Morphological Computing
and Physical Levels of Computation

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Abstract. Natural, embodied computation is a computational model of the physical world that in general can be seen as morphological computation on a variety of levels of organization of physical matter. It provides a basis for framing, parameter studies and simulations of physical systems – from nano-scale agents up to cognitive systems and from quantum mechanical to large-scale self-organized astrophysical structures. The aim of this article is to elucidate the relationships between computation, information and morphology on different levels of organization of physical systems, especially those with relevance for biology and robotics.

Keywords: Models of Computation, Natural Computation, Morphological Computing, Levels of Computation, Morphogenesis, Embodied computation

1 Computation. The Computing Nature

The Tuscan physicist, mathematician, astronomer, and philosopher Galileo Galilei in his book *The Assayer - Il Saggiatore* (1623) declared that “the book of nature is written in the language of mathematics” and that the way to understand nature is through mathematics. Today we understand nature not only in terms of symbolic languages like mathematics with *denotational semantics* but also through computational physical representations with *operational semantics* such as simulations which provide different (usually visual) rendering of natural phenomena in form of interactive models. We can paraphrase Galileo by saying that *the great book of nature is written in the programming languages of natural computing*. This challenges Kauffman’s (Kauffman 2008) view of nature without law, expressed in the following:

“Even deeper than emergence and its challenge to reductionism in this new scientific worldview is what I call breaking the Galilean spell. Galileo rolled balls down inclined planes and showed that the distance traveled varied as the square of the time elapsed. From this he obtained a universal law of motion. Newton followed with his Principia, setting the stage for all of modern science. With these triumphs, the Western world came to the view that all that happens in the universe
is governed by natural law. Indeed, this is the heart of reductionism. Another Nobel laureate physicist, Murray Gell-Mann, has defined a natural law as a compressed description, available beforehand, of the regularities of a phenomenon. The Galilean spell that has driven so much science is the faith that all aspects of the natural world can be described by such laws. Perhaps my most radical scientific claim is that we can and must break the Galilean spell. Evolution of the biosphere, human economic life, and human history are partially indescribable by natural law.” (Kauffman 2008)

In what follows we will argue that the new kind of understanding of lawfulness in the organization of nature, and especially living systems rests on generative computational laws, and not solely on a reduction of the whole to its constitutive parts. In order to understand the world, organization of the parts in the wholes and interactions between them are crucial. That is where generative models come in, as reductionist movie in reverse motion, collecting together pieces that make molecules, cells, organisms and other complex structures. That is where generative processes such as self-organization (Kauffman 1993), autopoiesis of (Maturana & Varela 1980) and other form-generating processes come in and they can be modeled through agent based system-level models such as actor model of computation (Hewitt 2012). The existing models of computation (Boolean networks, Petri nets, Interacting state machines, Process calculi and their hybrids) however need to “adjust formalisms that were originally developed for modeling hardware and software systems to the modeling of biological systems. We must also develop techniques that handle the complexity and magnitude of biological systems and modeling tools that are more accessible to biologists. For biology, some of the key challenges are to develop quantitative techniques to experimentally test dynamic scenarios proposed by executable models, to identify useful building blocks of complex biological networks and perhaps most importantly, to shift biology toward an engineering science, where students learn to use formal (computational- my comment) approaches.” So this two-way learning process between biology and computing will help us formalize biology in what we argue will be a complex but lawful dynamical structure.

Our basic claim is that nature computes by information processing going on in networks of its constituent parts, hierarchically organized in layers. Structures self-organize through processes of natural/physical/embodied computation. In biology all organisms develop from a single cell and all animals have the same basic toolkit of body-building genes, so the development and evolution suggest common generative processes. That is what we understand as computational processes of morphogenesis in biology. The underlying assumption is one of computing nature – all processes in nature are understood as some kind of computation (information processes) – natural computation. (Dodig-Crnkovic and Giovagnoli, 2013)

The idea of computing nature/universe has a long history and different flavors. Computer scientist Konrad Zuse was the first to suggest (in 1967) that the physical behavior of the entire universe is being computed on a fundamental level, possibly on cellular automata, by the universe itself which he called The Computing Space.

Subsequently emerging naturalist computationalism (pancomputationalism), developed among others by (Zuse 1969, Fredkin 1992, Wolfram 2002, Lloyd 2006,
Chaitin 2007) takes the universe to be a system that constantly computes its own next state from the current one, see (Dodig-Crnkovic 2012a).

The difference between the traditional physical law and generative method is dexterously analyzed in the (Fisher and Thomas 2007) and boils down to the difference between denotational and operational semantics of biological model. The main ingredient that is missing in denotational model is interactivity or explicit time dependence that can adequately represent concurrency of a biological system.

As an illustration, a newly formed Origins of Life project lead by Kauffman (University of Vermont) and Markus (CERN), in their Brainstorming Workshop in 2011 announced that the origins of life might be reconstructed within ten years and first living cells produced from purely chemical components. That indicates the level of our present day knowledge about the concrete mechanisms that drive morphogenetic computing in the physical world of cells. But there are numerous pieces of insights already now and as our tools are information and computation, the most efficient way to approach form generation and address among others questions emerging in origins of life and nano-technology is provided by the info-computational framework.

The distinction between denotational and operational semantics concerns models. However, models are tools of understanding and control, but they cannot replace phenomena they model. If we want tools to manipulate, let’s say nanosystems, those tools must be more than models – they will be computations “in materio” as Stepney (Stepney 2008) called them, arguing aptly: “We are still learning how to use all those tools, both mathematical models of dynamical systems and executable computational models and currently developing ‘computation in materio’.” All those tools will be needed in the search for the origins of life and the development of nano-technology.

2 Hierarchy of Levels of Physical Computation

If the whole of nature computes, this computation happens on many different levels of organization of the physical matter. In (Burgin and Dodig-Crnkovic 2011) three generality levels of computations are introduced, from the most general to the most specific/particular one:

1. **Computation as any transformation** of information and/or information representation. This leads to natural computationalism in its most general form.

2. **Computation as a discrete transformation** of information and/or information representation. This leads to natural computationalism in the Zuse and Wolfram form with discrete automata as a basis.

3. **Computation as symbol manipulation**. This is Turing model of computation and its equivalents.

There are also spatial levels or scales of computations (Burgin and Dodig-Crnkovic 2013):

1. **The macrolevel** that includes computations performed by current computational systems in global computational networks and physical computations of macro-objects.

2. **The microlevel** that includes computations performed by integrated circuits.
3. The nanolevel that includes computations performed by fundamental parts that are not bigger than a few nanometers.

4. The molecular level includes computations performed by molecules.

5. The quantum level includes computations performed by atoms and subatomic particles.

3  Info-Computationalism as a Computing Nature Framework

Before we start to explain the relationships between form and its development we will introduce the framework of info-computationalism as appropriate for this purpose. Info-computationalism is the view that combines informational structural realism (Floridi 2008, Sayre 1976, Burgin 2012) and natural computationalism (Zuse 1969, Fredkin 1992, Wolfram 2002, Lloyd 2006, Chaitin 2007) in the sense of computing nature, see (Dodig-Crnkovic 2011, and references therein).

Information and computation are two interrelated and mutually defining phenomena (Dodig-Crnkovic 2006). There is no computation without information, where computation is understood as information processing (Burgin, 2005), and vice versa, there is no information without computation - information is a result of computational processes.

Info-computationalism 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. Morphological computing is information (re)structuring through computational processes which follow/implement/realize physical laws. It is physical computing or natural computing in which physical objects perform computation. Symbol manipulation in this case replaced by physical object manipulation.

Morphology is the central idea in understanding of the connection between computation and information. Materials are represented by morphology on the more basic level of organization – the arrangements of molecular and atomic structures. What appears as a form on a more fundamental level of organization (e.g. an arrangement of atoms), represents “matter” as a higher-order phenomenon (e.g. a molecule).

According to natural computationalism/pancomputationalism (see Dodig-Crnkovic 2006-2013) every physical system is computational. But there are many different sorts of computations going on in nature, that can be seen as a network of networks of agents/actors exchanging “messages”, (Dodig-Crnkovic and Giovagnoli, 2013).

The simplest agents communicate with simplest messages such as elementary particles (with 12 kinds of matter and 12 kinds of anti-matter particles) exchanging 12 kinds of force-communicating particles. For example, we can recast into actor model of computation Yukawa’s theory of strong nuclear force modeled as exchange of mesons (as messages), which explains the interaction between nucleons. Composite physical agents such as cells have different ways of interaction via exchanges of different types of messages/information. Complex agents/actors like humans communicate through languages which use very complex messages for communication.

Exchange of information in the networks of agents causes changes in actors. Those changes are simple in a simple actor such as elementary particle that can change its
"Mathematical structures commonly consist of objects connected by operations or relations. Sometimes the difference between these classes is blurred, but in an interesting structure there are objects which accumulate information expressive of their context in the structure. Sometimes this information can be 'read' by the relations on the structure, which express a formal 'causality', whereby the distribution of information itself has a structure. This appears to be a feature of our own universe." (Cooper in Dodig-Crnkovic and Giovagnoli 2013)

Applied to a computational network as such mathematical structure, it describes the computing nodes/agents that can internalize the information from the outside network and thus change the way they interact as a consequence of previous interactions. Nodes in a network can be elementary particles exchanging elementary particles or nano-systems exchanging molecules, or animals in an eco-system exchanging sound signals or any other interacting agents exchanging messages. For more details about physical computation, see (Dodig-Crnkovic 2012c) and (Dodig-Crnkovic and Giovagnoli 2013), and for the actor model of computation see (Hewitt 2012).

4 Morphology and Morphogenesis

“We might be able to regard the terms shape and information as identical terms. That is, we might be able to regard the mathematical study of shape as a general, and more thorough, information theory than has been attempted in the current approaches to the study of information measurement.” (Leyton, 1999)

Morphology is a theory of the formative principles of a structure, (from the Greek morphê - shape), while morphogenesis in general is a study of the creation of shape.

Morphological computation is computational process realized through physical interactions of system components. Morphological computing includes physical changes of the material substrate of a physical system in the computational process. More exactly, morphological computing is information processing that includes symbolic operations, which are the base for the traditional (symbolic) computation, and morphological operations, which are morphological transformations of the material component (body) of the physical system where the computational process is performed. In particular, the result of morphological computing is a transformed form of the material component (body) of a physical system.

Morphogenesis is an evolutionary or embryological development of the structure (form) of an organism or of its part. 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). In order to reflect intrinsic properties, it is useful to define morphogenesis in the context of system theory. Generally, morphogenesis is a systemic development of the physical structure (form) of a system or of its part. “Morphogenesis (whether natural or artificial) is an example of embodied
computation, which exploits physical processes for computational ends, or performs computations for their physical effects.” (MacLennan 2010)

Morphogenesis in general can be seen as a process of morphological computing. Physical process – even 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, both synchronic and diachronic, going on in different time and space scales. Process of computation implements/executes/realizes physical laws which act on informational structures. Thus in this framework there is no opposition between natural laws and natural processes. Processes are lawful; otherwise the universe would lose its form. We just have to uncover those computational laws that lead to the assembly of the world as we know it, from the parts we have got by reductionist study. Through process of computation, structures change their forms. All of computation on some level of abstraction is morphological computation – a form-changing/form-generating process.

5 Morphological Computing in Nanoscale

“Life revolves around real-world information processing, and the gap between computers and living systems … is shrinking. Distributed intelligent technical systems with self-organizing and evolvable life-like properties are required both to make the next generation of self-repairing computer and robotics technology and to direct all kinds of complex production and remediation on the nanoscale.” (FET initiative PACE) The properties sought for are: robustness, homeostasis and self-repair; self-assembly, modularity and self-organization; self-reproduction, genetic programability and evolvability. MacLennan (2010) argues that post-Moore’s law era will necessitate a closer relationship between computational and physical processes when we reach nano-scale:

"By investigating embryological morphogenesis – a supremely successful example of what we want to accomplish – we can learn many lessons about how communication, control, and computation can be done well at very small scales."

Besides natural morphogenesis also synthetic morphogenesis/artificial morphogenesis (kind of amorphous computing) is instructive as well as the study of evolution and development, including phenomena of matamorphosis. At present, according to MacLennan “One of the biggest issues that embodied computation faces is the lack of a commonly accepted model of computation.” As “morphogenesis seems to have the characteristics of a coordinated algorithm [42]” it is of special interest to understand communication patterns of actors in a network that represents system with morphogenetic dynamics.
6 Morphological Computing in Biology: Morphogenesis as Computation (Information Processing)

Newly Eiraku et al. (2011) reported the following findings:

“This study has revealed that the complex morphogenesis of the retinal anlage, at least in the in vitro context, possesses a ‘latent intrinsic order’ involving dynamic self-patterning and self-formation driven by a sequential combination of local rules and internal forces within the epithelium. The in vivo situation should be certainly more complex, and extrinsic signals and forces from external structures (for example, the surface ectoderm, lens and periocular mesenchyme) as well as space constraints presumably work together with this intrinsic order to reinforce robust retinal morphogenesis.”

Specific forms of physical bodies of existing life forms have developed evolutionary through optimization of their function in the environment. In the development of an organism, based on the DNA code, body of a living being is created through morphogenesis governing a short time scale formation of life. On a long-time scale, morphological computing governs evolution of species. From an evolutionary perspective it is central that the environment provides a physical source of biological body of an organism, a source of energy and matter for its metabolism as well as information. Nervous system and the brain of an organism evolve gradually through interactions (computational processes) of a living agent with the environment. This process of mutual shaping is a result of information self-structuring (Dodig-Crnkovic 2008). Here both physical environment and the physical body of an agent can in every time instant be described by their informational structures.

The environment provides a variety of inputs in the form of information and matter-energy, where the difference between information and matter-energy is not in kind, but in type of use organism makes of it. As there is no information without representation, all information is carried by some physical carrier (light, sound, chemical molecules, etc.). The same object can be used by an organism as a source of information and a source of nourishment/matter/energy. Light signals are used by some organisms just as information necessary for orientation in the environment, while other organisms use it for photosynthetic processes in their metabolism. Thus the question what will be used “only” as information and what as food/ energy source depends on the type of organism/agent. In general, the simpler the organism, the simpler the information structures of its body, the simpler information carriers it relies on, and simpler interactions with the environment.

“(B)iotic information is nothing more than the constraints that allows a living organism to harness energy from its environment to propagate its organization.” (Kauffman et al. 2008)

The environment is not only a resource but at the same time it imposes constraints which limit the space of possibilities for an agent. In an agent that can be described as a complex informational structure, constraints imposed by the environment are driving time development (the computation) of the structure, and thus even agent’s shape
and behaviour, to specific trajectories. This relationship between an agent and its environment is by Maturana & Varela (1980) called structural coupling. Among processes that generate biological structures, autopoiesis has central place. According to Maturana and Varela (1980) p. 78, an autopoetic “machine” is organized as a network of processes of production, transformation and destruction of components which through mutual interactions continuously regenerate the network that produced them. Structural coupling with the environment for autopoetic systems is described as continuous dynamical process and considered as an elementary form of cognition possessed by all life forms.

There is a difference between morphological computing in general and autopoiesis in that autopoiesis presupposes operational autonomy and closure of a system, while morphological computing happens in non-living systems as well, such as crystals or hurricanes. Morphogenesis is a basis for self-organization as well as for autopoetic processes.

Deacon (2011) distinguishes between the following three forms of information:

− Information 1 (Shannon) (data, pattern, signal) (data communication) [syntax]
− Information 2 (Shannon + Boltzmann) (intentionality, aboutness, reference, representation, relation to object or referent) [semantics]
− Information 3 ((Shannon + Boltzmann) + Darwin) (function, interpretation, use, pragmatic consequence) [pragmatics]

Deacon’s three types of information parallel his three formative mechanisms: [Mass-energetic [Self-organization [Self-preservation (semiotic)]]] with levels of emergent dynamics: [Thermo- [Morpho- [Teleo-dynamics]]] and corresponding Aristotle’s causes: [Efficient cause [formal cause [final cause]]).

“Because there are no material entities that are not also processes, and because processes are defined by their organization, we must acknowledge the possibility that organization itself is a fundamental determinant of physical causality. At different levels of scale and compositionality, different organizational possibilities exist. And although there are material properties that are directly inherited from lower-order component properties, it is clear that the production of some forms of process organization is only expressed by dynamical regularities at that level. So the emergence of such level-specific forms of dynamical regularity creates the foundation for level-specific forms of physical influence.” Deacon (2011) p. 177.

In the above passage, Deacon expresses the same view that we argue for: matter as a structure, causality connected with a structure which determines its dynamics. We describe computation as a process, information as a substance and argue for inseparability of process and structure/substance. If we search for the source of the energy necessary to build the constraints and turn environment energy into the work needed by organisms to run their metabolism, Ulanowicz’s process ecology model offers the explanation: “Basically the answer is simply that an aleatoric event took place in which a constraint emerged that allowed a collection of organic molecules to do the work necessary to propagate their organization.” (Ulanowicz, 2009)
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7 Morphological Computing in Robotics and Embodied AI

Morphological computing emerged recently as a new idea in robotics, see (Pfeifer 2011), (Pfeifer and Iida 2005), (Pfeifer and Gomez 2009) (Paul 2004). It presents a fundamental change compared with traditional robotics which considered the body/machine and its control/computer as completely independent elements of a robot. However, successively it has become evident that embodiment itself is essential for cognition, intelligence and generation of behaviour. Embodiment is vital because cognition (and consequently intelligent behaviour) results from the interaction of the brain, body, and environment. (Pfeifer 2011) Instead of specifically controlling each movement of a robot, one can instead use morphological features of a body to automatically perform movements. Here roboticists can take the advantage of learning from biological forms and materials developed in nature.

When it comes to human development, Clark (1997) p. 163 talks about "the presence of continuous mutually modulatory influences linking brain, body and world." Talking about living beings in general, it would be the presence of continuous mutually shaping interactions between body and environment, where body in some organisms developed nervous system and brain as control mechanisms.

In morphological computing modelling of the agents behaviour (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. 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. For more information on morphological computing in robotics, see Dodig-Crnkovic 2012a and 2012b)

8 Cognition as Morphological Computation

As mentioned before autopoiesis (Maturana and Varela 1980) is considered the most fundamental level of cognition present even in as simple organisms as bacteria. Through evolution, increasingly complex living organisms developed that are able to survive and adapt to their environment. It means that they are able to register inputs (data) from the environment, to structure those into information, and in more complex organisms to structure information into knowledge. The evolutionary advantage of using structured, component-based approaches such as data – information – knowledge is improving response-time and efficiency of cognitive processes of an organism.

All cognition is embodied cognition – from microorganisms to humans and cognitive robots. In more complex cognitive agents, knowledge is built upon not only direct reaction to input information, but also on information processes governed by choices, dependent on value systems stored and organized in agent’s memory.
Information and its processing are essential structural and dynamic elements which characterize structuring of input data (data \(\rightarrow\) information \(\rightarrow\) knowledge) by an interactive computational process going on in the agent during the adaptive interplay with the environment. Not all available information is part of cognitive process. Humans for example talk to each other or exchange written messages but do not notice events on molecular or quantum level.

There is a continuum of morphological development from simplest living organism’s automaton-like structures to most complex life form’s elaborate interplay between body, nervous system and brain and the environment. Cognition thus proceeds through restructuring of an agent in the interaction with the environment where this restructuring can be identified as morphological computing.

9 Conclusions

Within the framework of info-computationalism nature is informational structure – a succession of levels of organization of information. Morphological computing on informational structure leads to new informational structures via processes of self-organization of information.

In tandem with distinct layers of structural organization found in nature (elementary particles, atoms, molecules, cells, organisms, ecologies, etc) there are distinct processes of self-organization of information that implement/realize physical laws. This self-organization is the result of the interactions between different nodes/agents/actors in coupled interaction networks on many different levels of organization. In such computational model actors exchange different kinds of messages that characterize each level of organization.

As Denning (2007) aptly noticed, computing is a natural science nowadays, and it assimilates knowledge from and facilitates development of natural sciences – from physics and chemistry to biology, cognitive science and neuroscience. Info-computational framework can be used to study processes of self organization of information in a population of physical embodied agents that re-structure themselves through interactions with the environment - morphological computation.

References


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