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Cognition as a Result of Information Processing in Living Agent's Morphology. Species-specific Cognition and Intelligence

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Abstract. Cognitive science, according to *The Stanford Encyclopedia of Philosophy* (Thagard, 2014) is an interdisciplinary study of *human mind* and *intelligence*. It investigates *knowledge generation* in humans through perception, thinking (reasoning), memory, learning, and problem solving. Under this framing of cognitive science, variety of unsolved/unsolvable problems appear, as it ignores the role of the physical world and the body of a cognizing agent, neglecting the dynamical systems aspects, and emotions, as well as the phenomenon of distributed cognition. Moreover, it is ignoring the existing mathematical results which indicate that the human brain cannot be a classical computer (the Turing machine), with cognition modeled as computation over mental representations. On the other hand, radical biologism argues "Cognition = Life" (Maturana and Varela, 1980) (Stewart, 1996), thus the totality of biological processes. The functional connection is still missing between those two views, the high-level view of cognition with thoughts, mind, and intelligence (symbol processing) and the low-level view where each living organism (and all its building blocks, cells) is processing information that has a function for survival. Development of both cognitive science and related research fields of psychology, philosophy of mind, linguistics, neuroscience, bioinformatics, anthropology, and artificial intelligence go in the direction of embodied, embedded, extended, and enacted cognition (EEEE).

Moreover, implementations of cognition and intelligence in artifacts are contributing to the more detailed view of the relationship between cognition and its substrate. To achieve a connection between symbolic and sub-symbolic cognition, the concepts of computation and cognition must be generalized. Computation can be understood as process of morphogenesis (the development/generation of morphological characteristics, such as shape, form, and material composition in material bodies) on different levels of organization: physical, chemical, biological, cognitive, and virtual-machine-level computation built on top of them. Morphological computation/information processing approach to cognition provides a framework that connects low-level with high-level approaches to cognition and meets challenges and open questions listed by (Thagard, 2014).

In addition, the idea of cognition is generalized from the exclusively human capacity to the capacity of a variety of goal-directed adaptive self-reflective systems, from simplest living organisms (cells) humans (Dodig-Crnkovic, 2018). The aim is to better understand generative mechanisms of cognition in the light of evolution, as according to (Dobzhansky, 1973) "Nothing in biology makes sense except in the light of evolution."

(Thagard 2013; 2014) makes an extension of the idea of "thinking" to include emotional experience "The term cognition, as used by cognitive scientists, refers to many kinds of thinking, including those involved in perception, problem solving, learning, decision making, language use, and emotional experience." Similarly, (Lerner et al. 2015) argues for the importance of emotion in the decision making. The extension of "thinking" to emotional decision-making, also found in (Kahneman 2011), bridges some of the distance between cognition as (rational) thinking and its embodiment, but the basic problems remain of *generative mechanisms* that can dynamically connect body (matter) and mind. Thagard's description of cognitive science that includes emotions, does not make connections to biology, chemistry, (quantum- nano-, etc.) physics or chaos theory, self-organization, artificial life or data science, extended mind, distributed cognition, network science, sociology, or ecology, thus offering a rather high-level and thus necessarily simplified view.

Despite various attempts to bridge this body-mind gap made by (Clark 1997, 1989, 2013), (Scheutz, 2002) (Pfeifer and Iida, 2005), and several others, who have been offering a connection between sub-symbolic (signal processing) and symbolic (higher level) notions of cognition, this is still not reflected in the view of cognition found in major encyclopedias.

For the study of physical implementations of computation and control in robotic systems, the idea of morphological computation has been proposed in robotics (Paul, 2004) (Pfeifer and Bongard 2006) (Pfeifer, Iida, and Gomez 2006) (Pfeifer and Gomez 2009) (Hauser, Füchslin and Pfeifer, 2014) (Müller & Hoffmann, 2017a, 2017b) which defines computation process in a more general way than the conventional Turing machine symbol manipulation, considering physical embodiment of computational devices. Morphological computation in robotics uses the body to perform computation by its physical morphology (material/ shape/form) and thus replaces detailed central control, as described in (Matsushita et al. 2005) (Pfeifer, Iida, Lungarella, 2014).

In the earlier work of the author (Dodig-Crnkovic, 2012, 2014, 2016, 2017, 2018) arguments have been presented for the broadening of the definition of cognition, in the direction of EEEE cognition to include sub-symbolic processes that precede language in humans such as feelings, emotions, intuitions, and values (von Haugwitz and Dodig-Crnkovic, 2015). This more inclusive notion of cognition, related to its generative processes, evolution, and possible generalization to artificial cognitive systems provides a link between "cognitivist" (i.e. classical "computationalist") and EEEE approaches through *the idea of general morphological computation, that is computation performed by the morphology of an agent*. In this context morphological computation is info-computational self-organization "*in materio*" (Dale et al. 2017) of cognizing agents.

In living organisms, profound insights can be made by studying evolution and mechanisms of cognition at a variety of levels of organization, from single cells up to most complex living organisms. Cognition in nature appears throughout biological systems (Baluška and Levin 2016; Lyon 2005; Lyon 2015) and it is important to understand its evolutionary development from the basal/basic/elementary cognition on the cell level, to the human level (Manicka and Levin 2019; Levin et al. 2021).

Naturalized evolutionary approach to cognition is based on the view of hierarchical recursive structure of information processing in nature, in 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, electro-magnetic), chemical (electric, molecular), biological, and symbolic (signs, languages).

By the ability to model cognition as embodied, embedded, enactive, and extended via interactions with the environment, morphological computing provides means of understanding how this capacity evolved, and how it develops during the life of an organism. Taking lessons learned from nature helps already in the engineering of artifactually cognitive and intelligent agents (Pfeifer, Iida, Lungarella, 2014).

In conclusion, current work in different fields informing cognitive science, from neuroscience (with neuroimaging) to robotics and AI, as well as novel insights about the inner working of cells, (especially neurons), and brains, all contribute to constructing a more complete picture of the physical basis of cognition and its underlying information processes. For the future, it remains to work out the details of this emerging view of cognition where not only thoughts (symbolic computation) but also perceptions, sensations, feelings, and emotions (sub-symbolic, physical computation "*in materio*", connecting cognizing agents with their bodies and the world will be recognized as a substantial part of cognition (Feldman Barrett, 2018) (Damasio, 2008). Tracing back cognition to its most rudimentary forms in unicellular organisms and carefully studying its complexification on the evolutionary scale helps understand physical basis of cognition and the emergence of symbolic computation that from chemical language of bacteria, leads to human-level linguistic competences.

Information processing in cognizing agents can be modeled as substrate-specific/species-specific morphological computation, from a single cell and up. If we want to learn how cognition functions in humans as the most complex living organisms, it is instructive to see how this ability developed through evolution, resulting in a variety of cognitive architectures of organisms from bacteria to humans (Ginsburg and Jablonka 2019)(Manicka and Levin 2019).

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