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SIXTY YEARS OF CYBERNETICS
Cybernetics Still Alive

Ivan M. Havel

This informal essay, written on the occasion of 60th anniversary of Wienerian cybernetics, presents a series of themes and ideas that has emerged during last several decades and which have direct or indirect relationships to the principal concepts of cybernetics. Moreover, they share with original cybernetics the same transdisciplinary character.[1]

Keywords: cybernetics, general systems, transdisciplinarity, feedback, self-reference, collective phenomena, scales, hierarchies, emergence, downward causation, connectnism, chaos, autopoiesis, domains of discourse, causal domains, metaphors

1. INTRODUCTION

> Cybernetics makes poets of us because it provides
> abstract descriptions that make metaphors possible.
>
> Mary C. Bateson[2]

Sixty years ago a peculiar science emerged under the name *cybernetics* [25]. Unlike standard natural sciences it was not interested in ordinary things like bricks, clocks, or frogs, but rather in certain phenomena, relations, effects, and processes that in various disguises occur in many, otherwise dissimilar situations. In the framework of theoretical cybernetics (unlike of some its later practical applications) various more or less familiar concepts – like feedback, homeostasis, control, finite automata, celular automata, logical or switching networks, information, entropy, signals, messages, communication, adaptation, stability, oscillation, self-organization, self-reproduction, etc. – are studied with emphasis primarily on such their aspects that frees them from concrete material carriers. Thus cybernetical studies set out for a journey across traditional divides between scientific disciplines – exemplifying a truly transdisciplinary endeavor.

Perhaps due to its distinctive nature, cybernetics in the Soviet block survived the period of scorn by communist ideologists of early 1950's, as well as of affected exaltations by the same ideologists only a few years later. Paradoxically, in Western

[1] The paper draws heavily, with revision, from various my earlier works, especially from [3]-[10] The research was sponsored by the Research Program CTS MSM 021620845.

[2] Quoted from her lecture in Crestone, Colorado, August 1998.

countries cybernetics gradually lost the status of an independent major discipline under that name, having been dissolved into various different fields like automata theory, control theory, system science, computer science, artificial intelligence, and somewhat later, into newly emerging areas of nonlinear science, complexity studies, network analysis, and certain topics in cognitive science.

I am not an advocate of trying to invent a precise and comprehensive definition of cybernetics for the 21st century. I am afraid that any definition would eventually confine cybernetics within strict disciplinary boundaries and render it just as an ordinary discipline in the conventional sense. This would deprive it of its original, inherently transdisciplinary character. Should we call it cybernetics, post-cybernetics or something else, we have to have in mind that we view it as an open area of study, always prepared to embrace entirely new themes, concepts, ideas, and theories. In spite of, and in addition to, their often formal and abstract conceptions, they may appear to be productive by enabling a metaphorical transfer of concepts from one to another scientific area.

In this essay I am going to present several ad hoc chosen samples of such ideas or concepts – some recent, some perhaps not so widely known, and some not yet conceptualized – that in one or another way keep on the transdisciplinary spirit conceived by the founding fathers of cybernetics. My intention is not to present a representative survey of such ideas and the limited space allows me only to outline them in a sketchy and informal way; moreover, I will not stick to the chronological order of their emergence in the history of cybernetics.

2. GENERAL SYSTEMS THEORY AND TRANSDISCIPLINARITY

The pervasive concept of a *system* attracted theoreticians already in the early 1950's. In 1954, a group of scientists representing various fields gathered around Ludwig von Bertalanffy in a research centre in Palo Alto, California. There they developed among themselves a stimulating resonance across disciplines, and in recognition of its importance they established the Society for Research of General Systems. For some reasons it was a time pregnant with cross-fertilization, interconnections, and cross-breeding of scientific fields. They formulated a manifesto comprising four principal tasks to be pursued (quoted from Klir [16, p. 33]):

1. To investigate the isomorphy of concepts, laws, and models from various fields, and to help in useful transfers from one field to another;
2. To encourage development of adequate theoretical models in fields which lack them;
3. To minimize the duplication of theoretical effort in different fields; and
4. To promote the unity of science through improving communication among specialists.

I can hardly imagine a more apt articulation of the idea of *transdisciplinarity*. Indeed, the attribute "transdisciplinary" can be associated with insights, motives, themes, principles, concepts, and ideas each of which is meaningful in a number (typically in many) of disciplines and perhaps even transcends them; it may appear in multifarious concrete shapes, forms and variations. I repeat and add some newer examples: feedback, information, entropy, representation, complexity, hierarchy, complementarity, evolution, stability, fluctuation, chaos, critical phenomena, catastrophes, synergy, collective behavior, emergence, adaptation, order, and various "selfs": self-similarity, self-reference, self-reproduction, and self-organization.

Notice that we may talk about (concrete) transdisciplinary concepts as well as about transdisciplinary research methodology.

3. FEEDBACK, SELF–REFERENCE, AND STRANGE LOOPS

The most paradigmatic principle of cybernetics, that of *feedback*, had been familiar to many scientists and engineers already before its transdisciplinary nature was accented by Norbert Wiener and his colleagues. The principle is so commonly used that the enigmatic charm inherent to the reciprocal efficacy associated with the feedback is rarely appreciated. It is more salient in the case of some other reciprocal phenomena, among them the phenomenon of *self-reference* being the most inspiring one.

Physical realizations of the ordinary feedback loop, whether in technology, biology, or society, have either a dumping or amplifying effect, and in addition they may trigger an oscillatory behavior. The associated processes necessarily evolve in real physical time. In contrast, the concept of self-reference transcends that of feedback by putting forth two essential options: first, the relationship may have an atemporal nature, and second, it may lead from one to another domain of discourse, for instance from the level of syntax to the level of semantics (as already the word "reference" indicates).

In the late 70's there appeared a famous book *Gödel, Escher, Bach* by Douglas Hofstadter [11]. In a witty and readable way, the book exposed various disguises of self-reference and reciprocal links in sciences, literature, and arts. He discussed many cases of what he calls *strange loop*: something returns to a state that should have been abandoned forever. Somebody utters a statement that is turned, by this very act of uttering, into falsehood (the well-known liar's paradox). A phonograph is destroyed by the vibrations of the sound it plays back. Computer algorithm recursively calls itself as a subroutine. A close-loop video camera scans its own screen. And last but not least, there is the ingenious idea behind Gödel's incompleteness theorem of mathematical logic. Unlike as in the case of ordinary feedback loops, strange loops always reveal something extraordinary that often escapes a scientific account in the classical sense.

Such phenomena can be always rendered in a twofold way: either in the *unfolded* form of an infinite process evolving in real or mental time, or in the *enfolded* atemporal form. The former case may help in explaining the phenomenon in question, the latter may yield a paradox – and a paradox often leads to a much deeper insight. The unfoldment and enfoldment are two complementary conceptions, and this very complementarity could be viewed as an epistemological contribution with cybernetic roots.

4. COLLECTIVE PHENOMENA

Almost anything in physics, nature and society that is scientifically interesting due to its inherent complexity exhibits a common characteristic: it consists of a multitude of elements or components which either influence, support and complement each other, or else which somehow compete, fight, push and stamp each other out. It may be electrons in heavy atoms, atoms in large molecules, molecules in matter, matter in continents. It may be cells in organs, organs in organisms, organisms in species, species in ecosystems. It may also be citizens in nations, nations in regions. It may be elements in logical circuits, circuits in computers, computers in computer networks. Individual data within scientific hypotheses, hypotheses in scientific disciplines, disciplines in the entire body of knowledge.

Due to the continuing interest by system theoreticians, students of synergy, statisticians and other interdisciplinary specialists, we are now on the verge of finding universal principles providing us with a unifying view of the above mentioned variety of collective systems. I cannot help but believe that when such principles are uncovered, we will be astonished by their simplicity.

Statistical physics is one of the classical disciplines relatively advanced in that direction. Already in the nineteenth century, Ludwig Boltzmann and his followers created a conceptual system which makes it possible to talk about characteristics of macro-systems (systems which surround us) in terms of the common or collective properties of particles (atoms or molecules). While the immense number of particles prevents us from describing global behavior in terms of microstates (complete collections of states of all particles) we may rather work with macrostates (each representing a large set of micro-states with a certain common macroscopic property). If done properly, nothing gets lost (nobody will ever see any microstate anyway) and a better understanding of reality may even be achieved.

Statistical laws help to understand the essential asymmetry of progress at the macro-level from the improbable macrostates to the more probable ones; the asymmetry can be expressed by the law of ever-increasing entropy. The asymmetry of nature related with respect to the time arrow may therefore be viewed as an *emergent phenomenon* of the macroworld (cf. Section 6 below). An interesting example of a topic addressed by statistical physics is a change occurring in the overall order of a system – the so called *phase transition.* The most commonly known phase transition occurs between solid, liquid and gaseous phases of water, but there are much more intricate cases in various other areas. In fact, a phase transition is a typical example of a transdisciplinary phenomenon: in each case it involves the collective behavior of a large number of elements. The nature of those elements may vary from case to case – not only atoms or molecules, but also, for instance, leaves of water lilies, burning trees, rabid foxes, and indecisive voters.

5. SCALES, LEVELS, AND HIERARCHIES

Previous examples of collective systems bring us to the trivial fact that a collection occupies more space than its elements. In general, we are used to associate spatial objects, relations and events with a certain *scale.* The world appears different on different scales – small scales, medium scales, and large scales – and we can talk about shifting our attention or concern smoothly, from one scale to another, by zooming in or zooming out – either in imagination, or, to a smaller extent, visually (say, with the aid of microscopes or telescopes). In theory we can conceive of a special coordinate axis, the *space-scale axis*, thereby adding an extra dimensionality to our world [4]. Somewhere in the "middle" of the space-scale axis there is situated the homely world of our everyday experience within our (human) *space-scalar horizon*.

Analogously to the space-scale axis we can think of the *time-scale axis*. Shifts along it would correspond to changes of our concern either towards temporally shorter events and durations (measured, e. g., in milliseconds, microseconds, and less) or towards longer ones (measured, e. g., in years, centuries, and more). Similarly to the space-scalar horizon, the *time-scalar horizon* of our everyday experience is confined to intermediate temporal scales (seconds, hours, and days). An intuitive analogy of spatial zooming in and zooming out can be now approached by imagining the decelerated or accelerated flow of world events (as it is often done in educational films).

It is interesting to note that typical space and time scales of many spatio-temporal entities (lasting things, extended events, physical processes) studied by empirical sciences are often mutually related. Metaphorically said, elephants live longer than flies (which statement, of course, does not apply to supernovas or neutrinos).

The original human intuitions, ideas and concepts have evolved within and are inherently linked to our space-time scalar horizons (and several other types of horizon that I do not discuss here). Consequently, those scientific theories that invite us to mental voyages into worlds unimaginably small or immensely large (or else too slow or too fast) must be rather cautious about their use of language. They must not fail to distinguish carefully three types of situation: first, when our everyday language is used in a literal sense; second, when a metaphorical transfer of words and idioms helps us to discuss things beyond the experiential horizon; and third, when an entirely new ad hoc language has to be created.

Now let us consider objects that may be classified as *complex*. Preliminary and somewhat minimal definition of a complex object may be based on the assumption that it is stretched over a multitude of spatial and/or temporal scales. It turns out that for such objects there is often a close relationship between its distribution over scales and the hierarchy of its structural, functional, or descriptional *levels*. Accordingly, Salthe [20] prefers the generic term *scalar hierarchy* whenever there is a nontrivial collection of levels, each related to a specific scale. A particular case is the *mereological hierarchy*, based on the part-whole distinction; indeed, apart from trivial cases, wholes are always larger than their parts.

As scientists, we are typically realists about mereological differences between parts and wholes (trees versus forests, water drops versus clouds, bees versus beehives, neurons versus brains). In the same manner we might be inclined to be realists about existence of, and differences between, various other types of discourse pertaining to the world (more about that in Section 6). Yet, undoubtedly, we have a great amount of freedom to fix the details of such differences. Our picture of the world is a dynamical outcome of a never-ending circular hermeneutic process: our world is *enacted* (a term coined in cognitive science by Varela et al. [24], elaborated by Noë [19] and widely used by Thompson [22]).

Two types of difficulty can be pointed to. The first one stems from our insufficient understanding of the nature of efficacious interactions, downward or upward, between distinct (possibly distant) levels of complex hierarchical systems. The second type of difficulty is related to the epistemological nature of the concept of level per se. I will return to this in Section 10 where I will treat it in relation to a more general concept of domain of discourse.

6. TWO–LEVEL SYSTEMS, EMERGENT PHENOMENA, AND DOWNWARD CAUSATION

There are many situations, both in nature and in social sphere, when a certain higher-level process evolving on a certain large, i. e., "slow" time scale is inherently linked to, dependent on, and perhaps realized in combined behavior of a multitude of lower-level processes or events, occurring each on much small, i. e., "fast" temporal scale. Here I give seven willfully diverse examples, some taken from nature, others from the human domain: (1) evolution of species vs. properties and life histories of individual organisms; (2) macroeconomics vs. market behavior; (3) an epidemic vs. particular cases of illness; (4) evolution of a language vs. speech acts; (5) history of technology (or science) vs. concrete inventions (or discoveries); (6) development of a legal system vs. particular court decisions; (7) evolving rules of a game vs. actual matches.

While on the lower level we encounter specific, concrete and sometimes isolated occurrences of individual entities or events, the corresponding upper-level entity usually has a latent, symbolic, or non-material, but long-term existence. It is by virtue of such a continuous nature of existence on the upper level that we may consider each entity or event on the lower level as a manifestation of a single higher-order entity (hence often the same term is used for both).

There may be a bi-directional, circular interaction between the two levels. For instance, the upper level process may provide "rules of the game" for its lower-level instances. Conversely, the lower-level events cumulatively influence the slow development of the higher-level system. Even if the lower-level individuals are conscious agencies with their own intentions and goals, they may not be aware of their influence on the upper-level process. The latter is then neither random nor controlled by a single agency – its conduct and properties are *emergent* (i. e., neither deterministic nor teleological in the narrow sense, but purposeful, cf. [8]). Due to such emergence, the combined two-level system may exhibit an ability of self-construction or self-improvement (these abilities are essential in autopoietic systems to be discussed in Section 9).

The concept of emergence may be nicely illustrated by an example of evolution based on the variation-selection-reproduction principle. Here the *upward* (bottom-up) efficacy can be explained with the help of statistical laws; in general, however, not only individual behavior may have higher-level effects, but also cooperation, entanglement and other collective phenomena on lower level may initiate emergent processes on various higher levels. Thus, e. g., the growth of complexity of the biosphere on Earth may be explained by a network of emergent processes on a multitude of different scales.

So far we have dealt more with the upward efficacy (or causation) in two-level systems. This may be, for purposes of theoretical treatment, relatively easily generalized to multi-level systems. On the other hand, the idea of *downward* (or top-down, or global-to-local) causation is much less understood. In certain cases its existence is obvious, for instance in the case of a global-to-local symbolic communication in human information society. Individuals learn about the global events and may change their behavior accordingly (recall our examples of macroeconomics or of the legal system). Individuals may even guide their behavior to comply with (putative) higher-level interests and so, conceivably, their decisions on the lower level may willfully favor some desired, purposeful evolutionary path on the upper level (according to the maxim "think globally and act locally"). This dynamics, sometimes called the reflexivity of the system, is actually a closed multi-level feedback loop.

The idea of downward causation is extensively discussed in contemporary cognitive science and philosophy of mind. What is at issue is how to explain that human conscious decisions (considered to happen, in this case, on the higher, mental level) may have instantaneous influence on neuronaly induced bodily behavior (think of, e. g., voting by raising the hand). This theme, however, would extend beyond the scope of this paper.

Let me close this section with one relatively precise definition of the concept of emergence according to Thompson ([22, p. 418]): A network, N, of interrelated components exhibits *an emergent process*, E, with emergent properties, P, if and only if:

(1) E is a global process that instantiates P, and arises from the coupling of N's components and the nonlinear dynamics, D, of their local interactions;

(2) E and P have a global-to-local (downward) determinative influence on the dynamics D of the components of N; and possibly

(3) E and P are not exhaustively determined by the intrinsic properties of the components of N, that is, they exhibit "relational holism".

7. CONNECTIONISM

Connectionism, neural network modeling or parallel distributed processing (PDP) are several names for trends in cognitive science of late 20th century based on attempts to concretize the ideas of emergence in collective systems. Connectionist models are reminiscent of, and/or inspired by, the neural networks in the brain, and are conceived as parallel-processing systems, involving cooperative "computations" grounded in local interactions between connected units, modifiable by training or by learning from past experience.

Many variants of connectionist models with different network topologies, unit activity functions, learning rules, and teaching strategies have been introduced; some models are deterministic, some involve noise or "temperature", some are discrete, some continuous. Surprisingly enough, these variants exhibit more or less the same type of global behavior.

On the lower level, a connectionist system is comprised of a number of units (neuron-like elements). At every moment of time each unit is in a certain state of activity, either excited or quiescent (alternatively, it may assume one value out of a continuous segment of possible values). Some units are mutually connected; each connection is associated with a weight, either positive (excitatory) or negative (inhibitory). Local dynamics is specified by a uniform activation rule, typically a nonlinear (threshold or sigmoid) function of the weighted sum of activities of connected units. The weights of connections are assumed (in the more interesting case) to increase incrementally when the activity of the corresponding pair of units is correlated. Importantly, the change of connection weights is much slower comparing to the changes of the activity of units. Thus a connectionist network can be viewed not only as a special case of a two-level system from Section 6, but also as a pair of *coupled dynamic systems* – one representing its locally defined fast active behavior, the other its globally meaningful slower "learning" process.

According to the degree of the autonomy of units we can distinguish two opposite modes of global behavior or, using the language of statistical physics, two *phases:* one corresponding to the rigid system of inherently deterministic units, the other having a chaotic and unpredictable global behavior. In a rigid system a new interesting pattern (or idea, if you like) occurs with a great difficulty, while in the chaotic system such a pattern (idea) is immediately dispersed. It is conceivable that under proper settings of parameters (like density of connections, the ratio of excitatory and the inhibitory ones, etc.) we obtain an intermediate system working on the "edge of chaos" (i. e., near the boundary between the ordered and the chaotic behavior; to be discussed in the next section). Then, for instance, a certain pattern may propagate easily through large areas of the network. In physical systems similar situations are known to exist near phase transitions (cf. Section 6).

Collective systems with highly parallel activity happen to be interesting alternatives to classical serial computational algorithms and overpower them in certain tasks (like pattern recognition, learning, etc.). Collective systems may have extremely large combinatorial complexity (the number of macrostates grows exponentially with the number of units). Such a complexity is not a disadvantage since it yields redundancy and redundancy supports self-organization and self-improvement. In a sense the theory of connectionist networks builds up on classical cybernetics by elevating the productive effect of feedback to complex systems with a tremendous number of interrelated feedback loops.

It is interesting to note that there exist recent theories in cognitive science informed by neuroscience [1, 2]. Crudely said, instead of a single connectionist network of individual neurons there is a collection of large neural populations, each of which may spontaneously oscillate due to a sufficient number of inhibitory feedback connections. This forms a higher-level network of oscillating units (neural populations) that mutually interact on a mesoscopic scale and under external influence may change their oscillatory patterns or even enter into chaotic attractors. The theory of complex dynamic systems is essential for the study of such multi-level networks.

8. ON THE EDGE OF CHAOS: RANDOM BOOLEAN NETWORKS

In the previous section we discussed a possibility of emergence of a nontrivial higher-level behavior in a complex system. In particular we touched upon a conceivable behavior on the edge of chaos. Such systems possess many interesting characteristics that are meaningful, mutatis mutandis, in many different areas of natural sciences as well as of social sciences. For instance, if certain parameters of a large complex system obtain a specified value, a small local anomaly (e. g., a mutation, idea, intent, slogan, joke, virus – depending on the domain of discourse) may spread very fast across the whole system.

The connectionist models described in the previous section are just a special case of a substrate prolific with collective phenomena. Another, considerably different example is the *random Boolean network* introduced by Stuart Kauffman [12].

Kauffmann's network consists of a large number of units, each instantiating a randomly chosen Boolean function of a certain number of input connections coming from other, randomly chosen units. Over a succession of moments the system passes through a sequence of total states; this sequence can be associated with a trajectory in the state space of the network. The state space is finite (even if, in general, rather large) and thus each trajectory ends up in a limit cycle attractor. For certain values of parameters (for instance the average number of inputs to an element, or certain quantifiable characteristics of chosen Boolean functions) the system exhibits a quasi-chaotic behavior (the cycle lengths of attractors grow exponentially with the increasing number of units); for other values the behavior is "ordered" (there are only small isolated groups of changeable units within a large web of elements that are "frozen" in one state or the other). Thus the system has two *phases*, one chaotic and the other ordered. Interesting dynamic behavior emerges when the network is near the phase-transition area in the parameter space – then, typically, both small and large unfrozen groups coexist. A small perturbation (e. g., a random change of the state of some unit) may cause a large avalanche of changes propagating through the network. In this way distant sites in the network can "communicate". Moreover, these special modes of behavior have *homeostatic quality*: structural mutations of the system do not considerably affect its dynamic behavior.

This was an example of a rather different system in comparison to the neuron-like connectionist network, yet with interesting emergent and unpredictable properties that resemble various collective phenomena.

9. AUTOPOIESIS: AN APPROACH TO THE PHENOMENON OF LIFE

The issue of the difference between living organisms and physical things is permanently in the focus of philosophers and scientists. There were various recent attempts to find necessary or sufficient conditions of something being alive; an instance of one of the relatively well-known approaches is that pursued by Kauffman [13, 14]. Here I want to mention another approach which became familiar under the term "autopoiesis".

The theory of autopoiesis was first formulated by Maturana and Varela [17] who originally aimed at the question of what is the minimal organization of living systems that would make them different from merely physical (natural or artificial) objects. By (simplified) definition, a system is *autopoietic* if it satisfies the following three conditions ([22, p. 101], here slightly modified):

(1) The system has a semipermeable boundary;

(2) The boundary is produced by a network of processes that take place within the boundary;

(3) The network of processes must include processes that regenerate the components of the system (as well as the boundary).

The paradigm case of an autopoietic system is a cell, at least if it is described as a network of chemical reactions producing molecules that, due to their interactions, generate, and participate recursively in the same network of reactions that produced them, and moreover, realize the cell as a material unity. This unity is established by the cell membrane that forms its semipermeable boundary, being itself a product of internal reactions within the cell.

In fact, the cell was the original inspiration for the notion of autopoiesis; the notion, however, applies also to embodied organisms, animals, and human beings. Then chemical reactions are supplemented with much more complex processes, up to sensorimotor and cognitive interactions with the environment. The ladder of life can not only be climbed upward but also downward. On the lowest partitions of the ladder the researcher leaves nature behind and resorts to computer simulations, under the banner of Artificial Life. As a matter of fact, certain minimal variants of autopoietic systems were already realized in computer-simulated two-dimensional cellular automata ([18], cf. also [22, pp. 107–118]).

In autopoietic systems there is a characteristic circular interdependency between various self-regulating processes on the one side, and the self-production of a boundary whereby the system forms a spatially distinct individual on the other side. Hence autopoiesis is a condition of possibility of dynamic emergence of *interiority*, in distinction to the *external milieu*. The dynamical character of autopoiesis is essential: the components needed for the constituent processes are continually re-created and the same holds for the boundary (which is one of the components of the system). Thus the difference between the system and its environment is maintained.

Autopoietic systems can be considered as a special case of *autonomous systems*, the latter not necessarily caring of its own material boundary. Thus other types of organizationally, or operationally closed systems whose boundaries are, say, only social or territorial (like ecosystems, insect colonies, human societies) may be autonomous but not autopoietic.

In the context of this study it is worth mentioning that several principal features of autopoietic systems have a typically cybernetic flavor: reciprocal links, levels, self-reproduction, nonlinear dynamics, and autonomy. What is even more akin to the original program of cybernetics, is that autopoietic theory, by offering a notion of minimal bodily "selfhood" or self-concern, is opening up the grounds for thoughts about bridging the explanatory gap between two large domains of discourse, that of physics and that of biology. Thompson ([22, p. 238]) argues for an expanded notion of the physical to account for the organism or living being. According to him, "life is not physical in the standard materialist sense of purely external structure and function. Life realizes a kind of interiority, the interiority of selfhood and sense-making." He goes even further, proposing what he calls the deep continuity of life and mind thesis, according to which "life and mind share a set of basic organizational properties, and the organizational properties distinctive of mind are an enriched version of those fundamental of life." (p. 128). However interesting this line of thought is, there is no space to elaborate on it here.

When discussing basic aspects of the living, one should not forget that *self-production* is not yet *self-reproduction* (producing its own copies). Some authors take self-reproducibility (e. g., the preservation of the continuity of a species) for a part of the definition of life – if for nothing else than as a precondition for the variation-selection-reproduction principle of evolution (as mentioned in Section 6). Self-reproduction, even if it is not included in the definition of autopoietic systems, is by no means an alien theme. Perhaps it is appropriate at this place to mention a lecture given by John von Neumann in 1948 (hence also something to be celebrated), in which he laid down the foundations of a formal theory of self-reproducing systems that can be, in principle, artificially realized in cellular automata [23].

10. DOMAINS OF DISCOURSE AND CAUSAL DOMAINS

In Section 5 above I mentioned the concept of a level, or a hierarchy of levels, in somewhat restricted form, related primarily to spatio-temporal scales. In scientific as well as philosophical literature there are frequent references to levels in a more profound sense. Thus, for instance, in sciences distinctions are made between the atomic level, molecular level, cellular level, neural level, etc., up to the mental level (cf., e. g., Scott [21]), and perhaps further to behavioral level, and societal level. Yet we are left alone with our intuition about what is precisely meant under the term "level". Judging from the usage, the only general, common feature of all levels is their epistemological sense: they indicate much better understanding, on the side of researchers, of relationships and laws *within* a particular level rather than *between* different levels.

I prefer to use the term *domain of discourse* instead of the term level and I have two reasons for this. First, it may be advantageous to suppress the tacit assumption of the existence of some underlying hierarchy of levels (where some levels are usually called "upper" and some others are called "lower") and prefer the term "domain of discourse" suggesting a substantially more general conceptual setting. The second reason is that the very word "discourse" aptly suggests that at least partly we deal with an observer-relative concept (see the end of this section). In fact, decades and centuries of specialization in science lead to various linguistic and methodological barriers between fields dealing with different domains of discourse. Here a revival of a transdisciplinary endeavor put forth by the founders of cybernetics is something to be desired.

Domains of discourse may be exemplified by particular subject areas of natural science (like, for instance, quantum physics, molecular biology, or evolutionary biology) and the fields delimited by different research methods. More or less anything we find in scientific and philosophical discourse that is designated, or recognized as, a "level", falls under the concept of domain of discourse. In scientific contexts domains (of discourse) and levels (of description) are typically shaped by intersubjectively shared knowledge.

Each domain of discourse can be viewed as a world for itself: it has specific individuals, universals, properties, aspects, relations, laws, etc. Such things may be peculiar to one particular domain, other things may belong to, or be meaningful in, several, perhaps many, domains − they are multidomain entities or shared concepts.

Multidomain entities, so to speak, "penetrate" through many different domains; typical examples are living organisms. In contrast, certain generic concepts may be shared by various domains, i. e. they may have analogous, or even the "same", meaning in various domains, partly due to their generality, partly due to the limitations of our language. Obvious examples are the concepts of space, time, causality, and most mathematical abstractions.

A typical domain of discourse lacks sharp borders, and what we count or do not count as part of it depends on how far its concepts, quantities, laws, and paradigms are significant. So, instead of a border, we deal with the notion of a *domain horizon* of which the spatio-temporal scale horizon discussed above is a specific component.

In the scientific enterprise one specific aspect of the concept of domain of discourse is particularly important, namely its causal underpinning. As a matter of fact, in the sciences all explanations and predictions are preferably based on *causal laws* that generalize the intuitive idea of one event (or state of affairs), – the *cause* – bringing about another event (or state of affairs) – the *effect*, whenever this "bringing about" is not assumed to happen just by coincidence. In contexts where causal efficacy is the main issue, it is advantageous to use a somewhat restrictive concept of a *causal domain*, instead of, or in addition to, the concept of domain of discourse.

We can think of a causal domain as of any segment (or fragment, or component) of reality within the scope of which causal relations appear to be (i. e., are presented to our knowledge as) *manifest* (obvious, apparent), *comprehensible* (intelligible), and *mutually coherent*. Or, more appropriately, they appear to be *more* manifest, *more* comprehensible, and mutually *more* coherent than causal relations *between different* domains. This formulation is admittedly vague but intuitively favorable; the implicit circularity should not be a hindrance. According to the traditional view, causes are events antecedent to their effects. Moreover, some theoreticians maintain that whenever one event causes another, it does so in accordance with a general law. The above concept of a causal domain (the term was used casually by Kim [15, p. 69]) deliberately presumes causation in the ordinary narrower sense (sometimes it is called the left-to-right causation). In fact, this enables us to make a distinction from a more general concept of efficacy (discussed already in Section 6), the latter applicable also to various relations between events of *different* domains of discourse (the upward or downward causations may serve as examples).

One may, of course, ask about the actual reality of causal domains, as well as of the reality of various levels and hierarchies within a complex system. Do they exist as ontological categories independent of our choice of presumably relevant objects, events and scales, or are they products of theoretical abstraction? There is no place here to venture into metaphysical issues; let me just remind that the horizon of human cognitive abilities and experience makes it difficult for us to mentally grasp at the same time more than a rather narrow spectrum of domains, or in particular, limited range of scales. For this (and other) reasons it is quite natural that scientists are compelled to think of the world as composed of various domains of discourse and of various structural and/or functional levels. Obvious differences between domains then yield different descriptions, different languages and, eventually, different disciplines. In this sense the concept of a domain of discourse is *observer-relative*.

11. CYBERNETICS IS STILL ALIVE

Of course, the few areas of the past and current research, discussed in the previous sections, are far from giving an exhaustive list of themes that could be viewed, in one or another way, as successors of the Good Old Cybernetics. There are two common features of our themes: first, that they are directly or indirectly built up on the original cybernetic ideas (feedback, homeostasis, etc.), and second, that they exemplify a genuine transdisciplinary scholarship. In many respects the presented directions of research converge on the ubiquitous and multifaceted notions of systemhood, structure, dynamics, and last but not least, complexity.

There was a peculiar hidden vivacity in old cybernetics, which is yet to be subjected to thorough analysis by historians of science. Its traces luckily endured through the six decades after the late forties in the less manifest layers in various other areas, mainly in those that are directly or indirectly concerned with dynamic and evolving entities – natural, artificial, or formal. Part of the vivacity can be attributed to effective use of abstract mathematical apparatus in new areas of study. I believe there is also another, less formal component of the vivacity, namely the strong heuristic power of *metaphors*.

Certain names of concepts, phenomena, relations, structures and regularities, originally introduced in one particular field, are helping to build bridges between various diverse scientific disciplines and paradigms. Transdisciplinarity at its best. Whole areas of study emerged in this way: cybernetics itself, but also system science, science of complexity, cognitive science, artificial life, and many others. Metaphors may induce, or already have induced, interesting discoveries and hypotheses that otherwise would hardly come to our minds. In other words, metaphors have the potential of triggering new streams of thought. Cybernetics and its follow-up styles of scientific discovery are both receivers and providers of strong scientific metaphors. The mysterious flavor of such metaphors lies in their ability to find similarities among dissimilarities and thus *to create a tension between likeness and difference*.

Whether or not the post-cybernetic trends will converge into a new, not yet established discipline, and whichever name it may eventually adopt, one thing can be put forth: cybernetic thinking has not disappeared after Wiener's time, it is still striding strongly.

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