

The Info-computational Nature of Morphological Computing

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Abstract

Morphological computing emerged recently as an approach in robotics aimed at saving robots computational and other resources by utilizing physical properties of the robotic body to automatically produce and control behavior. The idea is that the morphology of an agent (a living organism or a machine) constrains its possible interactions with the environment as well as its development, including its growth and reconfiguration. The nature of morphological computing becomes especially apparent in the info-computational framework, which combines informational structural realism (the idea that the world for an agent is an informational structure) with natural computationalism (the view that all of nature forms a network of computational processes). Info-computationalism describes morphological computation as a process of continuous self-structuring of information and shaping of both interactions and informational structures. This article argues that natural computation/morphological computation is a *computational model of physical reality*, and *not* just a metaphor or analogy, as it provides a basis for computational framing, parameter studies, optimizations and simulations – all of which go far beyond metaphor or analogy.

Introduction

In recent years, *morphological computing* emerged as a new idea in robotics, (Pfeifer 2011), (Pfeifer and Iida 2005), (Pfeifer and Gomez 2009) (Paul 2004). This presents a fundamental change compared with traditional

robotics which, based on the Cartesian tradition, treated the body/machine and its control (computer) as completely independent elements of a robot. However, it has become increasingly evident that *embodiment itself is essential for cognition, intelligence and generation of behavior*. In a most profound sense, embodiment is vital because cognition (and consequently intelligent behavior) 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 create motion. Here we can learn from specific structures of biological life forms and materials found in nature which have evolved through optimization of their function in the environment.

During the process of its development, based on its DNA code, the body of a living organism is created through morphogenesis, which governs the formation of life over a short timescale, from a single cell to a multicellular organism, through cell division and organization of cells into tissues, tissues into organs, organs into organ systems, and organ systems into the whole organism. *Morphogenesis* (from the Greek "generation of the shape"), is the biological process that causes an organism to develop its shape.

Over a long timescale, morphological computing governs the *evolution of species*. From an evolutionary perspective it is crucial that the environment provides the physical source of the biological body of an organism as well as a source of energy and matter to enable its metabolism. The nervous system and brain of an organism evolve gradually through the interaction of a living agent with its environment. This process of mutual shaping is a result of information self-structuring. Here, both the physical environment and the physical body of an agent can at all times be described by their informational structure¹. Physical laws govern fundamental computational processes which express changes of informational structures. (Dodig Crnkovic 2008)

The environment provides a variety of *inputs in the form of both information and matter-energy*, where the difference between information and matter-energy is not in the kind, but in the type of use the organism makes of it. As there is no information without representation, all information is

carried by some physical carrier (light, sound, radio-waves, chemical molecules able to trigger smell receptors, etc.). The same object can be used by an organism as a source of information and as a source of nourishment/matter/energy. A single type of signal, such as light, may be used by an organism both as information necessary for orientation in the environment, and for the photosynthetic production of energy. Thus, the question of what will be used 'only' as information and what will be used as a source of food/ energy depends on the nature of the organism. In general, the simpler the organism, the simpler the information structures of its body, the simpler the information carriers it relies on, and the simpler its interactions with the environment.

The environment is a resource, but at the same time it also imposes *constraints* which limit an agent's possibilities. In an agent that can be described as a complex informational structure, constraints imposed by the environment drive the time development (computation) of its structures, and thus even its shape and behavior, to specific trajectories.

This relationship between an agent and its environment is called *structural coupling* by (Maturana & Varela 1980) and is 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 affecting the generation of and responses to subsequent perturbations.”

This mutual coupling between living systems and the environment can be followed on the geological time scale, through the development of the first life on earth. It is believed that the first, most primitive photosynthetic organisms contributed to the change of the environment and produced oxygen and other compounds enabling life on earth. For example, Catling et al. (2001) explain how photosynthesis splits water into O_2 and H, and methanogenesis transfers the H into CH_4 . The release of hydrogen after CH_4 photolysis therefore causes a net gain of oxygen. This process may help explain how the earth's surface environment became successively and irreversibly oxidized, facilitating life on earth.

When talking about living beings in general, there are continuous, mutually shaping interactions between organisms and their environment, where

the body of some organisms evolved a nervous system and a brain as control mechanisms. Clark (1997) p. 163 talks about "the presence of continuous, mutually modulatory influences linking brain, body and world."

Morphological Computing

In morphological computing, the modelling of an agent's 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 sensory-motor coordination through interaction with the environment*. Through 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.

Morphology is the central idea in the understanding of the connection between computation and information. It should be noted that material also represents morphology, but on a 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). Isomers show how morphological forms are critical in interaction processes such as pharmacology, where the matching of a 'drug' to a 'receptor' is only possible if the forms are correct. The same is true for processes involving molecules in a living cell.

Info-computational naturalism (Dodig Crnkovic 2009) 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 structures of organisms over a long time scale. It will be instructive within the info-computational framework to study in detail processes of self organization of information in an agent (as well as in a population of agents) able to re-structure themselves through interactions with the environment as a re-

sult of morphological (morphogenetic) computation. Kauffman (1993) correctly identifies the central role of self-organization in the process of evolution and development. The order within a living organism grows by self-organization, which is lead by basic laws of physics.

As an example of morphological computing, in botany *phyllotaxis* is the arrangement of leaves on a plant stem (from ancient Greek *phýllon* "leaf" and *táxis* "arrangement").

“A specific crystalline order, involving the Fibonacci series, had until now only been observed in plants (phyllotaxis). Here, these patterns are obtained both in a physics laboratory experiment and in a numerical simulation. They arise from self-organization in an iterative process. They are selected depending on only one parameter describing the successive appearance of new elements, and on initial conditions. The ordering is explained as due to the system’s trend to avoid rational (periodic) organization, thus leading to a convergence towards the golden mean.” Douady and Couder (1992)

Morphological computing is information (re)structuring through computational processes that follow/implement physical laws. It is physical computing or natural computing in which physical objects perform computation. Symbol manipulation, in this case, is physical object manipulation.

Information as a Fabric of Reality

“Information is the difference that makes a difference. “ (Bateson, 1972)

More specifically, Bateson’s difference is the difference *in the world* that makes the difference *for an agent*. Here the world also includes agents themselves. As an example, take the visual field of a microscope/telescope: A difference that makes a difference for an agent who can see (visible) light appears when she/he/it detects an object in the visual field. What is observed presents a difference that makes the difference for that agent. For another agent who may see only ultra-violet radiation, the visible part of the spectrum might not bring any difference at all. So the difference that makes a difference for an agent depends on what the agent is able to detect or perceive. Nowadays, with the help of scientific instru-

ments, we see much more than ever before, which is yet further enhanced by visualization techniques that can graphically represent any kind of data.

A system of differences that make a difference (information structures that build information architecture), observed and memorized, represents the fabric of reality for an agent. Informational Structural Realism (Floridi, 2008) (Sayre, 1976) argues exactly that: *information is the fabric of reality*. Reality consists of informational structures organized on different levels of abstraction/resolution. A similar view is defended by (Ladyman et al. 2007). Dodig Crnkovic (2009) identifies this fabric of reality (Kantian Ding an sich) as *potential information* and makes the distinction between it and actual information for an agent. Potential information for an agent is all that exists as not yet actualized for an agent, and it becomes information through interactions with an agent for whom it makes a difference.

Informational structures of the world constantly change on all levels of organization, so the knowledge of structures is only half the story. The other half is the knowledge of processes – information dynamics.

Computation. The Computing Universe: Pancomputationalism

Konrad Zuse was the first to suggest (in 1967) that the physical behavior of the entire universe is being computed on the basic level, possibly on cellular automata, by the universe itself, which he referred to as "Rechnender Raum" or Computing Space/Cosmos.

The subsequently developed Naturalist computationalism/ pancomputationalism (Zuse, 1969) (Fredkin, 1992) (Wolfram, 2002), (Chaitin, 2007), (Lloyd, 2006) takes the universe to be a system that constantly computes its own next state. Computation is generally defined as *information processing*, see (Burgin, 2005)

Info-computationalism

Information and computation are two interrelated and mutually defining phenomena – there is no computation without information (computation understood as information processing), and vice versa, there is no information without computation (information as a result of computational processes). (Dodig Crnkovic 2006) Being interconnected, information is

studied as a structure, while computation presents a process on an informational structure. In order to learn about foundations of information, we must also study computation. In (Dodig-Crnkovic, 2011) the dynamics of information is defined in general as natural computation.

Information self-structuring (self-organization)

The embodiment of an agent is both the cause and the result of its interactions with the environment. The ability to process and to structure information depends fundamentally on the agent's morphology. This is the case for all biological agents, from the simplest to the most complex. According to (Lungarella et al. 2005), "embodied agents that are dynamically coupled to the environment, actively shape their sensory experience by structuring sensory data (...)." Because of the morphology which enables dynamic coupling with the environment, the agent selects environmental information which undergoes the process of self-structuring (by organizing the statistics of sensory input) in the persistent loops connecting sensory and motor activity. Through repeated processing of typically occurring signals, agents get adapted to the statistical structure of the environment. In (Lungarella & Sporns, 2004) it is argued that:

" in order to simplify neural computations, natural systems are optimized, at evolutionary, developmental and behavioral time scales, to structure their sensory input through self-produced coordinated motor activity. Such regularities in the multimodal sensory data relayed to the brain are critical for enabling appropriate developmental processes, perceptual categorization, adaptation, and learning." (Lungarella 2004)

In short, information self-structuring means that agents actively shape their sensory inputs by interactions with the environment. Lungarella and Sporns use entropy as a general information-theoretic functional that measures the average uncertainty (or information) of a variable in order to quantify the informational structure in sensorimotor data sets. Entropy is defined as:

$$H(X) = - \sum p(x) \log p(x)$$

where $p(x)$ is the first order probability density function.

Another useful information-theoretical measure is mutual information (Lungarella & Sporns, 2004). In terms of probability density functions, the mutual information of two discrete variables, X and Y , is expressed as:

$$M(X, Y) = - \sum \sum p(x, y) \log [p(x) p(y) / p(x, y)]$$

thus measuring the deviation from the statistical dependence of two variables.

In sum, statistical methods are used in order to analyze data self-structuring, which appears as a result of the dynamical coupling between the (embodied) agent and the environment. (Lungarella & Sporns, 2004)

Cognition as Restructuring of an Agent in the Interaction with the Environment

As a result of evolution, increasingly complex living organisms arise that are able to survive and adapt to their environment. This means that they are able to register input (data) from the environment, to structure it 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 the improved response-time and the efficiency of cognitive processes of an organism.

All cognition is embodied cognition in all living beings – microorganisms as well as humans. In more complex cognitive agents, knowledge is built not only as a direct reaction to external input information, but also on internal intentional information processes governed by choices, dependent on value systems stored and organized in the agent's memory as 'implemented' in the agent's body.

Information and its processing are essential structural and dynamic elements which characterize the structuring of input data (data → information → knowledge) by an interactive computational process going on in the agent during the adaptive interplay with the environment.

There is a continuum of morphological development from the automaton-like behaviors of the simplest living structures to the elaborate interplay

between body, nervous system and brain, and the environment of most complex life forms. Cognition thus proceeds through the restructuring of an agent in its interaction with the environment and this restructuring can be identified as morphological computing.

Morphogenesis as Computation (Information Processing). Turing's Reaction-Diffusion Model of Morphogenesis

Morphology (Greek morphê - shape) is a theory of *the formative principles of a structure*.

Morphogenesis is a study of the creation of shape during the development of an organism. It is one of the following four fundamental, interconnected classes of events in the development: *Patterning* - the setting up of the positions of future events across space at different scales; *Regulation of timing* - the 'clock' mechanisms and *Cell differentiation*: changes in a set of expressed genes (molecular phenotype) of a cell.

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).

“Patterns resulting from the sole interplay between reaction and diffusion are probably involved in certain stages of morphogenesis in biological systems, as initially proposed by Alan Turing. Self-organization phenomena of this type can only develop in nonlinear systems (i.e. involving positive and negative feedback loops) maintained far from equilibrium.” (Dulos et al. 1996)

Turing did not originally claim that the physical system producing patterns actually performs computation through morphogenesis. Nevertheless, from the perspective of info-computationalism (Dodig Crnkovic 2009) we can argue that morphogenesis is a process of morphological computing. Physical process, even though not 'computational' in the traditional sense, presents natural (unconventional), physical, morphological computation. An essential element in this process is the interplay between the informational structure and the computational process – information self-structuring (including information integration), both synchronic and diach-

ronic, proceeding through different scales of time and space. *The process of computation implements (represents) physical laws which act on informational structures.* Through the process of computation, structures change their forms.

All of computation on some level of abstraction is morphological computation – a form-changing/form-generating process.

Info-Computationalism and Morphological Computing are Models of Computation and not just Metaphors

“Perhaps every science must start with metaphor and end with algebra – and perhaps without the metaphor there would never have been an algebra.” (Black, 1962) p.242

According to the dictionary definition, *metaphor* is a figure of speech in which a term or phrase is applied to represent something else. It uses an image, story or tangible thing to represent a quality or an idea.

In the case of morphological computing, some might claim that morphological computing is just a metaphor, or a figure of speech, which would mean that morphogenesis can metaphorically be described as computing, for example, while in fact it is something else.

On the other hand, *analogy* (from Greek 'αναλογία' – 'proportion') is a cognitive process of transferring information or meaning from one particular subject to another particular subject, and a linguistic expression corresponding to such a process. An analogy does not make identification, which is the property of a metaphor. It just establishes similarity of relationships.

If morphological computing were just an analogy, it would establish only a similarity of some relationships, which is definitely not all it does.

Unlike metaphors and analogies, *models* are not primarily linguistic constructs. They have substantial non-linguistic, interactive spatio-temporal and visual qualities. Models are cognitive tools often used not only for description but also for *prediction and control* and interactive studies of modeled phenomena. Black (1962) noticed the line of development from metaphor to computational model:

“Models, however, require a greater degree of structural identity, or isomorphism, so that assertions made about the secondary domain can yield insight into the original field of interest, and usually the properties of the second field are better known than those of their intended field of application. Mathematical models are paradigmatic examples for science, and in physics and engineering, at least, their primary function is conventionally taken to be the enabling of predictions and the guiding of experimental research. Kant went so far as to identify science with mathematization...”
(Black, 1962) p.242

The process of modeling, designing and creating robots that are more life-like in their morphological properties, can both advance our understanding of biological life and improve embodied and embedded cognition and intelligence in artificial agents. Morphological computing is a model of computing, i.e. data/information processing. It is a type of natural (physical) computing, and as a model it has both important practical and theoretical implications.

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ⁱ Here is the definition by John Daintith, *A Dictionary of Computing* (2004) <http://www.encyclopedia.com/doc/1O11-datastructure.html>

Data structure (information structure) An aspect of data type expressing the nature of values that are composite, i.e. not atoms. The non-atomic values have constituent parts (which need not themselves be atoms), and the data structure expresses how constituents may be combined to form a compound value or selected from a compound value.