The POE Model of Bio-Inspired Hardware Systems: A Short Introduction

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Living organisms are complex systems exhibiting a range of desirable characteristics, such as evolution, adaptation, and fault tolerance, that have proved difficult to realize using traditional engineering methodologies. Recently, engineers have been allured by certain natural processes, giving birth to such domains as artificial neural networks and evolutionary computation. If one considers life on Earth since its very beginning, then the following three levels of organization can be distinguished:

Phylogeny: The first level concerns the temporal evolution of the genetic program, the hallmark of which is the evolution of species, or *phylogeny*. The multiplication of living organisms is based upon the reproduction of the program, subject to an extremely low error rate at the individual level, so as to ensure that the identity of the offspring remains practically unchanged. Mutation (asexual reproduction) or mutation along with recombination (sexual reproduction) give rise to the emergence of new organisms. The phylogenetic mechanisms are fundamentally non-deterministic, with the mutation and recombination rate providing a major source of diversity. This diversity is indispensable for the survival of living species, for their continuous adaptation to a changing environment, and for the appearance of new species.

Ontogeny: Upon the appearance of multicellular organisms, a second level of biological organization manifests itself. The successive divisions of the mother cell, the zygote, with each newly formed cell possessing a copy of the original genome, is followed by a specialization of the daughter cells in accordance with their surroundings, i.e., their position within the ensemble. This latter phase is known as cellular differentiation. *Ontogeny* is thus the developmental process of a multicellular organism. This process is essentially deterministic: an error in a single base within the genome can provoke an ontogenetic sequence which results in notable, possibly lethal, malformations.

Epigenesis: The ontogenetic program is limited in the amount of information that can be stored, thereby rendering the complete specification of the organism impossible. A well-known example is that of the human brain with some 10^{10} neurons and 10^{14} connections, far too large a number to be completely specified in the four-character genome of length approximately 3×10^9. Therefore, upon reaching a certain level of complexity, there must emerge a different process that permits the individual to integrate the vast quantity of interactions with the outside world. This process is known as *epigenesis*, and primarily includes the nervous system, the immune system, and the endocrine system. These systems are characterized by the possession of a basic structure that is entirely defined by the genome (the *innate* part), which is then subjected to modification through lifetime interactions of the individual with the environment (the *acquired* part). The epigenetic processes can be loosely grouped under the heading of *learning* systems.

In analogy to nature, the space of *bio-inspired* hardware systems can be partitioned along these three axes: phylogeny, ontogeny, and epigenesis, giving rise to the *POE* model, recently introduced by Sipper et al. (1997) (Figure 1). The distinction between the axes cannot be easily drawn where nature is concerned, indeed the definitions themselves may be subject to discussion. Sipper et al. (1997) therefore *defined* each of the above axes *within the framework* of the POE model as follows: the phylogenetic axis involves *evolution*, the ontogenetic axis involves the *development* of a single individual from its own genetic material, essentially without environmental interactions, and the epigenetic axis involves *learning* through environmental interactions that take place after formation of the individual. As an example, con-

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sider the following three paradigms, whose hardware implementations can be positioned along the POE axes: (P) evolutionary algorithms are the (simplified) artificial counterpart of phylogeny in nature, (O) multicellular automata are based on the concept of ontogeny, where a single mother cell gives rise, through multiple divisions, to a multicellular organism, and (E) artificial neural networks embody the epigenetic process, where the system's synaptic weights and perhaps topological structure change through interactions with the environment. Within the domains collectively referred to as *soft computing*, often involving the solution of ill-defined problems coupled with the need for continual adaptation or evolution, the above paradigms yield impressive results, frequently rivaling those of traditional methods.

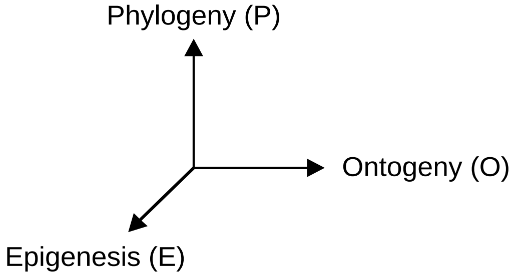

Figure 1: **The POE model. Partitioning the space of bio-inspired hardware systems along three axes: phylogeny, ontogeny, and epigenesis. See text for definition of these terms.**

Sipper et al. (1997) examined bio-inspired hardware systems within the POE framework, their goals being: (1) to present an overview of current-day research, (2) to demonstrate that the POE model can be used to classify bio-inspired systems, and (3) to identify possible directions for future research, derived from a POE outlook. Sipper et al. (1997) described each axis and provided examples of systems situated along them. A natural extension which suggests itself is the combination of two, and ultimately all three axes, in order to attain novel bio-inspired hardware, as discussed by Sipper et al. (1997) (Figure 2).

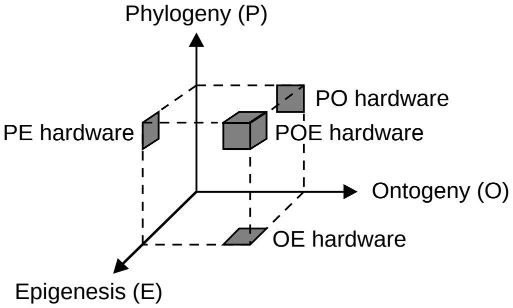

Figure 2: **Combining POE axes in order to create novel bio-inspired systems: The PO plane involves evolving hardware that exhibits ontogenetic characteristics, such as growth, replication, and regeneration, the PE plane includes, e.g., evolutionary artificial neural networks, the OE plane combines ontogenetic mechanisms (self-replication, self-repair) with epigenetic (e.g., neural network) learning, and finally, the POE space comprises systems that exhibit characteristics pertaining to all three axes. An example of the latter would be an artificial neural network (epigenetic axis), implemented on a self-replicating multicellular automaton (ontogenetic axis), whose genome is subject to evolution (phylogenetic axis).**

From a technological point of view we note that many current-day works in the domain of bio-inspired systems are based on so-called programmable circuits. An integrated circuit is called programmable when the user can configure its function by programming. The circuit is delivered after manufacturing in a generic state and the user can adapt it by programming a particular function. The programmed function is coded as a string of bits representing the *configuration* of the circuit. Note that there is a difference between programming a standard microprocessor chip and programming a programmable circuit – the former involves the specification of a sequence of actions, or instructions, while the latter involves a configuration of the machine itself, often at the gate level. The first programmable circuits allowed the implementation of logic circuits that were expressed as a logic sum of products. These are the PLDs (Programmable Logic Devices), whose most popular version is the PAL (Programmable Array Logic). More recently a novel technology has emerged, affording higher flexibility and more complex functionality: the Field-Programmable Gate Array (FPGA).

Looking (and dreaming) toward the future, one can imagine nano-scale (bioware) systems becoming a reality, which will be endowed with evolutionary, reproductive, regenerative, and learning capabilities.

References

Sipper, M., Sanchez, E., Mange, D., Tomassini, M., Pérez-Uribe, A., and Stauffer, A. 1997. A phylogenetic, ontogenetic, and epigenetic view of bio-inspired hardware systems. *IEEE Transactions on Evolutionary Computation*, vol. 1, no. 1.