Chapter 1

Natural Computation of Cognition, from single cells up

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For describing continuum of natural cognition, from basal cellular to human level, we use evolutionary info-computational framework, where natural/ physical/ morphological computation drives generation of increasingly adept cognitive systems. We build on novel developments in information physics, bioinformatics, information chemistry, computational neuroscience, complexity theory, self-organization, theory of evolution (new synthesis), information and computation, a constructive interdisciplinary framework for understanding of cognition in the context of computing nature. Interactions between constituents at different levels of organization lead to complexification of agency and increased cognitive capacities of organisms. Recently, possibility of controlling basal cell cognition attracted a lot of interest for its possible applications in medicine, new computing technologies, as well as micro- and nanorobotics. Biocognition of cells connected into tissues/organs, and organisms with the group (social) levels of distributed information processing provides insights into cognition mechanisms that can help us to better conceptualize human cognition with its evolution and support the development of new AI models and cognitive robots. It will also give us better understanding of the human as natural being and our connectedness with the rest of nature.

1. INTRODUCTION

When talking about cognition, it is typically assumed to be a human capacity,[1] seldom including animal cognition and hardly ever cognition of plants[2–5] or even simpler living organisms, such as bacteria[6–14] or slime molds.[15] Even though cognition is traditionally considered as a result of human mind and thought, cognition in nature appears throughout biological systems[16–20] in different degrees, and it is important to understand its evolutionary development from the basal/basic/elementary cognition to the human level.[21–23] Models of cognition in this context have considerable explanatory value.

Traditionally, cognition is argued to conflict with computational models, where computation is understood as abstract disembodied mechanical symbol manipulation. It has been claimed that natural embodied cognition is irreconcilable with computational models, and that dynamical systems cannot be computational. Those claims have been demonstrated to be false, based on empirical observations, once it is understood that computation fundamentally always is embodied and that cognitive processes are information processes. If computation is understood as information processing in nature (natural computation/ physical computation/ unconventional computation/ morphological computation) it is necessarily both embodied and dynamic.

This article presents computational framework of natural cognition based on info-communication (info-computation) in living agents. In this naturalistic approach, the underlying assumption is that cognition in nature is a manifestation of biological processes,[24–27] that subsume chemical and physical processes - from single cells to humans.

A significant move from human-only cognition, towards a broader approach can be found in the recent work of Piccinini,[28] who credits cognition to all organisms with nervous system. Moreover, Piccinini argues that cognition is a result of computation, neurocomputation. Even though he goes a step beyond conventional understanding, Piccinini does not include all living organisms. However, there is rich empiric evidence that "cognitive operations we usually ascribe to brains—sensing, information processing, memory, valence, decision making, learning, anticipation, problem solving, generalization and goal directedness—are all observed in living forms that don't have brains or even neurons.".[23] Thus, it is possible, and even necessary to generalize cognition a step further, to include all living forms, not only those with nervous systems.

Based on empirical and theoretical insights about cognition and its evolution and development in nature,[29,30] from basal/ basic/ primitive/ elementary/ cellular up to complex form of human cognition[21,23,25,27,31] modelled on natural information processing (natural computation), we can identify several generative mechanisms of cognition that deserve more attention.

The rest of the article is organized as follows. Section 2 addresses info-computational approach to cognition in biological systems, "thinking" fast and slow through sub-symbolic and symbolic computational processes and connection of cognition with evolution. Section 3 presents natural processes of info-computation as a basis of natural cognition, and morphogenesis as (morphological) computation. Section 4 discusses the importance of time aspects of cognition. Section 5 offers conclusions.

2. INFO-COMPUTATIONAL APPROACH TO NATURAL COGNITION. EVOLUTION OF A "SENSITIVE SOUL" THROUGH EXTENDED EVOLUTIONARY SYNTHESIS

Knowledge and skills of a living agent are embodied in an info-computational natural process that generates cognition. This process produces intelligent behavior (problem-solving ability) of natural systems in complex environments. Traditionally, cognition has been studied as a result of brain activity in humans, where there was an opposition between three different types of brain activities supposed to underlie cognition: brain function as a result of symbol processing of Turing computation type,[32] distributed computation models,[33] and dynamic models of a brain as a meta-stable oscillating system.[34] It is important to realize that all three "modi operandi" in the brain can suitably be modelled as natural computations (natural information processing) on different levels of organization. Let us start by introducing the framework for naturalizing cognition, with two basic elements: natural (embodied) information, and natural (physical) computation.

2.1. *Naturalized Cognition. Thinking Fast and Slow – Sub-symbolic and Symbolic Computing*

Info-computational naturalist model of cognition is a hybrid connectionist-symbolic, biologically realistic conceptual framework aiming to integrate current knowledge from variety of research fields, such as cognitive science, computational neuroscience, bioinformatics, computability, biology, and new evolutionary synthesis.[35] This approach is based on the view of hierarchical recursive structure of information processing in nature, which is especially important for living organisms, from cells, to tissues, organs, organisms, and their groups – all of them communicating at different levels of organization by exchanging specific types of information – physical (elementary particles, electromagnetic), chemical (electric, molecular), biological, and symbolic.

From the time when first models of cognition have been proposed until now, a lot has changed in our understanding of cognition, embodiment, functioning of the brain, neurons and neuronal networks. Within AI, the field of artificial neural networks with deep learning have made an impressive progress in modelling perception on the level of data/signal processing. In humans, two basic cognitive systems have been recognized, System 1 (reflexive, non-conscious, automatic, intuitive information processing, which is fast) and System 2 (reflective, conscious, reasoning and decision making, which is slow).[36,37] As Kahneman explains, System 1 and System 2 stand for informational processes that are functional abstractions, not the brain regions. As deep learning models are inspired by the human brain information processing, recent advances in understanding of natural cognitive systems can contribute both to better explanatory models and to future developments of constructive engineered cognitive models. Deep learning level corresponds to Kahneman's fast, intuitive System 1,[36] and current developments in AI are continuing towards even more ambitious goals of modelling System 2 symbolic reasoning.[38] Here we should add that Bengio's and Kahneman's interpretations of System 1 and 2 are not identical, which was evident from the discussion at AAAI-2020 conference, Fireside Chat with Lecun, Hinton, Bengio and Kahneman https://vimeo.com/390814190. However, the details are not essential for our present exposition.

It has long been recognized that mechanisms of cognition based on natural computation are far more sophisticated than the machine-like classical computationalist models based on abstract symbol manipulation.[39] They conform to the view expressed by[40–42] that rule-based machines are not good enough models of natural cognition which appears in highly complex living organisms. Embodiment is the fundamental feature of cognition, which implies that valence, affect, feelings and emotions must be taken into account as constitutive elements in the models of cognition[27,30,43–45] and they impact both System 1 and System 2 information processing.

2.2. *Information Processing in Embodied and Extended Cognition*

Naturalized cognition as a systemic perspective means broadening the scope beyond neurocentrism[17,23,27,46,47] to networks of networks of information-processing agents, down to molecular level as computational basis of distributed cognition. The physical mechanism of natural computation is morphological computation[48–51] where morphology refers to form, shape, and structure which defines interactions.[52]

As already discussed, cognitive models typically identify cognition with information processing in the brain. However, with the rise of embodied cognition, neurocentrism is being challenged by a systemic view of cognition, where body shapes cognitive functions. Furthermore, as Cowley et al.[46] show, living beings also connect their bodies with artefacts, in a sense of extended cognition (Clark 2008). The central importance of interaction we learn as well from Ginsburg and Jablonka[53] view of the evolution of "the sensitive soul", providing the naturalized communication between an agent and its environment, that changes both.

2.3. *Evolutionary View of Cognition in Nature. Scaling from Basal to Complex*

If we want to learn how cognition functions in human as the most complex living organism, it is instructive to see how this ability developed through evolution, resulting in variety of cognitive architectures of organisms from bacteria to humans.[21,27,53] In a naturalist approach of Maturana and Varela, cognition in any living organism is a result of embodied processes that make the organism alive,[24] or as Stewart[25] puts it, "Cognition = Life". Here life includes capability of growth and reproduction. All living systems are cell-based, from unicellular to complex ones, with cells organized in tissues and organs, where each cell possesses cognition. Groups of organisms like swarms and flocks exhibit social cognition. Cognitive capacities on different scales make living system goal-directed, robust and adaptive.

In biomimetic (nature-inspired) robotic systems, cognition is represented by the equivalents of living functions, implemented in a robot provided with sensors, actuators and information processing units. This basal level of cognition can be of practical interest, as robots do not always need human-level abilities to perform their tasks.[54] Cognition of a different, non-human type can be adequate in biomimetic soft robots.[55] Levin et al.[16,21–23,56] describe a variety of mechanisms of cognition where robust adaptive information processing and behavior can be used to develop new computational techniques in biological and engineered systems. In the naturalized, evolutionary concept of cognition, the development goes from the simplest organizational form of a single cell, as "cellular mind", up to the brain as "the society of mind".[57] In this process, body plays a vital role in shaping minds.[48] Organisms learn about the world by means of information exchanges/communication.[58–61] Reality for a cognitive agent is an informational structure[50,50] and biology computes. Processes of change in informational structures establish computational dynamics. This model of reality for an agent includes both the information about the agent itself and about the world as it appears for the agent via interactions with the environment. Proposed naturalist framework provides computational models for cognitive info communications which the author has been developing.[31,45,62–65] In the info-computational approach, evolutionary process unfolds in living organisms, and it happens in the sense of extended evolutionary synthesis[53,66–68] as a result of interactions (communication) between natural agents, be it cells, their groups or multi-cellular organisms.

Unlike the "Modern evolutionary synthesis", which supplemented Darwinism with added genetic determinism, in the computing nature approach, the emphasis is on the role of the interaction/communication with the environment for the development and evolution. Origins of life can be found in the interactions of the first simplest pre-biotic chemical agents, leading to more complex forms such as viruses and furthermore first cells as bacteria, continuing up in complexity through the information structures self-organization. Genes are important, but not the solely responsible for the development of cells and their aggregates up to organisms and ecologies. As Ginsburg, Jablonka and Witzany[41,53,67] describe, the interplay between the genetic code with the environment,, through material embodiment is crucial. Even Rovelli[69] argues for the central role of evolution as a mechanism that generates mental (intentionality, purpose, agency) from physical: "Meaning and Intentionality = Information + Evolution".

In the framework of info-computational nature, living organisms are cognitive agents, from single cells to humans,.[45,70] Cognitive artefacts can also be seen as natural physical systems with various degrees of cognitive capacities.[19,52] Cognition is an open-ended process of self-organization where computation proceeds as signal processing at physical and chemical levels, while on the biological and cognitive levels it takes form of symbol manipulation and language-based communication,.[71,72]

Simultaneous development of minds and bodies has been studied by Schröder[73] as natural information processes. In a cognitive agent, variety and its dynamics is tackled through dual concept of selective and structural aspects of information. Biological evolution of species is a dynamical information processing. What for a cognitive agent appears as "the world" is an interface, a shared boundary across which the information is exchanged,[74] with perception based on data/information obtained from the senses. Similar idea of computational boundary of a "self" is put forward by[22] who describes mechanisms driving biological agents towards multicellularity and scale-free cognition.

3. NATURAL PROCESSES OF INFO-COMPUTATION – COMPUTING AS MORPHOGENESIS – MORPHOLOGICAL COMPUTING

In our study of cognition as natural phenomenon we adopt Floridi's Informational structural realism[75,76] as an approach in which reality is "informational structure for an epistemic agent interacting with the universe by the exchange of data as constraining affordances." The dynamics of that informational structure is conceptualized through the idea of Computing nature - where the physical dynamics of informational nature is natural computation.[49,77–81] This provides a unified naturalist setting for studying structures and processes in both animate and inanimate world.[26] The underlying fundamental property of information which makes it suitable as a basis of naturalist approach is Landauer principle of naturalization of information: "there can be no information without physical implementation".[82] Our approach is thus based on naturalized metaphysics. As Ladyman et al.[83] explain, naturalists construct science-based, structural-realist, computational ontology. Physicist Rovelli contributes to the naturalization program with his proposal to build the foundation of physics on relative information.[69] Here Shannon's relative information between two physical systems defines a purely physical notion of information, which can be used to "glue everything together".[64] That means to connect networks of networks of information processing nodes in nature. Interactions between physical systems are exchanges of information that establish physical correlations between them, through Shannon's relative information (correlation). By combining physical correlations with Darwinian evolution, Rovelli builds a ground for emergence of meaning in nature.

Insights from informational chemistry helps further in bridging the gap between physics and biology, with supramolecular chemistry that connects molecular recognition, molecular information processing and self-organization.[84,85] Biology and cognitive sciences are already established as information-based and their processes have been modelled as natural computation.[86–89] Even the evolution of life has been modelled as a process of morphological info-computation (meta-morphogenesis).[90] The whole sequence of information-based sciences – from physics to chemistry, biology (including evolution of species), and cognitive sciences (including social cognition) makes it possible to understand cognition as natural information processing/natural computation.

3.1. *Natural/ Physical/ Morphological Cognitive Computation*

The concept of natural computation as presented by[77,91] addresses information processing (both discrete and continuous), as spontaneously appearing in nature.[92] Models of natural computation/natural information processing differ from the Turing model of computation, that is symbol manipulation. From the point of view of organization of computational processes, natural computation is different from von Neumann computation. Natural computation models of biological organisms with their multi-level processes of computing and distributed information processing are capable of capturing the dynamic behavior of natural cognitive agents, including neuronal networks.[93] In the framework of info-computational nature, the fundamental mechanism is morphological computation, i.e. a process of information self-organization such as described by Haken.[94,95] The author addressed this topic in.[31,45,62,63,65,91] Morphological computation in living nature is a network of morphological informational processes for cognitive agents, with cognition as layered morphological computation.

Recently, in robotics, specific use of the term "morphological computation" has been adopted to denote decentralized embodied control in robots. In the context of robotics, appropriate body morphology is saving information processing (computational) resources as well as enabling learning through self-structuring (self-organization) of information.[48,96,97] This is macroscopic view of morphological computation that do not concern lower levels of organization such as cellular, molecular or quantum computation.

Natural computation appears on all levels of organization in nature, from physical, chemical, biological to cognitive. Of special interest for us are the levels with chemical and biological computation contributing to cognitive behavior such as presented by,[98] showing biochemical basis of connectionism. On the level of cells and tissues there are numerous computational approaches such as.[20,99,100] Proposals have been made for synthetic analog computation of living cells with artificial epigenetic networks.[101] Extensive literature exists on specific neuronal computation,[28,102] as well as computational models of brain,.[103–108]

It is important to keep in mind the difference between new computational models of intrinsic information processes in nature (natural computing/morphological computing), and old computationalism based on computer metaphor of the Turing machine, performing symbol processing, that has been rightly criticized as inadequate model of human cognition.[86,109] As already pointed out, in humans there are two basic cognitive systems, System 1 (reflexive, non-conscious, automatic, intuitive information processing, which is fast) and System 2 (reflective, conscious, reasoning and decision making, which is slow).[36,37] Recognizing only symbolic information processing leaves the symbol grounding problem unsolved. Sub-symbolic Symbol 1 data/signal processing provides mechanisms of symbol grounding in deep learning.

Hybrid symbolic-dynamical models[110,111] have been proposed as well, capable of modelling a combination of the two as a reactive-deliberative behavior. According to Ehre,[72] the fast reflexive System 1 can be understood in terms of Rovelli's physical correlations (Shannon's relative information), and it can accommodate for emotion as argued in,[112] while the slow System 2, because of synonymity in the symbol system, introduces element of choice and indeterminism with higher computational demands. The latter has been addressed in,[113] also addressing the topic of parallel concurrent computation typical of biological systems, for which the Turing Machine model is not adequate.

3.2. *Computation vs Communication in Biological Systems*

Computation as well as communication involve the transition, transformation and preservation of information.[114] The relationship between communication and computation has been described by[115] who argues that they are not conceptually distinguishable. The only difference is that computation concerns actions within a system, while communication is a process of interaction between a system and its environment. Biological systems are open information processing systems in communication with the environment, where the boundary between the system and the environment is dynamic and blurred.

As all other fundamental concepts which are objects of intense research (including information, computation, and cognition), the concept of communication has no generally accepted definition.[37] We use the concept in the sense of computation between systems,[115] that is as exchange of information between the system and the environment. One often thinks of communication as being defined by language with addition of other symbol systems such as images and sounds. But if we think of a human being with all its senses, then communication takes place on different levels and through many channels that are interacting in the brain. For example, one does not think and feel clearly when disturbed by a constant noise, feeling strong anxiety, or is upset. The whole person participates in communication. Emotional signs may not always be as obvious as the conventional symbolic message, but can be orders of magnitude faster and more important for the receiver, like bodily language, tone of voice, smile, eye gaze etc.[43,79,112]

To understand communication in a more multifaceted way than the exchange of symbols or signs, it is instructive to look at communication in other, simpler organisms. All living beings communicate. A cell that is the basic building block of life is a complex communication system. Without communication, life would not be possible.[116] Naturalized communication is based on information defined by structures and computational processes in nature.[117] In the same way as epistemology (knowledge) can be naturalized[26,78] using natural information processing (natural computation), communication and cognition can be naturalized.

4. TIME ASPECT OF COGNITIVE MODELS, LEARNING AND MEMORY IN NATURALIZED COGNITION

Since Turing work on morphogenesis, study of morphological computation focuses on spatial structures, even though temporal aspects play equally fundamental role. Typically, cognitive models assume the mind/brain to be reactive, with information processing starting with a stimulus and ending with a response.[118] However, cells are inherently active, neurons are sustained oscillators, exhibiting electrochemical oscillations even in the absence of stimuli. Input data/information presents stimuli that modulate existing endogenous oscillations.[118] In the book "Rhythms of the Brain" Buzsaki[93] describes the important role that spontaneous activity of neurons plays. Spontaneous firing of neurons is the very basis of human cognition when it comes to its time aspects. A self-organized timing of oscillations has co-evolved as the main organizational principle of neuronal activity. Global computation (on multiple spatial and temporal scales) is enabled by small-world-connectivity of neurons in the cerebral cortex. In a small-world setting, any two of nodes are connected through a short sequence of intermediary nodes. Cortical system is in a metastable state, synchronized through weak links between network oscillations in constant interactions. Oscillator frequency determines periods of receiving and transferring information. Based on studies of oscillations, neural computations and learning, Penagos, Varela, and Wilson[119] proposed that "precisely coordinated representations across brain regions allow the inference and evaluation of causal relationships to train an internal model of the world." Training starts while awake, and processing continues during sleep when periodic nested oscillations induce hierarchical processing of information. Authors suggest that "general inference, prediction and insight" is enabled through periodic states of sleep. Related is the synaptic plasticity of the brain which changes its connections through the long-term potentiation (Hebbian and non-Hebbian), considered to be a basis for learning and memory. Oscillatory behavior is not only the characteristics of the human brain. Similar oscillatory rhythms have been observed in the brains of mice. Being made of oscillators, biological neural networks are able to filter inputs and to resonate with noise. In contrast to the observed oscillatory time behaviors in the biological brains, which appear as a result of their physical embodiment, artificial neural networks have no such temporal coupling and synchronizing mechanisms. It is an open question how essential oscillatory behavior and metastability are for "fine tuning to the world" and if their function can be obtained in a different way in artificial neural networks.

On the level of unified theories of cognition, time aspect[120] manifests itself in terms of Newell's bands of cognition[121]—the biological "10 millisecond band", cognitive, rational, and social ("long-term") bands. How important is it to have all of them represented and how detailed? Here we talk about understanding of temporal aspects of cognition as organized hierarchically in a metastable state, constantly tuning to the environment. Coordination obtained through communication is central for connecting different levels, from molecules to thoughts, in the same coordination dynamics.[34] Through the interplay with the environment this process results in eigenstates.[122] Technological approaches to cognitive models of brain-like computer, based on frequency-fractal computing have been proposed[123] and.[124]

5. CONCLUSIONS

This article presents advances in understanding of cognitive systems and processes in nature. Interpreting the nature in terms of computation (information processing), we can better understand processes of cognition as they function and evolve in living beings, from single cells to complex organisms and their networks. They can be used to inform future bio-inspired/biomimetic cognitive models in the range of applications, from nano-technology to medicine and robotics.

Novel developments in understanding of information physics, bioinformatics, information chemistry, computational neuroscience, complexity theory, self-organization, theory of evolution, information and computation as well as embodiment and evolution, support a constructive interdisciplinary framework for cognition in the context of computing nature, where interactions between constituents at different levels of organization lead to complexification of agency and increased cognitive capacities of organisms. Computation in nature/natural computation/physical computation/morphological computation stands for processes of self-structuring of information in a number of organizational levels: physical, chemical, biological, cognitive, and social with networks of communicating agents on every level of organization.[45]

It is important to note the parallel development of our understanding of cognition as natural phenomenon and its technological implementations that inform each other in a recursive manner.[125,126] At the same time as the knowledge of cognitive processes in living organisms increases, so do also our information processing/computational models.

We are pointing to the fact that biologically inspired models of cognition such as new developments of connectionist (hybrid deep learning) and dynamical models, including non-neural cognitive systems deserve place among cognitive models.

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