

Paper prepared for the special issue on
Physics and Evolution of Symbols and Codes
Biosystems, Luis Rocha & Michael Conrad, editors.

From Complexity to Simplicity: Nature and symbols

Arantza Etxeberria & Alvaro Moreno

Logika eta Zientziaren Filosofia Saila (Dept. of Logic and Philosophy of Science)
Euskal Herriko Unibertsitatea (University of the Basque Country)
1249 Posta Kutxa, 20.080 Donostia-San Sebastian, Spain
ylpetaga or ylpmobea @sf.ehu.es

Abstract

This paper reviews Pattee's ideas about the symbolic domain as a phenomenon related to the self-simplifying processes of certain hierarchical systems, such as the living. We distinguish the concepts of *constraint*, *record*, and *symbol* to explain how the Semantic Closure Principle, that is to say, the view that symbols are self-interpreted by the cell, emerges. Related to this, the notion of complementarity is discussed both as an epistemological and as an ontological principle. In the final discussion we consider whether autonomous systems can exist in which constraints are not symbolically preserved, and if biological *symbols* can be considered to have a descriptive nature.

Keywords

Constraint, record, Semantic Closure, symbol.

I. INTRODUCTION

What is the “natural” element of this world? This is a question with many edges. Although we communicate our thoughts about nature using language, symbols and codes are considered to be artificial, belonging to the realm of minds and knowledge, not natural elements. For this reason, influences of the so called “natural” sciences upon the “human” ones are accepted as beneficial to advance towards a better explanation (as symbols or knowledge can have naturalistic explanations), whereas the reverse tend to be seen as problematic (as nature appears to be interpreted in an anthropocentric way). In fact, a usual epistemological demand is that symbolic or mental aspects are slowly “reduced” with scientific progress until they are grounded on natural relations or interactions. However, it is not evident that this is possible, neither that a frontier or boundary between the categories of nature and symbols can be drawn, for they seem to be tightly intertwined together.

One of the areas where the relation between nature and symbols is discussed with certain objectivity is that of complex systems and their degree of order or organization. Unlike disordered or disorganized systems, where interactions among components are messy or chaotic, organized complex systems exhibit a form of internal action that may be associated to knowledge and symbols. Nature may be chaotic, messy, difficult to apprehend or, in sum, complex, but a clear description is comparatively simple. Thus, to know is to acquire a clear insight of a domain under inquiry, clarity being a focus on the relevant properties and features; thus, some simplicity. Similarly, the organized form of a complex system has been seen as a process of self-simplification achieved because some elements of the system act so as guides of the dynamics so that the system is able to maintain itself.

This is how we basically understand the motivation of H.H. Pattee’s work. For him (like for many others studying complexity in the 70s), the correct way to explain organizations and living structures is by studying how complexity can produce simplicity in certain conditions. This simplicity has to do with the existence of certain material mechanisms for self-preservation in these systems, which are simpler to describe as such (in their function) than according to the physicochemical conditions that made them appear in the first place (in their law-governed dynamics). Thus, complex, intricate webs of dynamical elements and interactions result in (some kind of) spontaneous ordering in the system because certain elements will serve roles or functions for the maintenance and preservation of the system.

In this paper, we analyze and discuss Pattee’s way of dealing with these simplifying, functional elements and how he presents their role in the basic living organization. We attempt to distinguish the concepts of *constraint*, *record* and *symbol* and to expound Pattee’s explanation of the self-interpretation of symbols within the cell (the Semantic Closure Principle) (section II). After this, we discuss the Principle of Complementarity, both as an epistemological and as an

ontological principle (section III). Finally, in the last section, we discuss some consequences of this framework: whether autonomous systems can exist in which constraints are not symbolically preserved and if biological *symbols* can be considered to have a descriptive nature.

II. FROM LEVELS TO SYMBOLS

1. Hierarchies and constraints

One of the sources of the complexity of natural systems stems from the fact that they are composed of elements or events occurring at different levels (according to size, scale, inclusion, etc.). Some hierarchically organized systems do not involve complex interactions among levels; they are easily decomposable (Simon 1969). Others, as it is the case of the cell or other living phenomena, involve an intricate web of interactions among elements at different levels. Pattee's hierarchical approach aims at the understanding of the nature of those interactions under a single framework, in order to explain the nature of the unity formed by the whole of such a complex system.

Pattee focuses on two-level hierarchies and analyzed two types of them according to the nature and the degree of constraint the upper level exerts upon the lower one: the structural hierarchy and the control hierarchy (Pattee 1973). In both cases the upper level may be seen as a natural classification of collections of low-level components into simpler categories. Structural hierarchies increase the order of the system by reducing some degrees of freedom enabled by the basic level. Examples are the production of crystals, or of self-organizing global patterns or macrostates. The order of these systems is a consequence of the dynamical properties of the lower level. In contrast, in systems with control hierarchies the upper level is functional, it selects for certain events within the range of possibilities allowed by the dynamics of the lower level (downward causation). However, in this case constraints cannot be integrated into the physical description of the system and require an alternative description from a very different framework (as non-holonomic constraints¹).

The notion of constraint is central in Pattee's work. All physical systems obey natural laws, and constraints do too. Yet, in the frame of a system, constraints are material structures that exert important limitations or modifications in the way natural laws are obeyed. They can select among alternative behavior and organization possibilities in the way laws are obeyed:

Constraints, unlike laws of nature, must be the consequence of what we call some form of material structure, such as molecules, membranes, typewriters, or table tops, these structures must be static or time-dependent, but in any case it is important to realize that they are made

¹Non-holonomic constraints are flexible constraints “that do not simply freeze-out degrees of freedom, but impose new functional relations between them. The enzyme molecule is our most elementary example of such a flexible constraint that classifies its complex, detailed collisions according to highly simplified functional rules” (Pattee 1973: 106).

up of matter which at all times obeys the fundamental laws of nature in addition to behaving as a constraint. (Pattee 1972: 250)

The action of constraints on the overall organization and behavior of a system may produce its closure. The closure of a system specifies its possible components through some set of relations, thus inducing an inside/outside distinction (that is to say, an identity or unity condition). In formal domains it is externally introduced to the system as a rule, but the characterization of the constraints responsible for the condition of closure of a natural system, requires an autonomous mechanism or organization. This is the reason why Pattee has paid so much attention to the analysis of constraints and the clarification of their origins and function.

The relations (brought about by constraints) responsible for closure in living systems have received two characterizations in different stages of Pattee's work: *statistical* closure (1973) and *semantic* closure (1982). Even if probably looking at the same phenomenon, the first one explains the nature and function of control constraints within a hierarchical system, whereas the second is based on the idea of symbolic records that preserve those constraints, and of how they are interpreted within the living system as a whole. From a hierarchical point of view, an upper level of controls of such a system limits the freedom of the underlying dynamical components and establishes arbitrary functional relations. Controls produce and maintain a closure precisely by creating a domain of autonomy or freedom from the low-level dynamics. This first form was called *statistical* because of the "selective loss of detail" a *record* (see next section) of a statistical classification presents in relation to the underlying dynamics.

The question is: do control constraints arise spontaneously? Many researchers expect that the science of the future will explain the evolutionary transition leading to closed organizations solely by means of physical, dynamical theories, such as self-organization. Although this may seem to be the ideal kind of explanation, Pattee's work, in fact, aims to show that such explanation is not possible, because there are in principle problems to reconstruct the causal sequence leading to the production of a control hierarchy and its typical interactions. The reason is that the required constraints do not freely emerge with each new living system², but are inherited from the previous generation. For this to happen, they must have been preserved as *records*, often codified in a *symbolic* form (see next subsection). Our ignorance of how life originated suggests that constraints operating today are to a great extent the product of relations whose evolutionary history we are not able to fully emulate (complex systems blur their causal origins). The living organization cannot be explained in terms of dynamics alone, because it depends on a system of storage and transmission of constraints through symbolic records.

²"The frozen accident theory (...) does not conflict with the idea of arbitrariness in the coding rules, but it does not help us understand the statistical closure property either. (...) The establishment of a statistical closure may in fact result in an apparent freezing of structures, although there must be earlier levels of freezing before the time the present complex code was established. What we still need to understand are the minimum conditions for the spontaneous appearance of statistical closure in a collection" (Pattee 1973: 104)

According to Pattee, their interpretation within the cell is the most important and complex problem we face, if we are to understand the nature of life. As a consequence, in his second characterization of closure (semantic closure), constraints are preserved through symbolic records in reproduction. Before we discuss this principle of organization, we need to distinguish the notions of *constraint*, *record* and *symbol* in the next section.

2. Types of simplicity: constraints, records, symbol vehicles

We may now attempt to characterize and classify Patten's different types of simplifying functional entities in natural systems:

- *Constraints* are material structures capable of local causal action. By freezing certain degrees of freedom left free or open in a law-governed dynamical system, they materially set up specifically selected conditions for the physical laws. Examples of constraints are a living cell membrane or a catalytic enzyme.
- *Records* are (dynamically) conservative constraints, acting as such due to a structure or configuration that transcends the dynamic system in which they act (that is to say, the constraining structure did not form as a consequence of the dynamics of the system in which it acts). They constitute some form of material and local (non distributed) memory, which is the basis of rate-independent processes. Examples of records are the dislocation of a growing crystal, RNA in a hypothetical RNA world, etc.
- *Symbol vehicles* are types of records preserved in an encoded form. They hold no intrinsic or material causal relation with their effect (they are arbitrary). Examples of symbols are DNA in a cell, certain computer metastable states during a program execution, etc.

Constraints are material components immersed in the closed organization that constitutes a natural system; their construction may depend on records preserved in an inert form. A record is a special type of constraint that acts as some form of memory. In general, it is a metastable structure that may be viewed as a very simplified "annotation" of a selected complex dynamical process. Under certain (energetically negligible) conditions, they can switch complex and specific dynamical events on and off, in a repeatable way. Most records of evolved cells are symbol vehicles (although this is not strictly necessary in physical terms, as some records are not preserved via a code). The distinctive feature of symbols is that they are not themselves causal, but their action is effective when other machinery (enzymes), freely links their form with the controlled dynamical events (see more on this in section IV).

The distinction of the different kinds of entities acting in a cell yields to an explanation of closure based in an organization in which constraints are expressions of symbols, constructed by

the closed machinery of the cell (including the symbolically stored constraints). This is the Semantic Closure Principle.

3. The Semantic Closure Principle

Pattee considers that the origin of life involves the origin of a semantically closed organization between DNA (symbolic records) and proteins (dynamical constraints). Thus, cells endowed with a genetic code are the most basic example of a symbol-matter organization. Symbols are internally interpreted by the very products they specify; as no external observer needs to interpret them, the process involves no infinite regress. Because the interpreting machinery includes constraints stored symbolically, these symbols have no “meaning” removed from the interpreting dynamical structures: what symbols represent comes into view functionally. In like manner, the dynamical structures that interpret the symbols (enzymes) depend on symbolic specification:

We can say that the molecular strings of the genes only become symbolic representations if the physical symbol tokens are, at some stage of string processing, directly recognized by translation molecules (tRNA's and synthetases) which thereupon execute specific but arbitrary functions (protein synthesis). The semantic closure arises from the necessity that the translation molecules are themselves referents of gene strings. (Pattee 1982: 333)

The mutual complementarity or closure between symbols and the dynamical processes that interpret them accounts for the autonomy – in the sense of independence of external control – of the process. Pattee's central question was how a molecule becomes a message. In other words, how an entity subject to dynamic laws becomes information (Pattee 1969a). The answer is a closed dynamical organization in which that molecule or structure keeps a record for (or specifies) the construction of other molecules within the system, in virtue of which the relation can be established. Proteins are assembled from nucleic acids, but the assemblage is only possible with additional protein action. From this perspective, the information of a given structure depends on its causal consequences in a recursive and functional context.

The two relevant kinds of normativity – law and rule-based – are related with the different kinds of components DNAs and proteins are, and with their different causal roles (Pattee 1977: 263, 265). The different nature of the two molecules is important: events taking place at the nucleic acid level are sequential and rate-independent, whereas the causal action of proteins is continuous and rate-dependent. The first are inert, stable and reliable; they have no catalytic activity; they can store and replicate sequential variety. Their effects are indirect, discrete, and linked to their linear configuration. Unlike them, proteins decompose very fast outside the cell; they are catalytic components immersed in the metabolic web of components and actions. Because their amino acid sequence is formed following the nucleotide sequence, proteins are the functional expression of genetic information. But unlike passive information, they act as real controls, as internally produced boundary conditions in the cell (Polanyi 1968). They trigger and

select specific physical-chemical processes in a direct, rate-dependent action, made possible by their three-dimensional configuration. According to these differences, one (DNA) is a symbolic record and the other (proteins), a constraint: the first is an arbitrary form, interpreted via the construction of a control structure; its change produces no intrinsic change or action.

According to Pattee, the existence of rule-based functions in the cell stems from the rate-independence of nucleic acids, storing a code-mediated and context-independent pattern in their one-dimensional structure, which is transformed through discrete events, along a historical process that transcends the metabolic dynamics of a particular cell. In other words, their relevant action does not consist on direct effects, but on the (protein) *forms* they code for. Consequently, rate-independent processes in the cell have to do with the storage of constraints that may trigger alternative courses of metabolic action. He conceives them as genuinely linguistic phenomena as far as they constitute some form of system self-description.

III. ONTOLOGICAL COMMITMENTS AND COMPLEMENTARITY

This basic model of the closure between two kinds of components and processes in the cell suggests a more general view on the nature of life and knowledge. Discussions on the relationship between mind (or symbols) and matter permeate western philosophy, but Pattee's work analyzes this problem in the line of considerations explained in the previous section and reaches an original position, difficult to qualify either as dualist or as monist (Etxeberria 2000).

His conception is based on several elements. One of them is a reflection on the nature of mathematics and formal systems in general, characterized as operations of discrete symbols according to rules, that is to say, as rate-independent processes. In contrast, physical processes are continuous or dynamic, and occur within an intrinsic time-scale and energy expenditure: they are rate-dependent. Another one is the symbol-constraint association (or even confusion, we discuss this in the next section). Although symbols, because of their formal nature, can be produced in a random and arbitrary process and be manipulated according to rules, they are only meaningful if considered as the expressed constraints within an autonomous system. As a consequence, meaningful events involving symbols are neither completely formal nor uniquely dynamic, the whole process is a complementarity that connects both domains. Finally, complementary processes (such as measurements or controls) are natural processes, but they are not found in inanimate systems, as they are characteristic of the living state (as is the principle of semantic closure itself).

The principle of complementarity characterizes phenomena occurring at the interface between the two standard modes of description, dynamic and symbolic, through some material structure. We refer to such a structure as a *complementary device* (because of the extensive use of measuring and control devices as examples of this kind of relation in Pattee's work). A *complementary device* is a two-level relation, realized by a material entity, that has, at least, two possible descriptions,

- (a) As detailed, stepwise, law-like operations, and
- (b) As a constraint that performs some function (perhaps stored as a record, symbolic or not)

These two kinds of descriptions are complementary. On the one hand, it is not possible to emulate or realize (b) without a detailed material emulation (a). The action of constraints cannot be isolated from the complex material or interactional basis where it originates and is functional. On the other hand, it is not possible to consider (b) if many details of (a) are not “left aside”. The functional aspect is required to understand the system, because a completely detailed emulation of the dynamics would yield nothing but useless information regarding the characteristics of natural systems we find relevant, such as function, heredity, and so forth. This relation appears only in the frame of autonomous systems in which there is some form of closure.

In our opinion, this characterization of complementarity is at the basis of Pattee’s distinction between natural and formal languages and of his requirements for a research line in Artificial Life based on realizations (Pattee 1989, 1995). An accumulation of details at a basic level of nature (for example, at the atomic or molecular components in biological explanations) does not constitute a genuine advancement of knowledge if there is no parallel advancement of the understanding of the hierarchical organization. As a consequence, the basic requirement for research in living phenomena is the study of situations in which complementary devices or relations appear autonomously in a system with closure.

This means that complementarity can be understood in two ways. In a purely epistemological sense, it is the pragmatic loss of detail of a functional description that chooses to ignore dynamic details; but, in a more ontological sense, it is a real relation, produced by some material device. For Pattee these two possible interpretations are not contradictory.

In what respects the epistemological version, if it is accepted that an explanation in terms of microscopic laws and dynamics is always possible in principle for every level, then another explanation in terms of constraints is obviously no more than a possible alternative to the first completely detailed explanation. In this sense, the need for complementarity stems from pragmatic reasons. Yet, an important consequence of his work is that these pragmatic reasons cannot be completely imputed to preferences of the human observer, as they arise from the nature of the observed system itself, if it is a living or epistemic agent. If an operational or detailed account does not explain the system “as a” living being, but merely as a collection of particles, there is place for a relevance argument in favor of pragmatic constraints (in the sense of Putnam 1981).

A more challenging version is the ontological one: complementary devices are objective relations taking place physically in certain complexly organized systems, as a real classification or selection of equally possible alternative dynamics left open by the degrees of freedom of the system. Only in this sense, does this type of explanation go beyond pragmatic requirements

attached to human preferences, and becomes a more ontological way to conceive relations that constitute life.

IV. DISCUSSION

This framework or perspective poses some problems we would like to refer to here. In our opinion, they are relevant to consider the consequences of complementary relations in developing a theory of life. They may also clarify how the notion of symbol and other epistemic concepts are used in the context of living processes.

1. Types of constraints and autonomy

Pattee's emphasis on the need for symbolic records to account for living organization (as characterized by the semantic closure principle or the epistemic cut) may conceal the fundamental question of what it is to be a constraint or a control in the physical realm. In fact, some of his passages seem to blur all distinction between the causal role of nucleic acids and proteins, and to suggest that both are control constraints. However, following Pattee's own argument, only proteins (or active components) can be *sensu stricto* control constraints, because DNAs (or passive records or symbols) do not control other events by themselves, but only through the construction of proper control constraints (by the constraints (tRNA aminoacyl synthetases) themselves). As a result, it seems that nucleic acids only should be considered to be control constraints in an indirect way. Yet, the fact that sometimes both kinds of components are called control constraints, takes us to a related topic: different types of autonomous systems and the constraints required by each of them.

If the condition that autonomous constraints only occur in systems endowed with symbolic records specifying them were made too strict, the possibility of primitive metabolisms without genetic information had to be discarded. The organization of such systems would be based on functional dynamical constraints, even if they would not be able to evolve by natural selection. Although these hypothetical prebiotic systems were presumably eradicated by the first the appearance of the first cells with genomes, they are conceptually conceivable and physically likely in the frame of prebiotic evolution.

In other papers we have discussed the conceptual basis of these possible prebiotic systems without symbolic records (cellular systems based on a primitive metabolism) as the stages precedent to the first systems informed by a self-interpreted genome:

1. *Protometabolic cellular systems* are recursive networks of component production, self-enclosed by a selectively permeable membrane, and able to adaptively tune the matter and energy flows that maintain them. In these systems enzymes are not constructed following symbolic information, but the information specifying the network is

distributed in the whole organization³ (Moreno & Ruiz-Mirazo 1999, Ruiz-Mirazo & Moreno 1998, Ruiz-Mirazo et al 1999).

2. A second stage would be that of *systems based on non symbolic records*⁴, in which some RNA like molecules may act at two levels: as a memory to be expressed, and as a way to express this memory. Hence, some records (sequences) are transmitted in reproduction and, thus, they directly instruct the synthesis of functional components in the system (Orgel 1986, Benner et al 1989, Moreno & Fernandez 1990, 1992).

If we disregard the possibility of autonomous organizations not based on informational records, we implicitly assimilate the causal roles of nucleic acids and of proteins. In our opinion, minimal control constraints positively require an operationally closed organization, but internally interpretable records or symbols do not necessarily have to specify them.

2. Description and evolution

The frequent use of the term self-description to refer to the symbolic records of the cell generates some misunderstandings about their epistemic nature. This use is supported by von Neumann's model of self-reproduction and his requirements for reliable and open-ended evolution (that Pattee always admired). It is certainly the case that the living systems we know transmit information to the offspring coded in DNA sequences, but this is not their only inheritance, and, in our opinion, it may be equivocal to call those self-descriptive. When von Neumann stated that a self-reproducing system must be endowed with a description, he provided an interesting view of evolvability and of the role of records or symbols in evolution, but his model was not realistic about their function in maintaining and reproducing the system organization⁵. Cells do not construct a daughter cell following a description; there is a material continuity in the process of reproduction, with replication of genetic material. Therefore, the construction of the new system may be aided by records, but does not follow a description.

In the context of the cell it is obscure to use the term "description" in a referential or semantic sense (unless we strictly refer to the correspondence between the unidimensional sequence of DNA and that of a protein). When Pattee thinks about the problem of self-interpreted symbols in biological systems, he considers that their meanings are precisely their causal effects (Pattee 1982). However, there are problems with a perspective on meaning or semantics that dissolves into causality. The core of the problem is how to relate rate-independent symbols with the metabolism of the cell. All action stems from proteins, whereas the only role of nucleic acids

³L. Rocha (1998) has called them "distributed memory-selected self-organization".

⁴ The idea of non symbolic records is mentioned by Pattee himself for the case of a screw dislocation in the growth of a crystal (1969b, p.172).

⁵In another paper we have compared different models of self-reproduction in cellular automata and considered that the different strategies used have different interest whether they are discussed from the point of view of the system identity or from that of evolvability (Etxeberria & Ibañez 1999).

is to store codified one-dimensional sequences of them. Thus, nucleic acids are just records or annotations to construct molecules used by the cell, not descriptions of the system. Genetic information is not a description in the sense of a representation of a given reality, because it is only some sort of instruction for protein synthesis. On the other hand, the individual cell does not create its own information (symbols or records), but it is inherited.

As a consequence, there is some overstatement (or at least, some ambiguity) in the use of terms such as epistemic or semantic to refer to genetic information. Pattee might be right in thinking that the Semantic Closure Principle grounds any natural symbol system, but this principle is not sufficient to explain the full epistemic or descriptive dimension of symbols. For Pattee a natural explanation of the constraints of living organizations is the first step to understand the epistemic cut, i.e. the subject-object epistemic relation, as a natural relation. In spite of the aforementioned problems, we acknowledge that the Semantic Closure Principle is a necessary condition in this direction.

Acknowledgements

Our work has greatly benefited from the use of a private compilation of most of Pattee's printed papers, collected by our colleague and friend Jon Umerez. We look forward to the appearance of an edited publication of this material. We thank the editors and the referees of their detailed comments and corrections of previous manuscripts. Funding for this work was provided by the DGICYT (MEC, Madrid) Grant PB95-0502, Basque Government Grants HU-1998-142 and EX-1998-146, and University of the Basque Country (UPV/EHU) Grant 003.230-HA079/99.

References

- Benner, S., Ellington, A., and Tauer, A., 1989, "Modern metabolism as a Palimpsest of the RNA world". *Proceedings of the National Academy of Sciences* 86, 7054-58
- Ettxeberria, A., 2000, "Complementarity and closure", in: *Closure. Emergent Organizations and their Dynamics*, G. Van der Vijver and J. Chandler (eds.), (Annals of the New York Academy of Sciences, Volume 901) pp. 198-206.
- Ettxeberria, A. and Ibañez, J., 1999, "Semiotics of the Artificial: The self of self-reproducing systems in cellular automata". *Semiotica* 127 (1/4), 295-320.
- Moreno, A. and Fernandez, J., 1990, "Structural limits for evolutive capacities in molecular Complex Systems". *Biology Forum* 83 (2/3), 335-347.
- Moreno, A. & Fernandez, J., 1992, "From records to self-description: the role played by RNA in early evolutive systems". *Acta Biotheoretica* 40, 1-9.
- Moreno, A. & Ruiz-Mirazo, K., 1999, "Metabolism and the problem of its universalization". *BioSystems* 49 (1), 45-61.
- Orgel, L. E., 1986, "RNA catalysis and the origin of life". *Journal of Theoretical Biology* 123, 127.

- Pattee, H. H., 1966, "Physical Theories, Automata, and the Origin of Life", in: *Natural Automata and Useful Simulations*, H. Pattee, E. Edelsack, L. Fein, and A. Callahan (eds.) (Washington DC: Spartan Books) pp. 73-104.
- Pattee, H. H., 1969a, "How does a molecule become a message?". *Developmental Biology Supplement 3*, 1-16.
- Pattee, H. H., 1969b, "Physical conditions for Primitive Functional Hierarchies", in: *Hierarchical Structures*, L. L. Whyte, A. Wilson and D. Wilson (eds.) (NY: American Elsevier) pp. 161-177.
- Pattee, H. H., 1972, "Laws and Constraints, symbols and Languages", in: *Towards a Theoretical Biology 4, Essays*, C. H. Waddington (ed.) (Edinburgh University Press) pp. 248-258.
- Pattee, H. H., 1973, "The physical basis and origin of hierarchical control", in: *Hierarchy Theory. The challenge of complex systems*, H.H. Pattee (ed.) (New York: G. Braziller) pp. 73-108.
- Pattee, H. H., 1977, "Dynamic and Linguistic Modes of Complex Systems". *Int. J. General Systems 3*, 259-266.
- Pattee, H. H., 1979, "The Complementarity Principle and the Origin of macromolecular Information". *Biosystems 11*, 217-226.
- Pattee, H. H., 1982, "Cell Psychology: An Evolutionary Approach to the Symbol-Matter Problem". *Cognition and Brain Theory 5* (4), 325-341.
- Pattee, H. H., 1987, "Instabilities and Information in Biological Self-Organization", in: *Self-Organizing Systems. The emergence of Order*, F. E. Yates (ed.) (New York: Plenum Press) pp. 325-338.
- Pattee, H. H., 1989, "Simulations, Realizations and Theories of Life", in: *Artificial Life*, C. Langton (ed.) (Redwood City CA: Addison Wesley) pp. 63-77.
- Pattee, H. H., 1995, "Artificial life needs a real epistemology", in: *Advances in Artificial Life*, F. Moran, A. Moreno, J. J. Merelo, & P. Chacon (eds.) (Berlin: Springer-Verlag) pp. 23-38.
- Polanyi, M., 1968, "Life's Irreducible Structure". *Science 160*, 1308-1312.
- Putnam, H., 1981, "Reductionism and the Nature of Psychology", in: *Mind Design*, J. Haugeland (ed.) (Montgomery VT: Bradford Books), pp. 205-219.
- Rocha, L., 1998, "Selected Self-Organization and the Semiotics of evolutionary Systems", in: *Evolutionary Systems*, G. Van der Vijver, S. Salthe & M. Delpos (eds.) (Dordrecht: Kluwer) pp. 341-358.
- Ruiz-Mirazo, K. and Moreno, A., 1998, "Autonomy and emergence: how systems become agents through the generation of functional constraints", in: *Emergence, Complexity, Hierarchy, Organization Acta Polytechnica Scandinavica Ma91*, G. L. Farre, & T. Oksala, (eds.) (The Finnish Academy of Technology) pp.273-282.
- Ruiz-Mirazo, K., Moreno, A., Moran, F., Pereto, J and Merelo, J., 1999, "Designing a Simulation Model of a Self-Maintaining Cellular System", in: *Advances in Artificial Life*, D. Floreano, J. Nicoud and F. Mondada (eds.) (Berlin: Spriger Verlag) pp 379-388.
- Simon, H., 1969, *The sciences of the artificial* (Cambridge MA: MIT Press)
- von Neumann, J., 1966, *Theory of Self-Reproducing Automata*. Edited and completed by A.W. Burks (University of Illinois Press).