Computing with Autopoietic Systems

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Introduction.

In 1973, in the middle of rather unfortunate political events, two Chilean biologists, Humberto Maturana and Francisco Varela, introduced the concept of Autopoietic systems ("auto"= self and "poiesis" = generating or producing) as a theoretical construct on the nature of living systems centering on two main notions: the circular organization of metabolism and a redefinition of the systemic concepts of *structure* and *organization*. This theoretical contruct has found an important place in theoretical biology, but it can also be used as a foundation for a new type of authentically "soft" computing. To understand the main point of our exposition, how Autopoietic systems can be used to compute, it is first necessary to give a brief summary of Autopoietic theory along with the notion of structural coupling.

Autopoiesis: a brief primer.

The notion of *circular organization*, the central aspect of living systems according to Maturana and Varela, is a given, or an axiom in Autopoiesis, and it is immediately clarified in the theory by the very definition of an *Autopoietic system*:

> "an Autopoietic system is organized as a bounded network of processes of production, transformation and destruction of components that produces the components which:
>
> (i) through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produced them; and
>
> (ii) constitute it (the machine) as a concrete entity in the space in which they (the components) exist by specifying the topological domain of its realization as such a network" (Varela, Maturana et al. 1974; Maturana and Varela 1975; Maturana and Varela 1980; Mingers 1995; Whitaker 2001).

In an Autopoietic system the result of any given process is the production of components that eventually would be transformed by other processes in the network into the components of the first process. This property, termed operational closure, is an organizational property that perfectly coexists with the fact that living systems are, from a physical point of view, energetically and materially open systems. The molecules that enter the system determine the system's organization, which generates pathways whose operation produces molecular structures that determine the physical system and the system's organization (Fleischaker 1990). Thus an Autopoietic system does not have *inputs* or *outputs*, instead it constitutes a web of molecular processes that maintain Autopoietic organization. Because an Autopoietic system's internal dynamics are self-determined, there is no need to refer any operational (or organizational) aspect to the outside. Thus the environment does not *inform*, *instruct* or otherwise *define* the internal dynamics, it only *perturbs* the system's dynamics.

The second clause (ii) demands that an Autopoietic system has sufficiently complex dynamics to self-produce the boundaries that separate the system from the "non-system". This apparently trivial clause has profound implications as it touches upon the problem of autonomy and also serves to weed out some pure formal systems. Thus Autopoietic systems are not simple relational devices; they must conform to an important topological property: their boundary (in the space where their components exist) is actively produced by the network of processes. This property of Autopoietic systems couples a purely relational property (operational closure) with a topological property, and it demands that an Autopoietic system be an autonomous unity, topographically and functionally segregated from its background. In the realm of molecules, the coupling of these two conditions necessarily implies that the minimal metabolism compatible with Autopoietic organization must be rather more complex than the spatial coupling of a direct chemical reaction with its reverse reaction.

In understanding Autopoietic systems, it is important to distinguish between *processes* and *components*. Components interact through processes to generate other components. With this distinction, it is possible to define the *organization* of a system as the pattern or configuration of processes between components that define the *type* of system. The *structure* is the specific embodiment (implementation) of these processes into specific material (physical) entities. According to this definition, organization is a subset of structure. To summarize, an Autopoietic system is an entity that, with a variable and dynamic structure, maintains its circular organization invariant. In this respect, Autopoietic systems are rather different from man-made machines where only *variables* are maintained unchanged.

The Impact of Autopoiesis a) The Formalizations. Autopoiesis, as originally described by Maturana and Varela (Maturana and Varela 1972; Maturana and Varela 1980), is an extremely coherent and formal theory formulated outside any mathematical framework. Many attempts have been made to mathematize and simulate Autopoiesis. The first tessellation computer models, initially done in an IBM 360 (Varela, Maturana et al. 1974; Zeleny 1981)] and recently re-done in Swarm (McMullin and Varela 1997) were a direct translation of a minimal Autopoietic system into a small bi-dimensional lattice. Varela used Indicational Calculus (Varela 1979) to model autonomous systems. But Indicational Calculus, developed by Spencer-Brown (Spencer-Brown 1969), is a difficult tool to master. Progress along this line, aside from Varela´s efforts, has been limited. Other mathematical formulations have included the use of differential equations to model feedback (Limone 1977). None of these quantitative, or semi-quantitative models has generated clear-cut, satisfactory results. Recently a new attempt has been made using a pure algebraic approach, the theory of categories, championed by Robert Rosen since 1958, to understand systems operating with operational closure (Letelier, Marin & Mpodozis, submitted).

<u>The Impact of Autopoiesis b) The Applications.</u> The uses of Autopoiesis have been rather surprising. First, Autopoiesis has been an extremely successful idea in various arenas outside of Biology ranging from law (Luhmann 1982) to business administration (Mingers 1995) and even psychotherapy (Snyder 1999). Second, because of Autopoiesis' epistemological foundations concerning the process of cognition, it has become a central paradigm of "second order cybernetics" (i.e. the observer is considered at least as part of the feedback loop defining the system) (Zeleny and Hufford 1992). Autopoiesis has also found some applications in computer sciences, specifically in image processing (Köppen and Ruiz-del-Solar 2001). In biology, apart from new versions of the original computer simulations (McMullin and Varela 1997), some applications to the problem of the origin of life (Fleischaker 1990; Mavelli and Luisi 1996), approximations to the origin of higher brain functions (Mpodozis, Letelier et al. 1995), and a new formalization of Evolution based on natural drift rather that natural selection (Maturana and Mpodozis 1992; Maturana and Mpodozis 1999; Maturana and Mpodozis 2000), the notion of Autopoiesis has had limited advance. Autopoiesis, acclaimed by theorists in many disciplines, has not penetrated the daily life of biologists .... yet.

<u>The Impact of Autopoiesis c) The opposition.</u> The notion of Autopoiesis in biology has certainly encountered an expected opposition as a result of the constructivist view of cognition described by Maturana (Maturana 1970). The literature commonly refers to "Autopoietic theory" as a conceptual body that covers areas as diverse as metabolism and epistemology. It is more precise, however, to distinguish two separate scientific ideas. One idea is the notion of Autopoietic systems and the other, known as *Biology of Cognition*, is the idea that the process of cognition is embodied, not only in logical and inferential rules, but in a specific neurophysiological substrate with specific cognitive consequences, where the nervous system cannot distinguish illusion from perception (Maturana 1970; Fleischaker 1988).

Autopoiesis and Computing: the basic idea.

<u>Structural coupling: a crucial and sometimes neglected concept</u>. Autopoietic systems do not simply behave or react passively in an environment that is *given* to them. A central aspect of Autopoieis is the mechanism of *structural coupling* by which the living system and its medium determine, in a mutual way and as a result of a historic process, some of their properties. In effect as the system's organization is maintained invariant, its structure can change in many dimensions that do not affect the organization (Figure 1). This change is not random; it is neither an accommodation or adaptation to outside features (*classical adaptationism*), nor the result of the deployment of internal plans embodied in structure of the Autopoietic system (*vitalism*).

The changes produced by structural coupling require the existence of recurrent interactions as well as a necessary level of plasticity (i.e the ability to change the structure) in the Autopoietic system and its medium. During the system's ontogeny, (or the phylogeny of the lineage) a congruence between the system and its medium is *selected* or *stabilized*, thus the *medium* gradually becomes the *environment* and, for external observers unaware of the buildup of the relationship, the organism appears to become *adapted* to some characteristics of the medium. Thus, and this is a crucial difference between Autopoiesis and the standard notion of evolution by adaptation, Autopoietic systems do not adapt to a previously defined ecological niche — they create their environment by the systematic production of congruencies.

These congruencies produced by the structural coupling of the Autopoietic system and its medium have meaning, in the sense of the *Umwelt* (see the special issue of *Semiotica* devoted to Jacob Von-Uexkull, vol134(1-4), 2001), for the Autopoietic system involved in the structural coupling but not for external observers whom, despite common conceptions, do not live in the same environment as the system. The structural change inside the Autopoietic system is due to the recurrent external trigger (perturbation) as well as its own internal, circular dynamics. Thus, a given external perturbation will not induce an internal structural change that can be viewed as its representation or internal model. The relation between the internal structural change and the external trigger is one of correlation or congruence rather than of identity or isomorphism. The external perturbation does not induce a one-to-one model in the Autopoietic entity, instead a congruence is constructed.

Finally, it is important to note that Autopoietic systems are intrinsically different from Turing machines. In effect they cannot be simulated by Turing Machines. In essence, the Turing-Church hypothesis fails when applied to them because the self-referential nature of circularity demands an infinite number of states (Rosen 1966). A demonstration of this can be arrived at by applying a result concerning the non-Turing computability of *(M,R) systems* (a theory concerning living systems developed by Robert Rosen, see his excellent book *Life Itself*, ((Rosen 1991)) to Autopoiesis (Letelier, Marin & Mpodozis, submitted). The non-computability of Autopoietic systems, a result that has been suggested at least twice during the last decade, (Kampis 1991; Boden 1999) shows that some intrinsic and fundamental part of their behavior escapes our standard analysis based on phase states and/or evolution equations. What escapes from the standard analysis can be interpreted as the *anticipatory behavior of Autopoietic systems*.

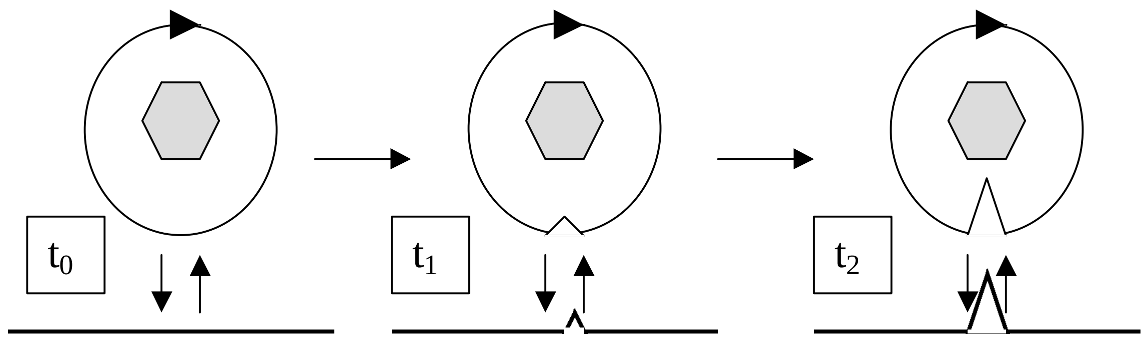

Figure 1. Structural coupling. The diagram depicts the basis of the mechanism of Strcutural Coupling. The Autopoietic system, represented by a circle and defined by its structure and its organization (hatched area), initially confronts a medium without organized "objects" (at t_0). As recurrent interactions (represented by the arrows) between the medium and the system are stabilized, at t_1, an "object" (represented by the triangle) begins to be configured. The "objects" is made of two complementary parts. One part exists in the medium and the other exists as a change in the Autopoietic system structure. Finally, at t_2, the "object" is totally configured. At this point the change in structure, but not in organization as the hatched area remains unchanged, could be very important. From the point of view of computing the important aspect is the existence of "objects" defined by spatio-temporal correlations, thus the change in the Autopoietic system structure also contains spatio-temporal corrrelations. Thus the study of the temporal changes in the systems's structure can predict the changes in the environment. This scheme of prediction works because the (spatio-temporal) objects in the environment are congruent with the structure of the Autopoietic system. The congruence is a consequence of structural coupling.

Anticipation. An anticipatory system is a system that computes its future state, $X(t+1)$, not only by taking into account its present state $X(t)$ and the perturbation just received $P(t)$, but by taking into account a prediction (or model) of its future state, $\hat{X}(t+1)$. Thus, according to the notion of anticipation, the future of any system can be computed according to one of the following three models:

(1) $X(t+1) = F(X(t), P(t))$ Standard non-anticipatory system

(2) $X(t+1) = F(X(t), \hat{X}(t+1), P(t))$ Weak anticipatory system

(3) $X(t+1) = F(X(t), X(t+1), P(t))$ Strong anticipatory system

The first equation is the model around which most of current science is built. Equation (1) denies the possibility of anticipation, as it supposes that the future is always a strict function of past states. Equations (2) & (3) model *weak* and *strong* anticipation. In weak anticipation the future state is computed using a model of the future, while in a strong anticipatory system, the system state, not a model, is used. Anticipatory systems, weak or strong, have slowly been introduced in the study of complexity over the last twenty years. Here we make a special mention of the notion of Anticipatory Systems introduced by Rosen (Rosen 1985) and of the new mathematical approach termed Hyperincursion (Dubois 2000). Also anticipation is growing in acceptance in the area of robotics with the notion of situated intelligence (Ziemke 2001). A challenge in the next few years would be to explore and clarify this puzzling concept that sometimes (like in equation 3) seems logically impossible but, without a doubt, represents a fundamental advance to understand complex systems in physics and biology (Dubois 2000).

Structural Coupling + Temporal Correlation => Anticipation. Structural coupling to any temporal correlation is the basis of anticipatory behavior for Autopoietic systems. Because structural coupling is the end result of a historical process, a given recurrent perturbation, with a clear temporal correlation, would trigger a *sequence of changes* inside the Autopoietic system with a temporal correlation that would map the temporal correlation found in the external trigger. In this context the external observer can interpret the initial changes suffered by the Autopoietic system as the beginning of an anticipatory response that is "computed" by the organism using an internal model of the organism and its environment. In other words, in a plastic system capable of structural coupling with its medium, the system responses to (complex) triggers having a non-trivial amount of temporal correlation would appear as anticipatory. The system responses would also have temporal correlations that could be mapped onto the temporal correlations originally found in the environment. In other words, anticipation is a characteristic that an external observer attaches to a given behavior, but from the point of view of the living system, it is only changing its internal states according to structurally coupled perturbations that are recurrent and have a certain amount of temporal correlations. The resulting internal changes, because of structural coupling, do possess temporal correlations that can be mapped onto the temporal correlation of the external perturbation. An Autopoietic system can be interpreted as a self-modifying theorem about its environment. The predictive capacities of an Autopoietic system are intrinsic to its structure: temporal correlations map onto molecules and the circular metabolic network they implement. In summary, Autopoietic systems, from bacteria to *Homo sapiens*, anticipate or at least an external observer will observe as much.

Computing = Cognitive Prediction

To "compute": a different idea. To use Autopoietic systems as computational tools, it is necessary to redefine the process of computation that we usually identify with the operation of Turing Machines. Turing machines compute by performing symbol manipulation. The symbol processing algorithm embodied in a Turing machine does not concern itself with the semantic content of those symbols; it only deals with the syntactical rules of symbol transformation. The semantics are left to the user who must map the string symbols with content. Autopoietic systems are rather different from Turing devices. First their structure is variable and hence they lack a true phase-space. More relevant Autopoietic systems do not have inputs or outputs, only a circular dynamic that is perturbed but not defined by external agents. The autonomy of Autopoietic systems implies that it is not possible to encode outside concepts, concepts pertaining to the *Umwelt* of the observer, into Autopoietic states, nor to control a trajectory of states. Thus external observers can only define a computation for an

Autopoietic system as the particular ontogeny for that system.

"Computing" = Prediction via temporal correlations. Thus, in the case of Autopoietic systems, we require a new definition of "computing" different from symbol processing. A useful definition is to identify "to compute" with "to predict". In effect the notion of prediction captures many, but not all, properties of computation. In fact usually we solve the problem of prediction by a complex process of translation, where we map the system states to numbers, and we associate the rule of system evolution with differential equations. Thus, in practice, we use computations to predict, and this is where we adopt the notion that computing equals predicting. Our problem now is how to use the internal and autonomous dynamics of an Autopoietic system to predict the future. The anticipatory behavior of Autopoietic systems, produced by structural coupling, allows us to do so.

Autopoietic Computing: The Praxis

The basic mechanism by which Autopoietic systems can compute, in the sense explained above, is the historic change in its structure triggered by recurrent temporal correlations. This change is the consequence of the recurrent interactions between the Autopoietic system and its medium. As a result of this relationship, every Autopoietic system transforms the original medium in its "environment". During this continuous process of transformation *truth does not matter, existence is everything*.

The "simple" case: Computing without language and without a nervous system: the case for bacterias. To compute with an Autopoietic system, the system structure is used as an indicator of the *future* states of its environment. First, and this is an essential requirement, a historical link must be established between the Autopoietic system and the medium (or space) that we want to obtain predictions of. Thus an Autopoietic system must be introduced in such a medium and a congruent lineage must be established via structural coupling. This first step would change the medium into an environment for this specific Autopoietic system. As time passes the structural changes induced by structural coupling would become more and more engrained in the Autopoietic system´s structure which would capture more and more temporal (and also spatial) correlations from its environment. This phase would be equivalent to the programming of a Turing machine, and once the Autopoietic system is full of induced correlations it could be used for prediction. Certainly this procedure has the important advantage that programming is endogenously produced, by the very fact of living inside the medium and forming a stable lineage. On the other hand, it is not possible to specify exactly the type of predictions we want. The intrinsic autonomy of Autopoietic systems makes it impossible to force the system (that has created its own *Umwelt*) to capture the temporal correlations that are important for us (our *Umwelt* is not the same as the system's). A solution to this conundrum can be achieved by the simple expedient of brute force. Instead of establishing a single lineage, we could use many different initial Autopoietic systems, ideally with rather different structures. Each lineage would transform the single medium (i.e. the space recognized by the observer/Autopoietic-programmer) into its environment. Thus a wider range of temporal correlations would be established and some of them would be useful.

The "reading part" of Autopoietic computing, when bacterias are used, is rather more involved that reading a binary (or unary) number from a uni-dimensional Turing tape. In practice a "mature" Autopoietic system, a system where the necessary temporal correlations have already been built, must be introduced into its environment and some measurement of its structure must be made. The changes of the system's structure would manifest the correlations and the direction of the environment's change. Thus to "read" the final state of a "prediction" we must necessarily know an interesting amount of the biology of the Autopoietic system.

Another "simple" case: Computing without language and with a nervous system: the case of the tennis player.. A world class tennis player provides a perfect example of computing through anticipation based on structural coupling. Tennis players perform amazing feats of sensori-motor coordination. They must run across the field and hit a fast moving ball whose trajectory is specially manipulated by the opposing player in order to make the hitting difficult or impossible. It is important to note that the reaction time of any visual task is about 0.1 s, too slow to account for the speed and frequency response of the overall action, thus each player anticipates elements of the ball trajectory and the position of the other player. Thus, if, by using telemetry, a neurophysiologically-wise external observer can collect enough neural and muscular signals of the visual and motor centers of a player, he can use this deluge of data to predict the future position of the ball many seconds, and some moves, in advance. In this case we can interpret the tennis player as a computing device that has a non trivial predictive power for the future position of the ball and of the opposing player. The programming of the device is rather long, many years of hard training, but it achieves millisecond temporal precision coupled with spatial precision of 1 cm, in the presence of enormous amounts of overloading information — a technological prowess that current robotics can only imagine.

The "complex" case: Computing with language. Language can be a wonderful tool to speed up the "reading" part of the computation/prediction. But before explaining its use we need to present a new view on the nature of language.

A theory of language in one paragraph. The "function" of language is not to convey meaning via the transmission of symbols, but it is the coordination of behaviors in order to achieve very complex goals among a group of organisms that belong to a given lineage. Thus the kernel of the "problem" of language is the problem of how we achieve, *transindividually* and *collectively*, coherent actions of increasing complexity. In this perspective every linguistic utterance, or sign, always refers directly, or indirectly, to actions in the environment or to "objects", that are also defined by actions. But, because of structural coupling and the fact that Autopoietic systems are anticipatory, "actions" and "the future effect of an action in the environment" are not disjoint entities. The action and its multiple effects conform a unitary entity that is accessible through language.

Thus every linguistic act always refers to the expected change and future states that the environment would adopt if a given action is performed. Then language serves to plan or predict complex sequences of actions, where each "action", as it has been shaped by structural coupling, contains also the expected changes that the environment would take in response to this action. In this light, language is a complex computational tool that predicts future states of the environment using a stream of actions generated by a nervous system as intermediate steps in the final calculation. This is only possible because, as these actions are not arbitrary, they are the result of structural coupling, ingrained in them they contain the congruent dynamic of the environment.

Is Autopoietic computing another name for Evolvable Hardware? During the last decade the concept of Evolvable Hardware (EH) has gained an ever increasing popularity, exemplified by the most intriguing eagerness of NASA and DOD (US Dept. of Defense) to organize a string of symposia (http://cism.jpl.nasa.gov/ehw). In essence, Evolvable Hardware has a vague resemblance to some of the ideas expressed here, as it uses the techniques of evolution (mutations and recombination) within the framework of Genetic Algorithms to design electronic hardware. But the basic idea of EH lacks the essential component of structural coupling. In effect, in each "generation" all the versions of a given hardware "lineage" are screened according to the criterion of an outside observer, who selects the best versions and uses them as "seeds" to the next generation. Thus EH devices are unable to construct a congruent relationship with their environment, as they are continuously tested by an agent (the experimenter who performs the selection) that is outside the circuit or outside the medium. Autopoietic computing has a crucial difference with respect to EH: no outside observer is needed, but the hardware must be really plastic, and not only simulate plasticity, as EH does (to see a detailed analysis of this question we refer to the web site of Dr. TomZiemke http://www.ida.his.se/ida/~tom/).

Concluding remarks.

The ideas expressed in this plenary lecture are not really new, the schools of *Situated Robotics*, *Genetics Algorithms* or *Evolvable Hardware* suggest similar ideas. We currently live in a transitional period where the shortcomings of traditional, *a la Turing*, computing procedures are becoming evident and new viewpoints are being investigated. A consequence of this search is the academic war between the camps of "traditional Artificial Intelligence" and the many flavors of constructivist theories of cognition (Riegler 2001). These constructivist theories, and Biology of Cognition is one of those, are gaining acceptance especially in robotics with the dream of building autonomous devices. Unfortunately the dense theoretical *salvos* of constructivist robotics (or constructivist theories of cognition) have not been followed by an embodiment in drawings, diagrams, empirical tricks or decently performing hardware. This imbalance between theory and practice indicates that a great deal of theoretical analysis is still needed. We believe that the main contribution of the notion of Autopoietic systems, for the endeavor of soft computing and constructing real autonomous devices, lies in the notion of temporally correlated structural coupling. Structural coupling, when all is said and (perhaps) done, is a mechanism by which a lineage of Autopoietic systems can change its structure (i.e. components and processes) in a manner that is congruent with the recurrent perturbations that arise in the medium. Although Autopoietic computing requires hardware that we cannot currently produce *de novo* (i.e. Artificial life hardware so to speak), we think we can implement these ideas even today though we are still far from the process of fabrication of living systems (Rosen 1991). The central idea would be to couple specially designed biochemical *netlets* (i.e. small metabolic networks) to the large metabolic network that constitutes the Autopoietic organization of a bacteria. These netlets would act as sensors for the bacterial metabolism, and through its metabolism we would predict future events in the medium.

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