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Morphological, Natural, Analog, and Other Unconventional Forms of Computing for Cognition and Intelligence †

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Abstract: According to the currently dominant view, cognitive science is a study of mind and intelligence focused on computational models of knowledge in humans. It is described in terms of symbol manipulation over formal language. This approach is connected with a variety of unsolvable problems, as pointed out by Thagard. In this paper, I argue that the main reason for the inadequacy of the traditional view of cognition is that it detaches the body of a human as the cognizing agent from the higher-level abstract knowledge generation. It neglects the dynamical aspects of cognitive processes, emotions, consciousness, and social aspects of cognition. It is also uninterested in other cognizing agents such as other living beings or intelligent machines. Contrary to the traditional computationalism in cognitive science, the morphological computation approach offers a framework that connects low-level with high-level approaches to cognition, capable of meeting challenges listed by Thagard. To establish this connection, morphological computation generalizes the idea of computation from symbol manipulation to natural/physical computation and the idea of cognition from the exclusively human capacity to the capacity of all goal-directed adaptive self-reflective systems, living organisms as well as robots. Cognition is modeled as a layered process, where at the lowest level, systems acquire data from the environment, which in combination with the already stored data in the morphology of an agent, presents the basis for further structuring and self-organization of data into information and knowledge.

Keywords: intelligence; cognition; information processing; morphological computing; natural computing; unconventional computing; agency; evolution; embodiment

1. Cognition and Intelligence

According to the currently dominant view, cognitive science is a study of mind and intelligence, focused on knowledge generation in humans. Under this traditional framing of cognitive science, the process of cognition is understood as computation over mental representations, that is a hypothetical internal cognitive mechanism manipulating concepts, ideas, and thoughts, all of which are vaguely defined abstract concepts described by symbols and their combinations without clear physicochemical equivalents. This approach is connected with a variety of unsolvable problems, as pointed out by Thagard [1,2], and I argue that the main reason is because it detaches the knowledge generation from the physical world and the body of a cognizing agent, neglecting the dynamical systems aspects of cognitive processes, emotions, consciousness, and social aspects of cognition (that is interactions with other cognitive agents).

On the other end of the spectrum of models of cognition, there is a radical biologism that argues, as explained in Maturana and Varela and Stewart [3,4] "cognition = life". There, the connection is still missing between the high-level view of cognition as studying thoughts, mind, and intelligence as computational symbol manipulation, and the low-level view seeing each living organism, no matter how simple, as a cognizing system, where cognition stands for very physicochemical processes of life. In this context, intelligence is seen as a subset of cognition, the ability of an agent to solve problems, which includes learning, reasoning, planning information storage and retrieval, and related processes.

Both approaches—the abstract symbol manipulation model and the biology–chemistry–physics-centered model—offer too restricted frameworks. The morphological computation approach to cognition proposes a framework that connects low-level with high-level approaches to cognition, meeting Thagard's challenges and open questions [1]. To achieve this connection, morphological computation generalizes the idea of computation from symbol manipulation to natural/physical computation and the idea of cognition from the exclusively human capacity to the capacity of a variety of goal-directed adaptive self-reflective systems from living organisms to robots [5].

After noticing limitations of the present view of cognition, Thagard [1,2] proposed an extension of the idea of "thinking" to include—apart from traditional ones involved in perception, problem solving, learning, decision-making, and language—the emotional experience. This addition bridges some of the distance between cognition as rational symbol-manipulating computing and its embodiment, but the basic problems remain regarding generative mechanisms that can dynamically connect cognition with its substrate, relating mind and matter. Thagard's account of cognitive science still lacks the connections to its physical basis that can be found in biology, chemistry, and physics, including chaos theory, self-organization with active matter, artificial life or natural computing, extended mind, distributed cognition, network science, sociology, and ecology, thus offering a rather narrow view of the top layer of cognition, by and large disregarding its embodiment. Historically, cognitivism has been based on the Turing machine type of computation, which is characterized by the independence of its physical substrate. The main criticism of traditional cognitivism is the inadequacy of the Turing machine model of computation that is used to describe high-level cognitive processes involving symbol manipulation, as presented by Scheutz [6].

2. Embodied, Embedded, and Enacted Cognition (EEEE)

Currently, both cognitive science and its underlying research fields of psychology, philosophy of mind, linguistics, neuroscience, anthropology, and artificial intelligence are in a process of rapid development in the direction of embodied, embedded, and enacted cognition (EEEE). Alongside, implementations of cognition and intelligence in artifacts are contributing to the more detailed view of the relationship between cognition and its physical substrate. The present-day schism between cognitivism/computationalism and EEEE cognition is based on the narrow view of cognition (computation over mental representations), as well as a narrow view of computation (Turing machine model). Despite the various attempts to bridge this gap made by Clark [7,8], connecting subsymbolic (signal processing) and symbolic (higher level) notions of cognition, Scheutz [6] has argued for new computation models, and Pfeifer, Bongard, and Iida [9,10] have worked on the role of morphology in robotics. Even with contributions of many others working on the EEEE paradigm [11–13], this development is still not adequately reflected in the view of cognition found in major commonly shared knowledge repositories, such as encyclopedias. It is in use in specialized research communities and it is not yet part of the widely received view.

3. Morphological Computation in Robotics and General Morphological Computation

The idea of morphological computing has been proposed in robotics in the study of physical implementations of computation and control [14–17]. It defines computation in a more general way than the conventional symbol manipulation, taking into account that the process of computation is implemented in the physical body of a computational device. Morphological computation in robotics uses the body to perform intended behavior through its own physical morphology (shape and form of a structure and relations between form, forces, and material properties) and thus replaces detailed central control, as described in [10].

In the earlier work of the author [18–20], arguments have been presented based on the unified constructivist info-computational framework for cognition. The info-computational framework takes the world to be information for an agent, with computation understood as the dynamics of information. This approach broadens the definition of cognition, incorporating the idea of "life = cognition" (=natural info-computation) and EEEE with both subsymbolic (data-based, signal mediated, low-level) and symbolic (high-level) information processing [21]. As a consequence, cognition in other living beings and distributed cognition of social networks have been part of the same approach. This more inclusive notion of cognition, aware of its generative processes, evolution, and possible generalization to artificial cognitive systems provides a link between the "cognitivist" (i.e., Turing machine computation-based) and (physical embodied morphological computation–based) EEEE approaches through the idea of general morphological computation, that is computation performed by morphology (shape/structure + material) of an agent.

Morphological computation, in general, is understood as info-computational self-organization in cognizing agents of any kind, both those developing spontaneously in nature and those engineered as robots. Even the simplest living cognitive systems, like the simplest cell, possess the highly complex structure of interacting parts in constant communication with the environment. Morphological computation is defined on a structure of nodes (agents) that exchange (communicate) information. The information processing capacities of a single node can be rather rudimentary (like in a single neuron), while the network can exhibit remarkably complex properties (like a brain). Similarly, unicellular organisms such as bacteria communicate and build swarms or films with far more advanced capabilities compared to individual organisms, through social (distributed) cognition based on information exchanges. Some groups of cells in nature have evolved into multicellular assemblies with differentiated control mechanisms from the cell level to the tissue, organ, organism, and groups of organisms, and this layered organization provides information processing benefits.

4. Morphological Computation, Cognition, Intelligence, and Evolution

In living organisms, the study of evolution and mechanisms of cognition [22] at a variety of levels of organization, from single cells up to most complex living organisms, provide insights into generative processes of cognition [19]. Through the ability to model cognition as embodied, embedded, enactive, and extended by interactions with the environment, morphological computing provides a means of understanding how this capacity has evolved in humans and how it develops during the life of an organism. Applied to humans, morphological computing [23] provides a framework for studying not only generation of knowledge in the conventional sense of traditional abstract cognitive science, but also modeling of feelings and emotions as an integral part of cognition. Taking lessons learned from nature helps already in the engineering of artifactually cognitive and intelligent agents [10]. However, the learning goes in both directions, and we use new knowledge from the design of artifacts to elucidate natural processes, as argued by Rozenberg and Kari in [24]. The ideal is to understand the mechanisms of cognition and intelligence from the most rudimentary ones, as found in unicellular organisms, to the most complex ones, represented in humans and human societies.

Ehresmann [22], who provided mathematical formulation of info-computational framework for a cognitive human-level architecture, modeled the bottom-level (cells) processes as pretty much "automata-like", describing indeterminism on the highest levels of language as a consequence of synonymy, as natural language is notoriously complex and one word can point to a network of underlying phenomena.

5. Conclusions

In conclusion, current work in different fields informing cognitive science, from neuroscience to robotics and AI, as well as novel insights in the inner working of cells, including neurons, and brains all help us in constructing a more complete picture of the physical basis of cognition and the underlying information processes. For the future, it remains to work out and incorporate already existing results from other research fields (neuroscience, bioinformatics, active matter, deep learning, etc.) with the details of the new emerging view of cognition, deeper than computation over mental representations, including natural information processing/natural computation/ morphological computation, which connect cognizing agents with their bodies and the world, through sensors and actuators.

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