Reality Construction Through Info-Computation

Gordana Dodig-Crnkovic [1]

Abstract. Some intriguing questions such as: *What is reality for an agent? How does reality of a bacterium differ from a reality of a human brain? Do we need representation in order to understand reality?* are still widely debated. Starting with the presentation of the computing nature as an info-computational framework, where information is defined as a structure, and computation as information processing, I will address questions of evolution of increasingly complex living agents through interactions with the environment. In this context, the concept of computation will be discussed and the sense in which computation is observer-relative. Using the results on morphological/morphogenetic computation as information self-organization I argue that reality for an agent is a result of networked agent-based computation. Consciousness is a (computational) process of information integration that evolved in organisms with nervous system. I present an argument why pancomputationalism (computing nature) is a sound scientific strategy and why panpsychism is not.

1 INTRODUCTION: WHAT IS REALITY (FOR AN AGENT)?

This paper addresses the question of reality for different classes of cognitive agents. When discussing cognition as a bioinformatic process of special interest, we use the notion of *agent*, i.e. a *system able to act on its own behalf* [1]. Agency in biological systems has been explored in [2][3]. The world as it appears to an agent depends on the type of interaction through which the agent acquires information [1].

Agents communicate by exchanging messages (information) that help them coordinate their actions based on the (partial) information they possess and share as a part of social cognition.

It starts from the definition of *agency and cognition as a property of all living organisms*. The subsequent question will be how artifactual agents should be built in order to possess different degrees of cognition and eventually even consciousness. Is it possible at all, given that cognition in living organisms is a deeply biologically rooted process? Recent advances in natural language processing, present examples of developments towards machines capable of both "understanding natural language" and "speaking" in a human way. Along with reasoning, language is considered high-level cognitive activity that only humans are capable of. Increasing levels of cognition developed in living organisms evolutionary, starting from basic automatic behaviours such as found in bacteria and even insects (even though they have nervous system and brain, they lack the limbic system that controls our emotional response to physical stimuli, suggesting they don't process physical stimuli emotionally) to increasingly complex behaviour in higher organisms such as mammals. Can AI "jump over" evolutionary steps in the development of cognition?

The framework for the discussion in this article is the *computing nature* in the form of *info-computationalism*. It takes *reality* to be *information* for an agent with a *dynamics* of information understood as *computation*. Information is a *structure* and computation its *dynamics*. Information is observer relative and so is computation. [1][4][5]

Cognition is studied as information processing in such simple organisms as bacteria [6], [7] as well as cognitive processes in other, more complex multicellular life forms. We discuss computational mind and consciousness that have recently been widely debated in the work of Giulio Tononi [8] and Christoph Koch. [9] While the idea that cognition is a biological process in all living organisms, as argued by Humberto Maturana and Francisco Varela [10], [11], it is not at all clear that all cognitive processes in different kinds of organisms are accompanied by anything akin to (human) consciousness. The suggestion is made that cognitive agents with nervous systems are the step in evolution that first enabled consciousness of the kind that humans possess. Argument is advanced that ascribing consciousness to the whole of the universe is not justified.

So defining reality as information leaves us with the question: what is it in the world that corresponds to information and its dynamics, computation? How do we model information/ computation? Answers are many and they are not unambiguous.

We can compare the present situation with the history of the development of other basic scientific concepts. Ideas about matter, energy, space and time in physics have their history. The same is true of the idea of number in mathematics or the idea of life in biology. So, we should not be surprised to notice the development in the theory of computation that goes along with the development of information science, robotics, cognitive science, computability, new computational devices and new domains of the real world that can be understood info-computationally.

2 THE COMPUTING NATURE. COMPUTATIONAL NATURALISM AND MINIMAL COGNITION

For Naturalism, *nature is the only reality*, in other words: no miracles, [12] p. 73. It describes nature through its structures, processes and relationships using a scientific approach. Naturalism studies the evolution of the entire natural world, including the life and development of humanity as a part of nature. Social and cultural phenomena are studied in its physical manifestations. An example of currently very active naturalist

[1] School of Innovation, Design and Engineering, Mälardalen University, Sweden. Email: `gordana.dodig-crnkovic@mdh.se`

research field is social cognition with its network-based studies of social behaviors.

Computational naturalism (pancomputationalism, naturalist computationalism, computing nature) is the view that the entire nature is a huge network of computational processes, which, according to physical laws, computes (dynamically develops) its own next state from the current one. Representatives of this approach are Zuse, Fredkin, Wolfram, Chaitin and Lloyd, who proposed different varieties of computational naturalism. According to the idea of computing nature, one can view the time development (dynamics) of physical states in nature as information processing (natural computation). Such processes include self-assembly, self-organization, developmental processes, gene regulation networks, gene assembly, protein-protein interaction networks, biological transport networks, social computing, evolution and similar processes of morphogenesis (creation of form). The idea of computing nature and the relationships between two basic concepts of information and computation are explored in detail in [1][4][5].

In the computing nature, cognition is studied as a natural process. If cognition is seen as a result of natural bio-chemical processes, the important question is *what is the minimal cognition*? Recently, empirical studies have revealed an unexpected richness of cognitive behaviors (perception, information processing, memory, decision making) in organisms as simple as bacteria. [6], [7][13] Single bacteria are too small to be able to sense anything but their immediate environment, and they live too briefly to be able to memorize a significant amount of data. On the other hand bacterial colonies, swarms and films exhibit an unanticipated complexity of behaviors that can undoubtedly be characterized as cognition.

Apart from bacteria and similar organisms without nervous system (such as e.g. slime mold, multinucleate or multicellular Amoebozoa, which recently has been used to compute shortest paths), even plants are typically thought of as living systems without cognitive capacities. However, plants too have been found to possess memory (in their bodily structures that change as a result of past events), the ability to learn (plasticity, ability to adapt through morphodynamics), and the capacity to anticipate and direct their behavior accordingly. Plants are argued to possess rudimentary forms of knowledge, according to [14] p. 121, [15] p. 7 and [16] p. 61.

In this article we take primitive cognition to be the totality of processes of self-generation, self-regulation and self-maintenance that enables organisms to survive using information from the environment. The understanding of cognition as it appears in degrees of complexity in living nature can help us better understand the step between inanimate and animate matter from the first autocatalytic chemical reactions to the first autopoietic proto-cells.

3 INFORMATIONAL STRUCTURE OF REALITY FOR A COGNITIVE AGENT

Talking about computing nature, we can ask: what is the hardware for this computation? The surprising answer is: the hardware on one level of organization of information is the software of the next level in the sense of Georg Kampis' self-modifying systems [17]. And on the basic level, the "hardware" is potential information, the structure of the world that one usually describes as matter-energy. [18] As cognizing agents interacting with nature through information exchange, we experience the world cognitively as information. *Informational structural realism* of Luciano Floridi [19] and Kennet Sayre [20] is a framework that takes information as the *fabric of the universe* (for an agent). Even the physicists Zeilinger [21] and Vedral [22] suggest that *information and reality are one* epistemologically. For a cognizing agent in the informational universe, the dynamical changes of its structures make it a huge computational network [1]. The substrate, the "hardware", is information that defines data-structures on which computation proceeds.

Info-computationalism is a synthesis of informational structural realism and natural computationalism (pancomputationalism, computing nature) - the view that the universe computes its own next state from the previous one[23]. It builds on two basic complementary concepts: information (structure) and computation (the dynamics of informational structure) as described in [24].

The physical world for a cognizing agent exists as *potential information*, corresponding to Kant's das Ding an sich. Through interactions, this potential information becomes actual information, "a difference that makes a difference" [25]. Shannon describes the process as the conversion of *latent information* into *manifest information* [26]. Even though Bateson's definition of information as a difference that makes a difference (for an agent) is a widely cited one, there is a more general definition that includes the fact that information is *relational* and subsumes Bateson's definition:

"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." [27] *p. 293*

Combining the Bateson and Hewitt insights, at the basic level, *information is a difference in one physical system that makes a difference in another physical system.*

4 COMPUTATION IN NETWORKS OF AGENTS

Informational structures constituting the fabric of physical nature for an agent can be seen as networks of networks, which represent semantic relations between data. [4] Information is organized in layers, from quantum level to atomic, molecular, and so on. Computation in general can be understood as information processing, or more specifically as data structure exchanges within informational networks, represented by Carl Hewitt's actor model [28]. Different types of computation emerge at different levels of organization in nature. [1]

According to the Handbook of Natural Computing [29], natural computing is "the field of research that investigates both human-designed computing inspired by nature and computing taking place in nature." It includes among others areas of cellular automata and neural computation, evolutionary computation, molecular computation, quantum computation, nature-inspired algorithms and alternative models of computation.

An important characteristic of the research in natural computing is that knowledge is generated bi-directionally, through the interaction between computer science and natural sciences. While natural sciences are adopting tools, methodologies and ideas of information processing, computer science is broadening the notion of computation, recognizing information processing found in nature as computation. [30][29] Based on that, Denning argues that computing today is a natural science. [31] Computation found in nature is understood as a physical process, where nature computes with physical bodies as objects. Physical laws govern processes of computation, which necessarily appears on many different levels of organization of physical systems.

With its layered computational architecture, natural computation provides a basis for a unified understanding of phenomena of embodied cognition, intelligence and knowledge generation. [32][33] Natural computation can be modelled as a *process of exchange of information in a network of informational agents* [28]. As mentioned before, an agent is defined as an entity capable of acting on its own behalf.

One sort of computation is found on the quantum-mechanical level where agents are elementary particles, and messages (information carriers) are exchanged by force carriers, while different types of computation can be found on other levels of organization. In biology, information processing is going on in cells, tissues, organs, organisms and eco-systems, with corresponding agents and message types. In biological computing or social computing the message carriers are complex chunks of information such as molecules, or sentences and the computational nodes (agents) can be molecules, cells, organisms or groups/societies. [5]

5 INFO-COMPUTATIONALISM. MORPHOLOGICAL/ MORPHOGENETIC COMPUTING

As a result of a synthesis of the *informational structural realism* [19][20] (the view of nature as a complex informational structure for a cognizing agent) with the idea of *computing nature (pancomputationalism,* or *natural computationalism)* [4] [23][34][35], *info-computationalism* is construed [32].

The notion of computation in this framework refers to the most general concept of *intrinsic computation* that is a spontaneous computation processes in computing nature, and which is used as a basis of specific kinds of *designed computation* found in computing machinery [36]. Intrinsic (natural) computation includes quantum computation [36][37], processes of self-organization, self-assembly, developmental processes, gene regulation networks, gene assembly, protein-protein interaction networks, biological transport networks, and similar. It is both analog (such as found in dynamic systems) and digital. The majority of info-computational processes are sub-symbolic and some of them are symbolic (like languages).

Within info-computational framework, computation on a given level of organization of information presents a realization/actualization of the laws that govern interactions between constituent parts. On the basic level, computation is manifestation of causation in the physical substrate. In every next layer of organization a set of rules governing the system switch to the new emergent regime. It remains yet to be established how this process exactly goes on in nature, and how emergent properties occur. Research in natural computing is expected to uncover those mechanisms.

In words of Rozenberg and Kari: "(O)ur task is nothing less than to discover a new, broader, notion of computation, and to understand the world around us *in terms of information processing*." [30] From the research in complex dynamical systems, biology, neuroscience, cognitive science, networks, concurrency and more, new insights essential for the info-computational universe may be expected in the years to come.

Back in 1952 Turing wrote a paper that may be considered as a predecessor of natural computing. It addressed the process of morphogenesis proposing a chemical model as the explanation of the development of biological patterns such as the spots and stripes on animal skin. [38] Turing did not claim that physical system producing patterns actually performed computation. Nevertheless, from the perspective of computing nature we can argue that morphogenesis is a process of morphological computing. Physical process – though not computational in the traditional sense, presents natural morphological computation. Essential element in this process is the interplay between the informational structure and the computational process - information self-structuring and information integration, both synchronic and diachronic, going on in different time and space scales in physical bodies. Informational structure presents a program that governs computational process [17] which in its turn changes that original informational structure obeying/ implementing/ realizing physical laws.

Morphology is the central idea in understanding of the connection between computation (morphological/ morphogenetic) and information. What is observed as material on one level of analysis represents morphology on the lower level, recursively. So water as material presents arrangements of [molecular [atomic [elementary particle []]]] structures.

Info-computationalism describes nature as informational structure – a succession of levels of organization of (natural) information. Morphological/morphogenetic computing on that informational structure leads to new informational structures via processes of self-organization of information. Evolution itself is a process of morphological computation on a long-term scale. It is also possible to study morphogenesis of morphogenesis (Meta-morphogenesis) as done by Aaron Sloman in [39].

Leslie Valiant [40] studies evolution by ecorithms – learning algorithms that perform probably approximately correct PAC computation. Unlike present paradigm of computing, the results are not perfect but just good enough.

Intrinsic/natural/ physical computation can be used for physical computing which, broadly construed, means building interactive physical systems by the use of software and hardware consisting of interactive system connected with the real world via sensors and actuators.

6 GENERATION OF REALITY FROM RAW DATA

Cognition can be seen as a result of processes of morphological computation on informational structures of a cognitive agent in the interaction with the physical world, with processes going on at both sub-symbolic and symbolic levels. This morphological computation establishes connections between an agent's body, its nervous (control) system and its environment. Through the embodied interaction with the informational structures of the environment, via sensory-motor coordination, information structures are induced in the sensory data of a cognitive agent, thus establishing perception, categorization and learning. Those processes result in constant updates of memory and other structures that support behaviour, particularly *anticipation*. *Embodied* and corresponding *induced* in the Sloman's sense of virtual machine) informational structures are the basis of all cognitive activities, including consciousness and language as a means of maintenance of "reality".

Essential element in this process is the interplay between the informational structures and the computational processes - *information self-structuring* and *information integration*, both synchronic and diachronic, going on in different time and space scales. [4]

From the simplest cognizing agents such as bacteria to the complex biological organisms with nervous systems and brains, the basic informational structures undergo transformations through morphological computation (developmental and evolutionary form generation).

Here an explanation is in order regarding *cognition that is defined in general way of Maturana and Varela who take it to be synonymous with life*. [10], [41] All living organisms possess some degree of cognition and for the simplest ones like bacteria cognition consists in metabolism and (my addition) locomotion. [1] This "degree" is not meant as continuous function but as a qualitative characterisation that cognitive capacities increase from simplest to the most complex organisms. The process of interaction with the environment causes changes in the informational structures that correspond to the body of an agent and its control mechanisms, which define its future interactions with the world and its inner information processing. Informational structures of an agent become semantic information first in the case of highly intelligent agents.

7 INFO-COMPUTATION, AGENCY AND MATTER-ENERGY

Even though we are far from having a consensus on the concept of information, the most general view is that information is a *structure consisting of data*. Floridi [19] has the following definition of datum: "In its simplest form, a datum can be reduced to just a lack of uniformity, that is, a binary difference." Bateson's "the difference that makes the difference" [25] is a datum in that sense. Information is both the result of observed differences (differentiation of data) and the result of synthesis of those data into a common informational structure (integration of data), as argued by Schroeder in [42] In the process of knowledge generation an intelligent agent moves between those two processes – *differentiation* and *integration* of data, see [43] p. 38. It is central to keep in mind that for something to be actual information *there must exist an agent* from which perspective this structure is established. Thus information is a network of data points related from an agent's perspective.

There is a distinction between the world as it exists autonomously, independent of any agent, Kantian "Ding an sich", (thing in itself, noumenon) and the world for an agent, things as they appear through interactions (phenomena).

Informational realists (like Floridi, Sayre, Zeilinger, Vedral) [19][20][21][22] take the reality/world/universe to be information. In [5] I added by analogy "information an sich" representative of the "Ding an sich" as *potential information*. When does this potential information become *actual* information for an agent?

The world in itself is (proto)information that gets actualized through interactions with agents. Huge parts of the universe are potential information for different kinds of agents – from elementary particles, to molecules, etc. all the way up to humans and societies.

Living organisms as complex agents inherit bodily structures as a result of a long evolutionary development of species. Those structures are embodied memory of the evolutionary past. They present the means for agents to interact with the world, get new information that induces memories, learn new patterns of behaviour and construct knowledge. World via Hebbian learning forms a human's (or an animal's) informational structures. As an example neural networks that "self-organize stable pattern recognition codes in real-time in response to arbitrary sequences of input patterns" can be used [44].

If we say that for something to be information there must exist an agent from whose perspective this structure is established, and we argue that the fabric of the world is informational, the question can be asked: *who/what is the agent*? An agent (an entity capable of acting on its own behalf) can be seen as interacting with the points of inhomogeneity (data), establishing the connections between those data and the data that constitute the agent itself (a particle, a system). There are myriads of agents for which information of the world makes differences – from elementary particles to molecules, cells, organisms, societies… - all of them interact and exchange information on different levels of scale and this information dynamics is natural computation.

On the fundamental level of quantum mechanical substrate, information processes represent laws of physics. Physicists are already working on reformulating physics in terms of information. This development can be related to the Wheeler's idea "it from bit". [45] For more details on current research, see the special issue of the journal Information dedicated to matter/energy and information [18], and a special issue of the journal Entropy addressing natural/unconventional computing [46] that explores the space of natural computation and relationships between the physical (matter/energy), information and computation.

When it comes to agents, our habitual way of understanding is in terms of energy and work. [47][3]

All living beings possess cognition (understood as all processes necessary for an organism to survive, both as an individual and as a part of a social group – social cognition), in different forms and degrees, from bacteria to humans. Cognition is based on agency; it would not exist without agency. The building block of life, the living cell, is a network of networks of processes and those processes may be understood as computation. Of course it is not any computation whatsoever, but exactly that biological process itself, understood as information processing.

Now one might ask what would be the point in seeing metabolic processes or growth (morphogenesis) as computation? The answer is that we try to connect cell processes to the conceptual apparatus of concurrent computational models and information exchange that has been developed within the field of computation and not within biology – we talk about "executable cell biology". [48] Info-computational approach gives something substantial that no other approach gives, and that is the *possibility of studying real-time dynamics of a system*.

Processes of life and thus mind are *critically time-dependent*.

Concurrent computational models are the field that can help us understand real-time interactive concurrent networked behaviour in complex systems of biology and its physical structures (morphology).

That is the pragmatic reason why it is well justified to use conceptual and practical tools of info-computation in order to study living being. Of course, in nature there are no labels saying: this process is computation. We can see as computation, conceptualize in terms of computation, model as computation and *call computation any process in the physical world*. Doing so we expand our understanding of *natural processes* (physical, chemical, biological and cognitive) and computation.

8 COMPUTATIONAL MIND. COMPUTATION ALL THE WAY DOWN TO QUANTUM

In his new book, *Explaining the Computational Mind* [49] Marcin Miłkowski portrays current state of the ideas about computational mind. The author presents and systematically dissects number of misconceptions about what is computation, clearly placing both neural networks and dynamical systems into the domain of computational. This is something that some philosophers would deny, while practitioners would agree with. [36] Miłkowski also proposes his own view of computational models in the following:

"(O)n my mechanistic account, only one level of the mechanism – the so-called isolated level – is explained in computational terms. The rest of the mechanism is not computational, and, indeed, according to the norms of this kind of explanation, it cannot be computational through and through."

In this article I argue that this one-level-approach is not adequate for natural (intrinsic) computation which appear in hierarchy of levels. The reason why Miłkowski tries to avoid multiplicity of computational levels is a fear of computationalism being trivial:

"Obviously, pancomputationalists, who claim that all physical reality is computational, would immediately deny the latter claim. However, the bottoming-out principle of mechanistic explanation does not render pancomputationalism false a priori. It simply says that a phenomenon has to be explained as constituted by some other phenomenon than itself. For a pancomputationalist, this means that there must be a distinction between lower-level, or basic, computations and the higher level ones. Should pancomputationalism be unable to mark this distinction, it will be explanatorily vacuous." [50]

Miłkowski's proposal is that "the physical implementation of a computational system – and its interaction with the environment – lies outside the scope of computational explanation".

From the above I infer that the model of computation, which Miłkowski assumes in his book, is a top-down, designed computation. Even though he rightly argues that neural networks are computational models and even dynamical systems can be understood as computational, Miłkowski does not think of intrinsic computation as grounded in physical process driven by causal mechanism, characteristics of computing nature.

The fundamental question that worries Miłkowski is the grounding problem that can lead to the conclusion about triviality. I will argue that this really is a non-problem.

To start with, grounding is always anchored in an agent who is the narrator of the explanation. The narrator choses the granularity of the account. No picture has infinite granularity and nothing hinders to imagine even lower levels of existence (such as more and more elementary particles). This means that grounding is done over and over again in all sciences.

When constructing computational models, Miłkowski's focus on only one layer is pragmatically justified, but not a matter of principle. Even though one can reconstruct many intrinsic computational layers in the human brain (depending on the granularity of the account), for an observer/narrator often one layer is in focus at a time. In such simplified models the layers above and below, even though computational, are sketchy and used to represent constraints and not mechanisms. That is at least the case in designed computation as found in conventional computers. But e.g. looking at the experimental work of Subrata Ghosh et al. building a functional model of brain, we find twelve-layer computational architecture applied. [51]

"Computational descriptions of physical systems need not be vacuous. We have seen that there is a well-motivated formalism, that of combinatorial state automata, and an associated account of implementation, such that the automata in question are implemented approximately when we would expect them to be: when the causal organization of a physical system mirrors the formal organization of an automaton. In this way, we establish a bridge between the formal automata of computation theory and the physical systems of everyday life. We also open the way to a computational foundation for the theory of mind." David Chalmers [52]

Causation is transfer of information [53] and computation is causation at work. What are the implications of the above view for the AI? Miłkowski mentions that currently, computers are beating humans in chess and Jeopardy, they are capable of theorem proving, speech recognition and generation, natural language translation etc. [49]

"However, AI systems are capable of all this and more, so we ought to be more careful: if there is no mathematical proof that something cannot be done, any verdicts are mere speculation." p. 204.

Regarding mathematical proof, it is not that simple. Mathematics is an intelligent adaptive system that develops continuously. If we lack mathematical tools within present state mathematics, we can construct them in the next step.

Possibility of human level AI will most likely be demonstrated constructively – by development of human level artifactual intelligent devices and not via mathematical proof that such devices are possible. That conclusion is based on the observation that human learning is an open-ended inductive and abductive process.

What is at stake in a theory of implementation? The problem seems to me exactly the opposite. It is not so instructive to study how brain implements computation (how do we know 1+1=2 top-down) but how intrinsic information processing, that is evidently going on in the brain can be interpreted as computation. What are the characteristics of that new kind of computation that information processes in the brain constitute?

In that sense *of bottom-up intrinsic computation* Chalmers characterization holds, [54] p. 326:

"A physical system implements a given computation when the causal structure of the physical system mirrors the formal structure of the computation."

This position is called the Standard Position (SP) by Sprevak. [55] p. 112. It is applicable to intrinsic computation (bottom up, natural/intrinsic), but not to designed conventional computation (top-down) as this "mirroring" would be a very complex process of interpretation, coding, decoding and interpretation again.

Thus, not only neurons and whole brains compute (in the framework of computing nature) but also the rest of nature computes at variety of levels of organization.

"As to information, there is also a precise and powerful mathematical theory that defines information as the reduction of uncertainty about the state of a system. The same theory can be used to quantify the amount of information that can be transmitted over a communication channel. Again, the mathematical theory of information does not tell us whether and how the brain processes information, and in what sense. So establishing the foundations of computational neuroscience requires more work." [56]

9 COMPUTATIONAL MODELS OF MIND EXCULPATED

Historically, computationalism as a theory of mind has been accused of many sins. In what follows I would like to answer three Sprevak's [55] p. 108 concerns about computationalism:

(R1) Clarity: "Ultimately, the foundations of our sciences should be clear." *Computationalism is suspected to lack clarity*.

(R2) Response to triviality arguments: "(O)ur conventional understanding of the notion of computational implementation is threatened by triviality arguments." *Computationalism is accused of triviality*.

Searle's [57] informal triviality argument ("that a brick wall contains some pattern of physical transitions with the same structure as Microsoft Word") and Putnam's triviality argument ("The physical transitions in the rock mirror the formal transitions: A → B → A → B. Therefore, according to SP, the rock implements FSA M.")

(R3) Naturalistic foundations: "The ultimate aim of cognitive science is to offer, not just any explanation of mental phenomena, but a naturalistic explanation of the mind." *Computationalism is questioned for being formal and unnatural.*

Sprevak concludes that meeting all three above expectations of computational implementation is hard, and that "Chalmers' account provides the best attempt to do so, but even his proposal falls short." Chalmers account, I will argue should be seen from the perspective of intrinsic, natural computation.

Let me summarize the distinction between intrinsic /natural/ spontaneous computation and designed computation used in our technological devices.

In the info-computationalism, that is a variety of pancomputationalism, physical nature spontaneously performs different kinds of computations (information dynamics) at different levels of organization. This is intrinsic, natural computation and is specific for a given physical system. Intrinsic computation(s) of a physical system can be used for designed computation, such as one found in computational machinery, but it is far from all computation that can be found in nature.

Why is natural computationalism not vacuous? For the same reason that physics is not vacuous which makes the claim that the entire physical universe is material. Now we will not enter the topic of ordinary matter-energy vs. dark matter-energy. Those are all considered to be the same kind of phenomena – natural phenomena that must be studied with methods of physics.

If we would apply the same logic as critics of natural computationalism, we would demand from physicists to explain where matter comes from. Where does elementary particle come from? They are simply empirical facts, for which we have enough evidence to believe that they exist. We might not know all of their properties and relationships, we might not know all of them, but we can be pretty sure that they exist.

When physical entities exist in nature, unobserved, they are part of Ding an sich. How do we know that they exist? We find out through interactions. What are interactions? They are information exchanges. Epistemologically, constraints or boundary conditions are also information for a system.

So the bottom layer for computational universe is the bottom layer of its material substrate and it is not different from the question of physical models and the status of matter-energy in the physical world. They are considered empirically justified.

10 WHY PANCOMPUTATIONALISM IS USEFUL AND PANPSYCHISM IS NOT

Some computational models of consciousness [8], [58], [59], [9] seem to lead to *panpsychism* - a phenomenon defined as follows:

"Panpsychism is the doctrine that mind is a fundamental feature of the world which exists throughout the universe." [60]

Pancomputationalism (natural computationalism, computing nature) is the doctrine that whole of the universe, every physical system, computes. In the words of [61]:

"Which physical systems perform computations? According to pancomputationalism, they all do. Even rocks, hurricanes, and planetary systems — contrary to appearances — are computing systems. Pancomputationalism is quite popular among some philosophers and physicists."

Info-computationalism starts bottom-up, from natural processes understood as computation. It means that computation appears as quantum, chemical, biological, …etc. Only those transformations of informational structure that correspond to intrinsic processes in natural systems qualify as computation. 'Studying biological systems at different levels of organization as layered computational architectures give us powerful conceptual and technological tools for studying of real world systems. Even though we can fancy any sort of imaginary mappings those will not work on the hardware of the universe. We can simulate virtual worlds, but computation behind this visualisation relies on physical substrate with causal processes.

Given the argument for info-computational modelling of nature, and the argument that every living organism possess some extent of cognition one can ask: why should we not do similar move and ascribe consciousness to the whole of the universe (hypothesis called panpsychism)? Searle describes consciousness as follows:

"Consciousness consists of states of awareness or sentience or feeling. These typically begin in the morning when you wake up from a dreamless sleep and go on all day until you go to sleep or otherwise become 'unconscious.' " [62]

The simple answer why panpsychism is not a good idea is: in the case of panpsychism we have no good model. Unlike *computational models* of physical processes we have no good *psychical models*. In fact only naturalists accounts of consciousness provide models, others prefer to see consciousness as totally inexplicable in rational terms, a "mystery". From the naturalist, knowledge generation point of view, trying to understand everything as psyche got it backwards – we do not know what to do after the very first move, other than to say that it is "mysterious".

On the contrary, if we try to understand psyche or better to say mind and consciousness as manifestations of physical info-computational processes in the nervous system of a cognizing agent, we immediately have an arsenal of modelling tools to address the problem with and successively and systematically learn more about it, even construct artefacts (such as cognitive robots) and test it.

That is the main reason why *panpsychism is not a good scientific hypothesis*. Instead of opening all doors for investigation, it declares consciousness permeating the entire universe and that's it. One can always generalize concepts if they lead to better understanding and enable further modelling. But generalizations of the idea of psyche is akin to homeopathic procedure diluting it to concentrations close to zero, and that will not give us anything in terms of understanding of mechanisms of mind.

Moreover, as a theory panpsychism belongs to medieval tradition – that which is to be explained is postulated. I wonder how would anyone ever get unconscious in a conscious universe? What would be the difference between human consciousness and the "consciousness" of a bacterium or even a consciousness of vacuum?

Up to now I explicated my info-computationalist position relative to natural computationalism, pancomputationalism, computing nature and computationalism (with respect to human mind, as presented by Miłkowski) as well as why I do not see panpsychism as a fruitful approach and coherent theoretical construal.

11 CONCLUSIONS AND FUTURE WORK

Questions that we posed in the beginning of the article: *What is reality for an agent? How does reality of a bacterium differ from a reality of a human brain? Do we need representation in order to understand reality?* led us to the discussion of info-computational models of cognition and consciousness. When talking about models of cognition, the very mention of "computationalism" typically evokes reactions against Turing machine model of the brain and perceived determinism of computation. Neither of those two problems affects natural computation or computing nature where model of computation is broader than deterministic symbol manipulation. Computing nature consists of physical structures that form levels of organization, on which computation processes differ. It has been argued that on the lower levels of organization finite automata or Turing machines might be adequate, while on the level of the whole-brain non-Turing computation is necessary, according to Andre Ehresmann [63] and Subrata Ghosh et al. [51]

Within info-computational framework, cognition is understood as synonymous with process of life. Following Maturana and Varela's argument from 1980 [10], we understand the entire living word as possessing cognition of various degrees of complexity. In that sense bacteria possess rudimentary cognition expressed in quorum sensing and other collective phenomena based on information communication and information processing. Brain of a complex organism consists of neurons that are networked communication computational units. Signalling and information processing modes of a brain are much more complex and consist of more layers than bacterial colony. Even though Maturana and Varela did not think of cognition as computation, given the broader view of computation as found in info-computationalism, capable of representing processes of life as studied in bioinformatics and biocomputation. Reality for an agent is an informational structure that is established as a result of as well the interactions of the agent with the environment as the information processes in agents own intrinsic structures – reasoning, anticipation, etc.

Finally, an argument is advanced that the idea of panpsychism as a consequence of computational models by no means should be understood as necessary. It rather seems to be an artefact of the model and there is a variety of ways to correct the model so that non-physical properties do not follow.

For the future a lot of work remains to be done, especially on the connections between the low level cognitive processes and the high level ones. It is important to find relations between cognition and consciousness and the detailed picture of info-computational mechanisms behind those phenomena.

REFERENCES

[1] G. Dodig-Crnkovic, "Information, Computation, Cognition. Agency-based Hierarchies of Levels," in *Fundamental Issues of Artificial Intelligence (Synthese Library)*, V. C. Müller, Ed. Berlin: Springer, 2014, p. forthcoming.

[2] S. Kauffman, *Origins of Order: Self-Organization and Selection in Evolution*. Oxford University Press, 1993.

[3] T. Deacon, *Incomplete Nature. How Mind Emerged from Matter*. New York. London: W. W. Norton & Company, 2011.

[4] G. Dodig-Crnkovic and R. Giovagnoli, *Computing Nature*. Berlin Heidelberg: Springer, 2013.

[5] G. Dodig-Crnkovic, "Physical Computation as Dynamics of Form that Glues Everything Together," *Information*, vol. 3, no. 2, pp. 204–218, 2012.

[6] E. Ben-Jacob, "Bacterial Complexity: More Is Different on All Levels," in *Systems Biology- The Challenge of Complexity*, S. Nakanishi, R. Kageyama, and D. Watanabe, Eds. Tokyo Berlin Heidelberg New York: Springer, 2009, pp. 25–35.

[7] E. Ben-Jacob, "Learning from Bacteria about Natural Information Processing," *Ann. N. Y. Acad. Sci.*, vol. 1178, pp. 78–90, 2009.

[8] G. Tononi, "The Integrated Information Theory of Consciousness: An Updated Account," *Arch. Ital. Biol.*, vol. 150, no. 2/3, pp. 290–326, 2012.

[9] C. Koch, *Consciousness - Confessions of a Romantic Reductionist*. Cambridge Mass.: MIT Press, 2012.

[10] H. Maturana and F. Varela, *Autopoiesis and cognition: the realization of the living*. Dordrecht Holland: D. Reidel, 1980.

[11] H. Maturana, "Biology of Cognition," Defense Technical Information Center, Illinois, 1970.

[12] H. Putnam, *Mathematics, Matter and Method*. Cambridge: Cambridge University Press, 1975.

[13] W.-L. Ng and B. L. Bassler, "Bacterial quorum-sensing network architectures," *Annu. Rev. Genet.*, vol. 43, pp. 197–222, 2009.

[14] R. S. Pombo, O., Torres J.M., Symons J., Ed., *Special Sciences and the Unity of Science*, Logic, Epi. Berlin Heidelberg: Springer, 2012.

[15] R. Rosen, *Anticipatory Systems*. New York: Pergamon Press, 1985.

[16] K. Popper, *All Life is Problem Solving*. London: Routledge, 1999.

[17] G. Kampis, *Self-modifying systems in biology and cognitive science: a new framework for dynamics, information, and complexity*. Amsterdam: Pergamon Press, 1991, pp. 1–564.

[18] G. Dodig-Crnkovic, “Information and Energy/Matter,” *Information*, vol. 3, no. 4, pp. 751–755, 2012.
[19] L. Floridi, “A defense of informational structural realism,” *Synthese*, vol. 161, no. 2, pp. 219–253, 2008.
[20] K. M. Sayre, *Cybernetics and the Philosophy of Mind*. London: Routledge & Kegan Paul, 1976.
[21] A. Zeilinger, “The message of the quantum,” *Nature*, vol. 438, no. 7069, p. 743, Dec. 2005.
[22] V. Vedral, *Decoding reality: the universe as quantum information*. Oxford: Oxford University Press, 2010, pp. 1–240.
[23] G. Dodig-Crnkovic, “Info-computationalism and Morphological Computing of Informational Structure,” in *Integral Biomathics. Tracing the Road to Reality*, P. L. Simeonov, L. S. Smith, and A. C. Ehresmann, Eds. Berlin, Heidelberg, 2012.
[24] G. Dodig-Crnkovic, “Dynamics of Information as Natural Computation,” *Information*, vol. 2, no. 3, pp. 460–477, 2011.
[25] G. Bateson, *Steps to an Ecology of Mind: Collected Essays in Anthropology, Psychiatry, Evolution, and Epistemology*. University Of Chicago Press, 1972, pp. 448–466.
[26] D. McGonigle and K. Mastrian, “Introduction to information, information science, and information systems,” in *Nursing informatics and the foundation of knowledge*, Burlington, MA: Jones & Bartlett, 2012, p. 22.
[27] C. Hewitt, “What Is Commitment? Physical, Organizational, and Social,” in *Coordination, Organizations, Institutions, and Norms in Agent Systems II*, P. Noriega, J. Vazquez-Salceda, G. Boella, O. Boissier, and V. Dign, Eds. Berlin, Heidelberg: Springer-Verlag, 2007, pp. 293–307.
[28] C. Hewitt, “What is computation? Actor Model versus Turing’s Model,” in *A Computable Universe, Understanding Computation & Exploring Nature As Computation*, H. Zenil, Ed. World Scientific Publishing Company/Imperial College Press, 2012.
[29] G. Rozenberg, T. Bäck, and J. N. Kok, Eds., *Handbook of Natural Computing*. Berlin Heidelberg: Springer, 2012.
[30] G. Rozenberg and L. Kari, “The many facets of natural computing,” *Commun. ACM*, vol. 51, pp. 72–83, 2008.
[31] P. Denning, “Computing is a natural science,” *Commun. ACM*, vol. 50, no. 7, pp. 13–18, 2007.
[32] G. Dodig-Crnkovic and V. Mueller, “A Dialogue Concerning Two World Systems: Info-Computational vs. Mechanistic,” *Information and Computation*. World Scientific Pub Co Inc, Singapore, pp. 149–84, 2009.
[33] Y. Wang, “On Abstract Intelligence: Toward a Unifying Theory of Natural, Artificial, Machinable, and Computational Intelligence,” *Int. J. Softw. Sci. Comput. Intell.*, vol. 1, no. 1, pp. 1–17, 2009.
[34] G. Dodig-Crnkovic, “The Info-computational Nature of Morphological Computing,” in *Theory and Philosophy of Artificial Intelligence*, SAPERE., V. C. Müller, Ed. Berlin: Springer, 2012, pp. 59–68.
[35] G. Dodig-Crnkovic, “Significance of Models of Computation from Turing Model to Natural Computation,” *Minds Mach.*, vol. 21, no. 2, pp. 301–322, 2011.
[36] S. Crutchfield, James P.; Ditto, William L.; Sinha, “Introduction to Focus Issue: Intrinsic and Designed Computation: Information Processing in Dynamical Systems-Beyond the Digital Hegemony,” *Chaos*, vol. 20, no. 3, pp. 037101–037101–6, 2010.
[37] J. P. Crutchfield and K. Wiesner, “Intrinsic Quantum Computation,” *Phys. Lett. A*, vol. 374, no. 4, pp. 375–380, 2008.
[38] A. M. Turing, “The Chemical Basis of Morphogenesis,” *Philos. Trans. R. Soc. London*, vol. 237, no. 641, pp. 37–72, 1952.
[39] A. Sloman, “Meta-Morphogenesis: Evolution and Development of Information-Processing Machinery p. 849.,” in *Alan Turing: His Work and Impact*, S. B. Cooper and J. van Leeuwen, Eds. Amsterdam: Elsevier, 2013.
[40] L. Valiant, *Probably Approximately Correct: Nature’s Algorithms for Learning and Prospering in a Complex World*. New York: Basic Books, 2013.
[41] H. Maturana and F. Varela, *The Tree of Knowledge*. Shambala, 1992.
[42] M. Schroeder, “Dualism of Selective and Structural Manifestations of Information in Modelling of Information Dynamics,” in *Computing Nature*, SAPERE 7., G. Dodig-Crnkovic and R. Giovagnoli, Eds. Berlin, Heidelberg: Springer, 2013, pp. 125–137.
[43] G. Dodig-Crnkovic, *Investigations into Information Semantics and Ethics of Computing*. Västerås, Sweden: Mälardalen University Press, 2006, pp. 1–133.
[44] S. Grossberg, Gail A. and Carpenter, “ART 2: self-organization of stable category recognition codes for analog input patterns,” *Appl. Opt.*, vol. 26, no. 23, pp. 4919–4930, 1987.
[45] J. A. Wheeler, “Information, physics, quantum: The search for links,” in *Complexity, Entropy, and the Physics of Information*, W. Zurek, Ed. Redwood City: Addison-Wesley, 1990.
[46] G. Dodig-Crnkovic and R. Giovagnoli, “Natural/Unconventional Computing and its Philosophical Significance,” *Entropy*, vol. 14, pp. 2408–2412, 2012.
[47] S. Kauffman, R. Logan, R. Este, R. Goebel, D. Hobill, and I. Shmulevich, “Propagating organization: An enquiry,” *Biol. Philos.*, vol. 23, no. 1, pp. 27 – 45, 2008.
[48] J. Fisher and T. A. Henzinger, “Executable cell biology,” *Nat. Biotechnol.*, vol. 25, no. 11, pp. 1239–1249, 2007.
[49] M. Miłkowski, *Explaining the Computational Mind*. Cambridge, Mass.: MIT Press, 2013.
[50] M. Miłkowski, “Is computationalism trivial?,” in *Computation, Information, Cognition – The Nexus and the Liminal*, G. Dodig-Crnkovic and S. Stuart, Eds. Newcastle UK: Cambridge Scholars Press, 2007, pp. 236–246.
[51] S. Ghosh, K. Aswani, S. Singh, S. Sahu, D. Fujita, and A. Bandyopadhyay, “Design and Construction of a Brain-Like Computer: A New Class of Frequency-Fractal Computing Using Wireless Communication in a Supramolecular Organic, Inorganic System,” *Information*, vol. 5, no. 1, pp. 28–100, Jan. 2014.
[52] D. J. Chalmers, “Does a Rock Implement Every Finite-State Automaton?,” *Synthese*, vol. 108, pp. 309–33, 1996.
[53] J. Collier, “Causation is the transfer of information,” in *Causation, natural laws and explanation*, H. Sankey, Ed. Dordrecht: Kluwer, 1999, pp. 279–331.
[54] D. J. Chalmers, “A computational foundation for the study of cognition,” *J. Cogn. Sci. (Seoul).*, vol. 12, pp. 323 – 357, 2012.
[55] M. Sprevak, “Three challenges to Chalmers on computational implementation,” *J. Cogn. Sci. (Seoul).*, vol. 13, no. 2, pp. 107–143, 2012.
[56] G. Piccinini and O. Shagrir, “Foundations of computational neuroscience.,” *Curr. Opin. Neurobiol.*, vol. 25, pp. 25–30, 2014.
[57] J. R. Searle, *The Rediscovery of the Mind*. Cambridge Mass.: MIT Press, 1992.
[58] G. Tononi, “Consciousness as Integrated Information: A Provisional Manifesto,” *Biol. Bull.*, vol. 215, no. 3, pp. 216–242, 2008.
[59] G. Tononi, “An information integration theory of consciousness,” *BMC Neurosci.*, vol. 5, no. 42, pp. 1–22, 2004.
[60] W. Seager and S. Allen-Hermanson, “Panpsychism,” *The Stanford Encyclopedia of Philosophy*. Edward N. Zalta (ed.), 2013.
[61] G. Piccinini, “Computation in Physical Systems,” *The Stanford Encyclopedia of Philosophy*. 2012.
[62] J. R. Searle, “Consciousness: What We Still Don’t Know,” *New York Rev. Books*, vol. 52, no. 1, 2005.
[63] A. C. Ehresmann, “MENS, an Info-Computational Model for (Neuro-)cognitive Systems Capable of Creativity,” *Entropy*, vol. 14, pp. 1703–1716., 2012.