Information, Computation, Cognition. Agency-Based Hierarchies of Levels

Gordana Dodig-Crnkovic

Mälardalen University, Västerås, Sweden
gordana.dodig-crnkovic@mdh.se

Abstract. This paper connects information with computation and cognition via concept of agents that appear at variety of levels of organization of physical/chemical/cognitive systems – from elementary particles to atoms, molecules, life-like chemical systems, to cognitive systems starting with living cells, up to organisms and ecologies. In order to obtain this generalized framework, concepts of information, computation and cognition are generalized. In this framework, nature can be seen as informational structure with computational dynamics, where an (info-computational) agent is needed for the potential information of the world to actualize. Starting from the definition of information as the difference in one physical system that makes a difference in another physical system – which combines Bateson and Hewitt's definitions, the argument is advanced for natural computation as a computational model of the dynamics of the physical world, where information processing is constantly going on, on a variety of levels of organization. This setting helps us to elucidate the relationships between computation, information, agency and cognition, within the common conceptual framework, with special relevance for biology and robotics.

Keywords: Information, Computation, Cognition, Natural Computation, Morphological Computing, Morphogenesis, Embodied computation

Introduction

At present we are lacking adequate understanding of cognition in humans (which is what is commonly thought of as "cognition") while at the same time we are trying to develop cognitive robotics and cognitive computing. The contemporary research into artifactual cognition performed in parallel with studies of cognition in humans and animals provide us with two-way learning that will result in both better insights in mechanisms of biological cognition and better solutions for cognitive robotics.

In order to study within one framework cognition in living organisms (including humans) and machines (including cognitive software), this article is generalizing some common ideas, thus using extended concepts of <agent>, <observer>, <information>, <computation>, <evolution>, <cognition>, <learning>, and <knowledge>. The basis is the idea of nature as a network of networks of <agents> that exchange information. This generalized type of <agents> exist on the level of fundamental particles, then on the higher level of atoms as composed of networks of elementary particles, then higher still there are molecules consisting of atoms as agents. Up in hierarchy of levels of organization of agents there are cells as networks of molecules, organisms as networks of cells, ecologies as networks of organisms, etc. In short there is a fractal structure of agents within agents on variety of levels of organization. Dynamics on each level of organization is a result of information exchanges between agents.

<Information> is relational, based on differences, and thus <agent>-dependent. <Agents> are entities capable of acting on their own behalf (elementary particles, atoms, molecules, cells, organisms, etc.) <Computation> is a process of <information> exchange between <agents>, i.e. <information> dynamics or processes on informational structures (Hewitt 2012).

Epistemology is formulated as theory of information (Chaitin 2007), or more specifically as theory of informational structures (Floridi 2008)(Sayre 1976) in <cognitive> agents. Even though informational structural realism is formulated from the perspective of human agents, it is readily generalizable to any other kind of agents processing information from the outside world that guides their organization and behavior.

In this generalized framework, agents exist already on a basic physical level, and they form, via processes of self-organization, increasingly complex structures, including living organisms. Living <agents> (all biological systems) are critically dependent on the capability to acquire energy for their own <agency>. Their <cognition> is a property that ensures and governs their process of being alive. Understanding of living <agency> is closely tied to the understanding of origins of life and its evolution.

In present approach we look at evolution as a process that unfolds through morphological <computation>, through morphogenesis and meta-morphogenesis as introduced in (Turing 1952) and further studied in (Sloman 2013a) and (Dodig-Crnkovic 2012d). At different levels of complexity of living <agents>, different levels of <cognitive> information-processing capacities develop – from bacterial colonies with distributed information processing (Xavier et al. 2011) via plants to organisms with nervous systems such as C. elegans (See OpenWorm project http://www.openworm.org that is building the computational model of this microscopic worm) to mammals and finally humans. Organisms preserve evolutionary memory in their body structures, that in interaction with the environment exhibit different behaviors. From biological structures as information-processing mechanisms we can hope to learn more not only about the details of form generation (morphogenesis) in biological systems, but also about possible future computational methods and devices inspired by intrinsic natural computation. A lot can be learned from information processing in the brain.

> “The uniformity of the cortical architecture and the ability of functions to move to different areas of cortex following early damage strongly suggests that there is *a single basic learning algorithm for extracting underlying structure from richly-structured, high- dimensional sensory data*.” (Hinton 2006) (Italics added)

Based on the uniformity of cortical architecture, *Deep Learning Algorithms* have been recently developed as machine learning algorithms using artificial neural networks that learn in a succession of levels corresponding to increasing levels of abstraction of concepts, with higher-level concepts defined in terms of lower-level ones; typically used for pattern recognition (Hinton et al. 2006)[1] (Hawkins & Blakeslee 2005)

Similarly, based on the behavior of natural systems, Probably Approximately Correct "PAC" algorithms (Valiant 2013) have been proposed as a way of *learning from nature how to learn*. The scope of PAC algorithms is wider than the scope of Deep Learning Algorithms as they offer in general "the unified study of the *mechanisms of evolution, learning, and intelligence* using the methods of computer science". Valiant argues that "to understand the fundamental character of life, learning algorithms are good place to start."

While both PAC algorithms and Deep Learning are centered on *machine learning*, notwithstanding the fact that Valiant makes important connection between (machine) learning algorithms and evolution, I introduced a different path searching for grounding of learning in the mechanisms of <*cognition*> starting with simplest living organisms like bacteria whose processing of information is form of natural computation. Within the framework of info-computationalism, I proposed the unified view of computing nature with <agent>-based fundamental notions of <*information*> and <*computation*> (information exchanges between <agents>). (Hewitt 2012) especially focused on interaction and mechanisms of computation as discussed in (Dodig-Crnkovic & Giovagnoli 2013). In this approach it is essential that both informational structures and computational processes *appear on variety of levels of organization* (levels of abstraction).

This naturalist strategy aims at explaining human cognitive capacities as a result of evolutionary and developmental processes that we want to model and simulate in order to be able to both better understand humans and other living organisms, how they function and what causes their malfunctions, as well as to learn how to build intelligent computational artifacts that will add to our extended cognition.

Nature as Info-Computation for a Cognizing Agent[2]

In this article I will propose a framework with the aim to naturalize cognition, meaning that we will not study the *concept of cognition* but <cognition> as *natural phenomenon* in any kind of living <agent>. The framework of info-computationalism, presented earlier in (Dodig-Crnkovic 2012a)(Dodig-Crnkovic & Giovagnoli 2012) (Dodig-Crnkovic & Müller 2011) (Dodig-Crnkovic 2006) is based on concepts of <information> and <computation> as two fundamental and mutually dependent concepts defined in a broader sense than what one typically is used to.

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[1] The deep learning model (Hinton et al. 2006) involves learning the distribution of a high level representation using a restricted Boltzmann machine to model each higher layer. (Smolensky 1986)

[2] Some of the issues discussed here have been discussed by the author in a recent book Computing Nature and in the book Information and Computation. This paper presents a synthesis of the previously developed arguments.

Information is understood according to *informational structural realism* (Floridi 2003) (Floridi 2009)(Floridi 2008)(Sayre 1976) as the *structure*, the fabric of the relationships in the universe (for an agent).

Computation is defined as information processing (Burgin 2010) and presents all processes of *changes of the structures of the universe*[3] (natural computationalism or pancomputationalism) (Zuse 1969, Fredkin 1992, Wolfram 2002, Lloyd 2006, Chaitin 2007)[4].

Combining the ideas of informational structural realism and natural computationalism results in the model of the universe as a huge computational network where computation is understood as the dynamics of natural information, i.e. *natural computation* (Rozenberg et al. 2012). Computing nature represents all processes existing in the physical universe, which necessarily appear in both discrete and continuous form, on both symbolic and sub-symbolic[5] level.

From now on, given the above non-standard definitions I will omit brackets around <agent>, <information>, <computation>, <cognition> etc. and I hope the reader will keep in mind generalized notions that are used in the rest of the article.

A consequence for epistemology for an agent processing information is that *information and reality are seen as one by an agent* (Zeilinger 2005) (Vedral 2010), not only in case of humans, but also for other living organisms as cognizing agents. (Maturana & Varela 1992) (Ben-Jacob et al. 2011) (Shapiro 2011)

The Relational Nature of Information and Levels of Organization

The world exists independently from cognizing agents (realist position of structural realism) in the form of *proto-information/potential information*, the potential form of existence corresponding to Kant's das Ding an sich. That *proto-information* becomes actual information ("*a difference that makes a difference*" according to (Bateson 1972)) *for a cognizing agent* in a process of interaction through which aspects of the world get uncovered/registered[6].

Hewitt proposed the following general relational[7] definition that subsumes Bateson's definition:

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[3] This "processing" can be either *intrinsic* (spontaneously going on) for any physical system or *designed* such as in computing machinery.

[4] For majority of computationalists, computing nature is performing discrete computation. Zuse for example represents his calculating space as cellular automata, but the assumption about the type of computation is not essential for the idea that the universe <computes> its next state from the previous one.

[5] Sub-symbolic computations go on in neural networks, as signal processing which leads to concept formation from pattern recognition.

[6] The expression "registered" is borrowed from Brian Cantwell Smith (Cantwell Smith 1998)

[7] More on current understanding of information can be found in the Handbook of the Philosophy of Information (Benthem van & Adriaans 2008)

> ”Information expresses the fact that *a system is in a certain configuration that is correlated to the configuration of another system*. Any physical system may contain information about another physical system.” (Hewitt 2007) (Italics added)

Bateson’s definition follows from the above formulation if “another system” is an observer for whom the difference in the first system makes a difference. This relational view of information has consequences for epistemology and connects to the ideas of participatory universe (Wheeler 1990), endophysics (Rössler 1998) and observer-dependent knowledge production of second-order cybernetics. Combining Bateson and Hewitt insights, on the basic level, *information is the difference in one physical system that makes a difference in another physical system, thus constituting correlation between their configurations*.

Among correlated systems, of special interest in our discussion of naturalized cognition are *agents - systems able to act on their own behalf*, and among agents we will focus on *living agents, that is cognizing agents,* based on Maturana and Varela’s understanding that *life is identical with cognition*[8] (Maturana & Varela 1980). In what follows, it should become evident why it is so that all living agents possess some degree of cognition.

The world as it appears (actualizes) for cognizing agents depends on the types of interactions through which they acquire information. Potential information in the world is obviously much richer than what we observe, containing invisible worlds of molecules, atoms and sub-atomic phenomena, distant objects and similar. Our knowledge about this potential information which reveals with help of scientific instruments continuously increases with the development of new devices and the new ways of interaction, through both theoretical and material constructs (Dodig-Crnkovic & Müller 2011).

For an agent, potential information actualizes in present time to transform into potential again. Transformations between potential and actual information (information process, computation) parallel transformation between potential and kinetic energy. Kampis’ component systems (described later on) model information processing in the cell that undergoes cycles of transformations of potential (original informational structure) and actual (current process) in creating new informational structure that is potentiality for a new process. Notions of potentiality and actuality can be traced back to Aristotle, for whom potentiality presents a possibility, while actuality is the change/activity/motion/process that presents realization of that possibility. This relationship parallels being and becoming. Along Aristotle’s transitions from potentiality to actuality, we discuss even the transition from actuality to potentiality, closing the cycle of transformations. That would correspond the cycle from original structure (information) via dynamical process (computation) to a new structure (information).

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[8] Even though Maturana and Varela identify process of life with cognition, Maturana refuses the information processing view of cognition. It should be noted that it is based on traditional concept of information.

The Hierarchy of Levels of Natural Information

This article provides arguments for the new kind of understanding, in the sense of (Wolfram 2002), of lawfulness in the organization of nature and especially living systems, emergent from *generative computational laws* of *self-organization based on the concept of agents*. In order to understand the world, organization of the parts in the wholes and interactions between them are crucial. That is where generative processes come in such as *self-organization* (Kauffman 1993) (that acts in all physical systems), and autopoiesis (Maturana & Varela 1980) (that *acts in living cells*).

Self-organization and autopoiesis is effectively described by agent-based models, such as actor model of computation (Hewitt 2012) that we adopt. Given that processes in the cell run in parallel, the current models of parallel computation (including Boolean networks, Petri nets, Interacting state machines, Process calculi etc.) need to adjust to modelling of biological systems (Fisher & Henzinger 2007).

Interesting framework for information processing in living systems is proposed by Deacon (2011) who distinguishes between the following three levels of natural information (for an agent):

- *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 levels of information organization parallel his three *formative mechanisms*: [Mass-energetic [Self-organization [Self-preservation (semiotic)]]] with corresponding *levels of emergent dynamics*: [Thermo- [Morpho- [Teleo-dynamics]]] and matching *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 presents a structure, while causality determines the dynamics of the structure (that we interpret as computation).

In sum, the basic claim of this article is that nature computes through information processes going on in networks of agents, hierarchically organized in layers. Informational structures *self-organize* through intrinsic processes of natural embodied computation, as presented in the Introduction to (Dodig-Crnkovic & Giovagnoli 2013).

The 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, namely computation defined as:

1. *Any transformation* of information and/or information representation. This leads to natural computationalism in its most general form.
2. *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. *Symbol manipulation*. This is Turing model of computation and its equivalents.

There are also *spatial levels or scales* of computations (Burgin & 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. *The molecular* level includes computations performed by molecules.
4. *The quantum* level includes computations performed by atoms and subatomic particles.

For more details see (Burgin & Dodig-Crnkovic 2013) which present the current state of the art on typologies of computation and computational models. By systematization of existing models and mechanisms, the article outlines a basic structural framework of computation.

Computation on Submolecular Levels

In Hewitt's model of computation, Actors are the universal primitives of concurrent distributed digital computation. In response to a message that it receives, an Actor can make local <decisions>, create more Actors, send more messages, and choose how to respond to the next message received.

> "In the Actor Model (Hewitt et al. 1973) (Hewitt 2010), computation is conceived as distributed in space, where computational devices communicate *asynchronously* and the entire computation is *not in any well-defined state*. (An Actor can have information about other Actors that it has received in a message about what it was like when the message was sent.) Turing's Model is a special case of the Actor Model." (Hewitt 2012)

The above Hewitt's "computational devices" are conceived as computational agents – informational structures capable of acting on their own behalf.

For Hewitt, Actors become Agents only when they are able to process expressions for commitments including *Contracts, Announcements, Beliefs, Goals, Intentions, Plans, Policies, Procedures, Requests* and *Queries.* In other words, Hewitt's Agents are human-like or if we broadly interpret the above capacities, life-like Actors. However, we take all Hewitt's Actors to be <agents> with different competences as we are interested in a common framework encompassing all living and artifactual agents.

The advantage of Hewitt's model is that unlike other models of computation that are based on mathematical logic, set theory, algebra, etc. the Actor model is based on physics, especially quantum physics and relativistic physics. (Hewitt 2012) Its relational nature makes it especially suitable for modeling informational structures and their dynamics.

Quantum-physical objects such as elementary particles of Standard Model, interacting through gauge bosons as force carriers (mediating the strong, weak, and electromagnetic interactions) can be modeled as actors exchanging messages. The <agency> in simplest physical systems such as elementary particles is exactly their physical capacity to act, to interact and to undergo changes.

Within the framework of info-computationalism, nature is informational structure – a succession of levels of organization of information for an agent. Of course, this reality is different for different agents. Physical reality, das Ding an sich exists as potential information that actualizes for an agent through interactions. This leads to understanding proposed by Von Baeyer in his book Information: The New Language of Science argues that (Baeyer von 2004) who states that "*information is going to replace matter as the primary stuff of the universe*, *providing a new basic framework for* describing and predicting reality".

Info-computational approach is supported by the current work in physicists on reformulating physics in terms of information, such as proposed by (Goyal 2012) in "Information Physics—Towards a New Conception of Physical Reality" and (Chiribella et al. 2012) in "Quantum Theory, Namely the Pure and Reversible Theory of Information". For the case of Statistical Thermodynamics based on information (or rather lack of information) instead of entropy, see (Ben-Naim 2008).

Very simple systems can act as <observers> as described in (Matsuno & Salthe 2011) who present possible approach to naturalizing contextual meaning in the case of chemical affinity as material agency.

However, if we want tools to manipulate physical systems, such as molecules in the case of studies of origins of life, our tools must be more than theoretical models – they will be *computations "in materio"* as Stepny (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'." That is the reason why physical/natural computing is so important.

Molecular Computation, Self-Organization and Morphogenesis

Both intrinsic or natural morphogenesis and designed/synthetic/artificial morphogenesis are instructive in the study of evolution and development as computational processes. At present, according to MacLennan "One of the biggest issues that embodied computation faces is the lack of a commonly accepted model of computation." (MacLennan 2010) As morphogenesis seems to have "the characteristics of a coordinated algorithm" it is of special interest to *understand communication patterns of actors in a network* that represents system with morphogenetic dynamics.

> "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." (MacLennan 2010)

In the development of an organism, based on the DNA code together with epigenetic control mechanisms, 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. The environment provides a physical source of biological body of an organism, as a source of energy and matter for its metabolism as well as information, which governs its behavior. Nervous system and the brain of an organism have evolved gradually through interactions (computational processes) of simpler living agents with the environment. This process is a result of information self-structuring (Dodig-Crnkovic 2008).

The environment provides an agent with 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 that organism makes of it*. As there is no information without representation, (Landauer 1991) (Allo 2008) 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. Some organisms use light signals 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. In that sense

> "(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)

According to (Maturana & 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*.

We describe cognition as information processing in living organisms, from cellular to organismic level and up to a social cognition. In this framework information is a substance, computation is a process and we argue for inseparability of structure/substance and its dynamics/process. If we search for the source of the energy necessary to build the constraints and turn environmental energy into the work needed by organisms to run their metabolism, Ulanowicz's process ecology model offers an explanation: "Basically the answer is simply that an aleatoric[9] 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)

(Bonsignorio 2013) studies evolutionary self-structuring of embodied cognitive networks and proposes a framework for the modeling of networks of self-organizing, embodied cognitive agents that can be used for the design of artificial and 'reverse engineering' of natural networks, based on the maximization of mutual information.

Biological systems are networks of interacting parts exchanging information. They are shaped by physical constraints, which also present information for a system, as argued in (Kauffman et al. 2008). A living agent is a special kind of <computational> actor that can reproduce and that is capable of undergoing at least one thermodynamic work cycle. (Kauffman 2000)

Kauffman's definition (that we adopt) differs from the common belief that (living) agency requires *beliefs* and *desires*, unless we ascribe some primitive form of <belief> and <desire> even to a very simple living agents such as bacteria. The fact is that they act on some kind of <memory> and <anticipation> and according to some <preferences> that might be automatic in a sense that they directly derive from the organisms' morphology. (Ben-Jacob 2009; Ben-Jacob 2008; Ben-Jacob et al. 2011) Nevertheless bacteria show clear preferences for behaviors that increase organism's survival.

Although the agents capacity to perform work cycles and so persist in the world is central and presents the material basis of life, as (Kauffman, 2000) and (Deacon, 2007) have argued, a detailed physical account of it remains to be worked out, especially relevant is the abiogenesis. Present article is primarily focused on the info-computational aspects of life as cognitive process with its basic elements information and computation on different levels of organization of living systems.

Self-organization and Autopoiesis

In order to understand cognition as a natural phenomenon, and reconstruct the origins, development and evolution of life, ideas of self-organisation and autopoiesis are central.

The concept of self-organisation was introduced in general systems theory in the 1960s, and during the 1970s and 1980s in complex systems. Prigogine (Prigogine & Stengers 1984) studied the self-organisation in thermodynamic systems far from equilibrium, which showed *an ability of non-living matter to self-organize when energy is provided from the environment* that is used for self-organization. This process of self-organization is what we will describe in subsequent chapters as a form of morphogenetic/ morphological computing.

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[9] Characterized by chance or indeterminate elements, Merriam-Webster online dictionary

Unlike Newtonian laws of motion, which describe *inert matter* that opposes any change of its state of motion, *self-organizing matter* is *active* and spontaneously changes. The ability of inanimate matter (chemicals) to self organize has been studied in detail by Kauffman (Kauffman 1995; Kauffman 1993). It has inspired research into the origins of life connecting the self-organisation of chemical molecules with the autopoiesis in living beings. Self-organization as fundamental natural process ongoing in all forms of physical systems provides mechanisms for autopoiesis characteristic for living organisms.

For our understanding of life as cognition, the work of Maturana and Varela on the understanding of basic processes and organization of life is fundamental. They define the process of autopoiesis of a living system as follows:

> An autopoietic machine is a machine organized (defined as a unity) as *a network of processes* of production (transformation and destruction) of 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 unity in space* in which they (the components) exist by specifying the topological domain of its realization as such a network. (Maturana & Varela 1980) p. 78 (emphasis added)

As argued in (Dodig-Crnkovic 2014) p. 7, biological systems change their structures and thereby the information processing patterns in a self-reflective, recursive manner through autopoietic processes with structural coupling (interactions with the environment) (Maturana & Varela 1992) (Maturana & Varela 1980). Yet, self-organisation with natural selection of organisms, as a basis for information that living systems build up in their genotypes and phenotypes, is a costly method of <learning> by adapting bodily structures. Higher organisms (which are "more expensive" to evolve) have evolutionary developed a capability of learning via nervous systems that enable flexible memory with capacity of reasoning as a more efficient way to accumulate knowledge about the world. The transition from "genetic learning" (typical of more primitive forms of life) to the cognitive skills on higher levels of organisation of the nervous system balances the high "production cost" for increasingly complex organisms.

Maturana and Varela argue that the autopoietic process of self-constitution of life is the most fundamental cognitive process.

> Living systems are cognitive systems, and *living as a process is a process of cognition*. This statement is valid for all organisms, with or without a nervous system." (Maturana & Varela 1980) p. 13, emphasis added.

In the info-computational formulation, the process of "life as cognition" (Maturana 2002; Maturana & Varela 1992; Maturana & Varela 1980; Maturana 1970) corresponds to information processing in the hierarchy of levels of organisation, from molecular networks, to cells and their organizations, to organisms and their networks/societies (Dodig-Crnkovic 2008).

Thus the fundamental level proto-information (potential information) corresponds to the physical structure, the fabric of reality for an agent, while cognition is a process that unfolds in real time as information self-structuring driven by interactions (morphological computing). It develops on a long-time scale (meta-morphogenesis) as a product of evolution in complex biological systems, as argued in (Sloman 2013b) (Dodig-Crnkovic & Hofkirchner 2011).

In short, the information-processing model of organisms incorporates basic ideas of self-organization and autopoiesis, from the sub-cellular to the multi-cellular, organismic and societal levels. Being cognitive, life processes present different sorts of morphological computing which on evolutionary time scales affect the organisation (structures) of living beings even in a sense of meta-morphogenesis (i.e. morphogenesis of morphogenesis), (Sloman 2013a).

Morphological Computing in Component Systems -"Computing in Materio"

Living organisms are described by Kampis as self-modifying systems that must be modeled as self-referential, self-organizing "component-systems" (Kampis 1991) which are self-generating and self-sustaining (autopoietic) and whose behavior, though computational in a general sense, is more general than Turing machine model.

> "a component system is a computer which, when executing its operations (software) builds a new hardware.... [W]e have a computer that re-wires itself in a hardware-software interplay: the hardware defines the software and the software defines new hardware. Then the circle starts again." (Kampis 1991) p. 223

Living systems are modular and organized in a hierarchy of levels that can be understood as a result of propagation of information (Kauffman et al. 2008). A detailed account of the present state of the art of hierarchy of levels/layers can be found in (Salthe 2012a)(Salthe 2012b). Within info-computational framework, levels are informational structure with specific computational modes (intrinsic computation).

An example of a simple biological (component) system, studied in terms of information and computation is given in (Xavier et al. 2011) in the following way:

> "Thus, each bacterium must be able to sense and communicate with other units in the colony to perform its task in a coordinated manner. The cooperative activities carried out by members of the colony generate a social intelligence, which allows the colony to learn from their environment. In other words, bacterial intelligence depends on the interpretation of chemical messages and distinction between internal and external information. Then a colony can be viewed as a system that analyzes contextual information from its environment, generates new information and retrieves information from the past."

This agrees with the results of Ben-Jacob (Ben-Jacob 2009; Ben-Jacob 2008; Ben-Jacob et al. 2011). Talking about grand challenges in the research of natural computing (Nunes de Castro et al. 2011) and (Maldonado & Gómez Cruz n.d.) identify the central aim of this field to unveil and harness the above information processes as natural computation.

Cognition as Cellular Morphological Computation

The origin of <cognition> in first living agents is not well researched, as the idea still prevails that only humans possess cognition and knowledge. However, as we have seen in the previous sections, there are different types of <cognition> and we have good reasons to ascribe simpler kinds of <cognition> to other living beings. Bacteria *"sense the environment and perform internal information processing (according to the internally stored information) to extract latent information embedded in the complexity of their environment. The latent information is then converted into usable or "active" information that affects the bacterium activity as well as intracellular changes."* (Ben-Jacob 2009) Plants as well can be said to possess memory (in their bodily structures) and ability to learn (adapt, change their morphology) and can be argued to possess simple forms of cognition. (Pombo, O., Torres J.M., Symons J. 2012)

As already mentioned, autopoiesis (Maturana & Varela 1980) is considered to be the most fundamental level of cognition that is present even in the simplest living organisms. Through evolution, increasingly complex organisms have developed that are able to survive and adapt to their environment. Organisms are able to register inputs (data) from the environment, to structure those into information, and to structure information into knowledge. The evolutionary advantage of using structured, component-based approaches such as data – information – knowledge is based on improved response-time and efficiency of cognitive processes of an organism (Dodig-Crnkovic 2008).

All cognition is embodied – 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 agents own 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 (as the succession data → information → knowledge → data etc.) by an interactive natural computational process going on in an agent during the adaptive interplay with the environment. Not all information potentially available is part of cognitive process of an agent. For fungi, written content of a book presents no information, but they may use a book as a source of energy (food), that is a basis of information-dynamics for their own bodily structures. Similarly, sunlight triggers just energy production by photosynthesis in plants while in a human it can trigger the reflection about the nuclear fusion in the sun.

There is a continuum of morphological development from simplest living organism's automaton-like structures to most complex life forms elaborate interplay between body, nervous system with 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. From bacteria, that organize in colonies and swarms via more complex multi-cellular organisms and finally humans, cells as the basic cognitive units present the basis for a distributed process of cognition that in vertebrates is dominated (but not exclusively performed) by the nervous system.

Summary and Conclusions

To conclude, let me sum up the main points. Firstly, it is important to emphasize that info-computational approach relies on *naturalist methods and scientific results* and even though it assigns <cognitive> capabilities to all living beings, those capacities correspond to empirically established behaviors of biological systems (Ben-Jacob 2008). Thus, it has no connection to *panpsychism,* that is the view that mind or soul fills everything that exists. Info-computationalism is strictly naturalistic understanding based on physics, chemistry and biology and does not make any assumptions about things like a "mind of an electron". Exactly the opposite, it aims at explaining cognition, and subsequently mind, through entirely natural processes going on in physical/chemical/biological systems of sufficient complexity.

In general, *naturalization* is the ideal of this project: naturalization of information, computation, cognition, agency, intelligence, etc.

Shortly, within the info-computational framework we start with the following basics elements:

<Information> is a structure consisting of differences in one system that cause the difference in another system. In other words, <information> is < observer>-relative. This definition is a synthesis of Bateson and Hewitt definitions.

<Computation> is <information> processing (dynamics of <information>).

Both <information> and <computation> appear on different levels of organization/ or abstraction/resolution/granularity of matter/energy in space/time.

Of all <agents>, i.e. entities capable of acting on their own behalf, only living <agents> are characterized by the ability to actively make choices to increase the probability of their own continuing existence. This ability to persist as highly complex organization and to act autonomously is based on the use of energy from the environment, as argued by Kauffman and Deacon.

<Cognition> is living <agency> consisting of all processes that assure living agent's organizational integrity and continuing activity, and it is equivalent with life.

The dynamics of informational structure leading to new informational structures via processes of self-organization of information can be described as *morphological computing*. Consequently, corresponding to distinct *layers of structural organization* found in nature (elementary particles, atoms, molecules, cells, organisms, societies, etc.) there are distinct *computational processes of self-organization of information* that implement/realize physical laws. This self-organization is the result of the interactions between different agents/actors as nodes in interaction networks on many levels of organization. In this model each type of actors (in themselves informational structures) exchange messages of the form specific for their level of organization.

Finally, as Denning (2007) noticed, *computing is nowadays a natural science*, and it assimilates knowledge from and facilitates development of natural sciences – from physics and chemistry to biology, cognitive science and neuroscience. The info-computational approach can contribute to rethinking cognition as a self-organising bio-chemical process of life, emerging from inorganic matter and evolving spontaneously through information self-structuring (morphological computation). Thus we can start to learn how to adequately model living systems, which until now have been impossible to effectively frame theoretically, simulate and study in their full complexity. (Dodig-Crnkovic & Müller 2011)

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