own words). This theory was reworked by the author in 1983, 1990 and 1994 and is now a very rich source of insights into a synthetic understanding of systemics.

Most theoretical and practical economists after Boulding have consistently ignored systems concepts. However, there has been one outstanding exception with Georgescu-Roegen's work (1971). This author showed that economy is submitted to the thermodynamic laws, and particularly to the irreversible and irrevocable global increase of entropy.

Other authors — in the United States Odum (1971), from the ecological viewpoint, Daly (1973) on the conditions of a steady-state economy, Pimentel (1977) about the energy balance in agricultural production; in the United Kingdom Mishan (1967) about the costs of economic growth; and in France, Passet (1979) about economic sustainability in general — have tackled the subject. However, the main currents in economic thinking still ignore these very basic problems. As a result, as observed by Warfield, economics in systemic terms is still largely a pending subject. This is at the same time a very serious failure of systemics and a very dangerous situation for mankind in general. Subjects like global management of energy flows, ecological accounting, specific and general national and global patrimonial accounting for sustainability, sources depletion and sinks saturation, waste recycling, etc., should urgently be researched through a systemic–cybernetic approach. General systemic conditions, as short- and long-term stability and instability thresholds, chaos, cycles and trends, dissipative structuration, criticality and power laws, could lead to a better understanding of the whole subject and be quite useful in this task.

De Greene in the United States has contributed since 1988 a series of significant studies in systemic terms on long cycles in economic and social systems. This work could lead to a renewed interest in this topic, important for any non-linear forecasting or planning activity.

Various social scientists, mainly from the United States, made use of the concept of system, in particular since the periodic conferences instated by Grinker and Ruesch in Chicago during the 1950s (see Grinker, 1956). The participants freely used notions such as adaptation, autonomy, boundaries, communication nodes, effectors, energy system, environment, Gestalt, hierarchy, homeostasis, information, levels, processes of interaction and communication, open systems, organization, circularity of processes, rhythms, structures, steady state, stability, stress, threshold, etc., showing clearly the influence of the then developing cybernetics and systems theory. Among the most prominent participants were Deutsch, Parsons, Rapoport (one of the founders of the original Society for General Systems Research), Thompson and Weiss.

To this list we may add Berrien (1968), Buckley (whose compilations of 1967 and 1968 are still useful), Vickers and Easton. However, the systemic movement in sociology never really took off, perhaps because most sociologists only got a smattering of notions about systemics and in many cases confused it with structuralism, with functionalism or even with applied systems analysis or with systems dynamics.

The controversy around Wilson's sociobiology obscured still more the whole subject. Taking into account the ever growing complexity of our societies, it would be urgent to reconsider anew the whole field from an all-embracing systemic viewpoint.

One interesting angle in this sense is Maruyama's concept of 'mindscapes', personal and to a point cultural.

In a different perspective, von Glasersfeld has been developing since 1976 his 'constructivism' as a general reflection on the conditions of learning and knowing (see von Glasersfeld, 1995). He uses the following significant quotation of von Förster: 'Objectivity is the delusion that observations could be made without an observer'. Consequently, von Glasersfeld's aim is to discover how we perceive and construct reality, to retrace the ways we follow to construct concepts and to elaborate abstractions, and to better understand the relation of the self with others and with the environment in general.

Such a work amounts to a cybernetic–systemic theory of knowledge, which is needed to put the whole of cybernetic–systemic thinking into perspective.

The Argentinian-Canadian epistemologist Bunge developed a very acute critical study of systemics as a scientific methodology, and in a sense philosophy. He debunked some myths concerning abusive holism, but at the same time revindicated the usefulness of systemics, especially in the fourth volume of his *Treatise on Basic Philosophy: Ontology II: A World of Systems* (Bunge, 1979).

Finally, Troncale's (1985) widely developed paper on systemic thinking and modelling methodology, unfortunately not sufficiently known, seems fundamental if systemics and cybernetics are to be practically used specifically in the future as useful transdisciplinarian tools in their own right. The fact that Troncale's observations and proposals still largely remain unheeded reflects a quite frequent and regrettable indifference for practicality in many systemic circles.

SOME SIGNIFICANT RECENT CONTRIBUTIONS (AFTER 1985)

Some other very recent developments should still be signalled. One is the Hungarian Csanyi's work on the 'replicative model of self-organization' (1989), which should be neatly distinguished from the autopoiesis model. This is a significant step towards a general systemic understanding of systems genesis. Before becoming autopoietic (replicative in Csanyi's terminology), any system has to get through its own autogenesis, i.e. to successfully become an identifiable and viable new entity ordered from formerly free elements.

Csanyi describes the conditions — i.e. rules for a specific organizational process — needed for a minimal set of components to be able to start a replicative system and calls such a set the autogenetic system precursors. Until such a set does not start to develop functions it is a 'zero-system'. The initial action of the rules is triggered by some energy input and leads quite swiftly to a growingly differentiated organization which acquires closure through the appearance of closed cycles and thus becomes self-replicative, i.e. autopoietic. This sequence is becoming one of the most active fields of biological study and promises to be a very general set of guidelines for the study of any type of social genesis and sociality. The connection with Eigen's hypercycles and the present research on AL is noteworthy.

The new field of AL, opened by various investigators — Brooks, Langton (1989) and others in the United States (1989); Steels in Belgium; Delhaye and others in France, etc. is leading to the discovery of uncanny similarities between artificial and natural processes of social construction in systems, from cellular automata to social insects and, quite probably, human societies. Sociality is obviously one of the most general topics to be covered in a transdisciplinarian way by systemics and cybernetics.

Sabelli (an Argentinian physician and psychiatrist working in the United States) and collaborators have been developing since 1985 a new and quite general systemic theory of processes, which puts much emphasis on the dynamic aspects of systems and, furthermore, insists on other characteristics such as symmetry-breaking, process and structures oppositions, and thermodynamical aspects mainly related to entropy. Sabelli uses these concepts widely in biology, physiology, psychology and social sciences, revealing some unexpected relations between these disciplines (1991). A better connection of Sabelli's work with other systemics theories is still to be worked out.

In 1993, McNeil proposed still another quite general systems theory based on a set of concepts reminiscent of the French Laville theory of whorls, or vortexes (Laville, 1950). McNeil, who was unaware of Laville's work, sees any system as the result of dynamic interactions between fields. Some of these lead, according to him, to the stabilization of helical generated structures called toroids. These toroids are a very general model of dynamic equilibrium. The theory has thermodynamic overtones and seems to be related to Bénard's dissipative structures and to Prigogine's principle of minimum entropy production. It is rooted in physical notions, which makes it interesting as to the possibility of a better synthesis between physical sciences and living systems. Its possibilities in biology, economics and sociology are intriguing.

As the editor of my recent *Encyclopedia of Systems*, I included in this work some very generally unknown concepts, which seem, however, of a quite systemic nature and, as such, potentially useful. Three of the most significant among these are:

- the 'aura' (Prat), i.e. whatever traces remain of the system after its demise (petrified wood, a ship's wreck, Hammurabi's and Justinian's code, Aristotle's logics);
- 'stigmergy' (Grassé), i.e. the alternate and reciprocal transfer of structural and/or functional information from individuals to the system they are part of, or conversely;
- 'invisibility' (de Zeeuw), i.e. the non-perception of some objects, features or situations due to the insufficiency of our observational competence.

I am convinced that there must still be a number of other concepts or models of potentially systemic generality scattered in some (un)fairly unknown works of disappeared or living researchers. We should dive for them in the deeps of literature.

I dearly hope that I did not forget any important innovator in this study. If this should be the case, victims should feel free to protest and I will be ready to amend!

Systemics and cybernetics practitioners will be considered in another paper: Beer, Checkland, Warfield, Banathy, Ackoff, Mitroff and Linstone, Flood and Jackson, Johannessen and Hauan among them.

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