

Info-computationalism and Morphological Computing of Informational Structure

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Abstract. Within the framework of info-computationalism, morphological computation is described as fundamental principle for all natural computation (information processing).

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1 Foundations of a New Science of Computation

Present computational machinery evolved from mechanical calculators to electronic machines with vacuum tubes and then transistors, and to integrated circuits and eventually microprocessors. During this remarkable development of hardware towards ever smaller, faster and cheaper devices, the computational principles remained unchanged: an isolated machine calculating a function, executing an algorithm. Such machines were adequately represented by the Turing Machine model. However, computational machinery gradually started to change its character from isolated calculators to networked communicating devices. In the 1970s first networks were created with computers linked together via telecommunications. The emergence of networking involved a changed nature of computers and computing as operating systems and applications started to access and use the resources of each other, exchanging information.

Turing Machine model is sequential. As long as parallel processing, such as occurring in networks, is synchronous, it can be sequentialized, and thus Turing Machine model can be applied. However for networks with asynchronous processes Turing Machine is not appropriate. As (Sloman 1996) points out, concurrent and synchronized machines are equivalent to sequential machines, but some concurrent machines are asynchronous. (Dodig Crnkovic 2011)

One of the main arguments in favor of universal computing is the often repeated claim in Computer Science (based on Turing machine model of computation) that it is invariant on the details of implementation (hardware). Computational complexity classes, themselves based on Turing model of computation, are supposed to be substrate-independent general abstractions. However, it turned out that Turing Machine model depends essentially on the underlying assumption of classical physics:

The Turing machine is entirely classical, and does not allow for the possibility that paper might have different symbols written on it in different universes, and that those might interfere with one another. (Deutsch 1997)

This fascinating insight in the fundamentals of computing leads us directly to the nascent field of Natural Computing, which sometimes is called Unconventional Computing or Physical Computing.

2 Natural Computation

According to the *Handbook of Natural Computing* (Rozenberg et al. 2011) Natural Computing is “the field of research that investigates both human-designed computing inspired by nature and computing taking place in nature.” In particular, the book addresses:

Computational models inspired by the natural systems such as neural computation, evolutionary computation, cellular automata, swarm intelligence, artificial immune systems, artificial life systems, membrane computing and amorphous computing.

Computation performed by natural materials such as bioware in molecular computing or quantum-mechanical systems in case of quantum computing.

Study of computational nature of processes taking place in (living) nature, such as: self-assembly, developmental processes, biochemical reactions, brain processes, bio-networks and cellular processes.

Especially important in the context of Natural Computing is that knowledge is generated bi-directionally, through the interaction between computer science and the natural sciences. While the natural sciences are rapidly absorbing ideas, tools and methodologies of information processing, computer science is broadening the notion of computation, recognizing information processing found in nature as (natural) computation. (Rozenberg and Kari 2008) (Stepney et al. 2005) (Stepney et al. 2006)

This new concept of computation allows for nondeterministic complex computational systems with self-* properties. Here self-* stands for self-organization, self-configuration, self-optimization, self-healing, self-protection, self-explanation, and self(context)-awareness. Dodig Crnkovic in (Dodig Crnkovic and Müller 2009) argues that natural computation (understood as processes acting on informational structures) provides a basis within info-computational framework for a unified understanding of phenomena of embodied cognition, intelligence and knowledge generation.

While computing nature is an old idea, dating back to Zuse, and developed by number of other researchers (Fredkin, Wolfram, Chaitin, Lloyd) who argue that all of the physical world computes, the question may be asked: on what substrate does this computation goes on? Within the info-computational framework, the answer is: information. All computational processes in the Nature take place on informational structures (protoinformation).

3 Universe as Informational Structure

Von Baeyer (2003) suggests that information is to replace matter/energy as the primary constitutive principle of the universe. Wolfram supports the equivalence between the two descriptions:

Matter is merely our way of representing to ourselves things that are in fact some pattern of information, but we can also say that matter is the primary thing and that information is our representation of that. (Wolfram in Zenil 2011, p. 389).

The universe is "*nothing but processes in structural patterns all the way down*" (Ladyman, et al. 2007) p. 228. Understanding patterns as information, one may infer that information is a fundamental ontological category. What we know about the universe is what we get from sciences, as "special sciences track real patterns" (p. 242). Thus the realism of this approach is based on the claim that "successful scientific practice warrants networks of mappings as identified above between the formal and the material" (p. 121). The ontology is scale-relative, as we generate knowledge through interactions with the world (Dodig Crnkovic 2008) on different levels of abstraction (organization).

Information may be considered the most fundamental physical structure, as in Floridi's Informational Structural Realism (Floridi 2008). It is in permanent flow, in a process of transformation, as observed in physics. We know the world as a result of interaction and exploration:

Structural objects (clusters of data as relational entities) work epistemologically like constraining affordances: they allow or invite certain constructs (they are affordances for the information system that elaborates them) and resist or impede some others (they are constraints for the same system), depending on the interaction with, and the nature of, the information system that processes them. (Floridi 2008).

4 Info-computational Universe

Info-computationalism (Dodig Crnkovic 2006, 2009) is a unifying approach that brings together Informationalism (Informational Structural Realism) of Floridi (2008); Informational Realism of Sayre (1976) and (Ladyman, et al. 2007) – the informational universe - with the Naturalist Computationalism/ Pancomputationalism (Zuse, Fredkin, Wolfram, Chaitin, Lloyd) – the computing universe. Info-computationalist naturalism understands the dynamical interaction of informational structures as computational processes. (Dodig Crnkovic 2011) It includes digital and analogue, continuous and discrete as phenomena existing in the physical world on different levels of organization (Dodig Crnkovic and Müller 2009). Digital computing is a subset of a more general natural computing.

In what follows I will present the idea of *morphological computation* which is, as much of natural computation, different from the execution of an in advance given procedure in a deterministic mechanical way. The difference is in the computational mechanism based on *natural physical objects as hardware* which at the same time *acts as software or a program governing the behavior of a computational system*.

Physical laws govern processes which cause dynamical development of a physical system. Or in other words, computational processes are manifestation of physical laws. The new structure (data structure, informational structure) produced by computational processes is a new program in the next step of time development. Interestingly, morphological computation is not one of the topics of the Handbook of Natural Computing, even though the fundamental principles of morphological computing are underlying all of natural computing.

5 Morphological Computation

Recently, morphological computing emerged as a new idea in robotics, (Pfeifer 2011), (Pfeifer and Iida 2005), (Pfeifer and Gomez 2009) (Paul 2004). It has conceptually very important generalizable consequences with regard to info-computationalism.

From the beginning, based on the Cartesian tradition, robotics treated separately the body (machine) and its control. However, successively it became evident that *embodiment itself is essential for cognition, intelligence and generation of behavior*. In a most profound sense, embodiment is vital because cognition results from the interaction of brain, body, and environment. (Pfeifer 2011)

From an evolutionary perspective it is clear that the environment presents a physical source of biological body which through morphological computational processes leads to the establishment of morphogenesis (governing short time scale formation of an organism) and on long time scales governing evolution of species. Nervous system and brain evolves gradually through interactions (computational processes) of a living agent with the environment as a result of information self-structuring (Dodig Crnkovic 2008).

The environment provides a variety of *inputs*, at the same time as it imposes *constraints* which limit the space of possibilities, driving the computation to specific trajectories. This relationship is called *structural coupling* by (Maturana & Varela 1980) and described by (Quick and Dautenhahn 1999) as “non-destructive perturbations between a system and its environment, each having an effect on the dynamical trajectory of the other, and this in turn effecting the generation of and responses to subsequent perturbations.” (Clark 1997) p. 163 talks about “the presence of continuous mutually modulatory influences linking brain, body and world.”

In morphological computing modeling of the agents behavior (such as locomotion and sensory-motor coordination) proceeds by abstracting the principles via information self-structuring and sensory-motor coordination, (Matsushita et al. 2005), (Lungarella et al. 2005) (Lungarella and Sporns 2005) (Pfeifer, Lungarella and Iida 2007). Brain control is *decentralized based on the sensory-motor coordination through the interaction with environment*. Some of the examples of the use of morphological computation (Pfeifer 2011) in robotics are: “Yokoi hand” which can grasp any shape, acting through self-regulation; “Passive dynamic walker” – the brainless robot who walks down the slope; for which the dynamics of the interaction with the environment

is used for self-stabilization and “Insect walking” with no central control for leg-coordination but global communication through interaction with the environment.

6 Morphological Computing as Information Self-structuring

In morphological computation, generation of sensory stimulation is achieved by the interaction with the environment through constraints imposed by the morphology and materials. Through this interaction with the environment, generation of correlations in sensors (self-structuring of sensory data) is achieved by physical process. *The induction of correlations leads to reduction of complexity.* Interaction occurs across multiple time scales between body and control structure of an agent, and its environment. According to (Lungarella et al. 2005) “sensory input and motor activity are continuously and dynamically coupled with the surrounding environment.” and “the ability of embodied agents to actively structure their sensory input and to generate statistical regularities represents a major functional rationale for the dynamic coupling between sensory and motor systems. *Statistical regularities in the multimodal sensory data relayed to the brain are critical for enabling appropriate developmental processes, perceptual categorization, adaptation, and learning*” (emphasis added). (Mirza et al. 2007) present an embodied, grounded individual sensorimotor interaction history, based on information theoretic metric space of sensorimotor experience, dynamically constructed as the robot acts in the environment. (Lungarella and Sporns 2005) give details of the study of the *coupling and interplay across multiple time scales between the brain, body, and environment.* Their findings are supported by the results of (Der 2011). It is important to notice that structures emerge on all levels of control:

Embodied interactions impose statistical structure not only on “raw pixels” within primary sensory channels, but also (and perhaps more powerfully so) on neural activity patterns far removed from the sensory periphery. We predict that embodied systems operating in a highly coordinated manner generate information and additional statistical regularities at all hierarchical levels of their control architectures, including but not limited to the immediate sensory input. (Lungarella and Sporns 2005)

The above mechanism provides the basis for the evolutionary understanding of embodied cognition and knowledge generation. (Dodig Crnkovic 2008) In the process of self-organization of information, the states of the distant parts of the system are synchronized by *stigmergy* - indirect coordination between agents or actions. The trace left in the environment by an action increases the probability of the next action; so subsequent actions reinforce and build on each other, resulting in a coherent behavior.

The results on self-organization of information and the development of embodied cognition in living organisms have inspired the research program in *developmental robotics*. Learning is a continuous and incremental process and development proceeds through morphological change, growth and maturation. Boundary conditions and physical limitations play an important role in the development of an agent, as they

cause reduction of the amount of information. Motor learning results in the reduction of space of possible movements and enables acquisition of motor skills through exploratory activity in the environment. It has been noticed that the greatest learning occurs in childhood when the most vigorous growth occurs. (Elman 1993) showed in training of networks to process complex sentences that neural processing limitations appear advantageous as they contribute to gradual learning. In a new born child initial low resolution vision successively increases, and coarse control becomes gradually more fine-grained (Pfeifer 2011) as learning proceeds. Only simple organisms are born in their final form, while for complex organisms, development seems necessary in order to successively achieve complexity, while avoiding chaos.

7 Info-computational Character of Morphogenetic Computing

Morphological computation makes visible essential connections between an agent's body, (nervous) control and its environment. Through the embodied interaction with the environment, in particular through sensory-motor coordination, *information structure is induced in the sensory data, thus facilitating perception, learning and categorization*. The same principles of morphological computing (physical computing) and data self-organization apply to biology and robotics. Interesting to note is that in 1952 Alan Turing wrote a paper proposing a chemical model as the basis of the development of biological patterns such as the spots and stripes on animal skin, (Turing 1952). Turing morphogenesis did not originally claim that physical system producing patterns actually performed computation. Nevertheless, from the perspective of info-computationalism we can argue that *morphogenesis is a process of morphological computing*. Physical process – though not “computational” in the traditional sense, presents natural (unconventional), morphological computation. Essential element in this process is the interplay between the informational structure and the computational process - *information self-structuring* and *information integration*, both synchronic and diachronic, going on in different time and space scales.

Morphology is the central idea in understanding of the connection between computation (morphological/morphogenetical) and information. Materials represent morphology on the lower level of organization – the arrangements of molecular and atomic structures i.e., how protons, neutrons and electrons are arranged on the level below.

Info-computational naturalism describes nature as informational structure – a succession of levels of organization of information. Morphological computing on that informational structure leads to new informational structures via processes of self-organization of information. Evolution itself is a process of morphological computation on a long-term scale. It will be instructive within the info-computational framework to study processes of self organization of information in an agent (as well as in population of agents) able to re-structure themselves through interactions with the environment as a result of morphological (morphogenetic) computation.

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