Morphological Computing of Cognition and Intelligence, MORCOM 2021-Online Conference

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Editorial

Morphological Computing of Cognition and Intelligence, MORCOM 2021-Online Conference †

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Abstract: The theme of the conference, "Morphological Computing of Cognition and Intelligence" (MORCOM 2021), focused on the unconventional forms of computing, which bring the promise of more efficient intelligent and cognitive computing. The present editorial, written by the organizers of the conference, reports the ideas and goals of MORCOM 2021 and provides an overview of the contributions.

Keywords: artificial intelligence; intelligence; unconventional computing; morphological computing; natural computing; computation; information

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1. Conference "Morphological Computing of Cognition and Intelligence" (MORCOM 2021): Objectives

MORCOM 2021@-online was fourth in a series of workshops held on IS4SI Summit, in conjunction with the 13th International Workshop on Natural Computing—IWNC 2021.

Past workshops in the MORCOM series include:

MORCOM-2019@IS4SI-Berkeley: Morphological, natural, analog and other unconventional forms of computing for cognition and intelligence.

MORCOM-2018@-Gothenburg Wallenberg Symposium: Morphological and embodied computing.

MORCOM-2017@IS4SI-Gothenburg: Morphological computing and cognitive agency.

Each of the past events was a step forward towards a better understanding of the alternative ways of computing in the context of its potential to understand natural cognition and intelligence, as well as to the design of cognitive intelligent artefacts.

By adopting the framework of computing with natural computation that is performed spontaneously/intrinsically by different natural systems on a variety of organizational levels—physical, chemical, biological, and cognitive systems—it becomes necessary to reconsider and re-examine fundamental concepts, such as computing, cognition and intelligence. There are examples of novel studies of, for instance, morphological computing and embodied cognition, that succeed in escaping the inertia of thinking habits, and set forth to question conventional theoretical and practical approaches to computing, cognition, and intelligence.

Morphological computing entails that the morphology (shape + material properties) of an agent (physical system, a living organism, or a machine) both enables and constrains its possible physical and social interactions with the environment. This constrains its development, including its growth and reconfiguration. The role of morphological computation for cognitive systems includes the off-loading of control onto the body and its interaction with the environment, thus enabling a flexible and adaptive behavior; this is particularly studied in the field of robotics.

Embodied cognition means that cognition is grounded in environmental interactions with the world. That connection is invisible in classical symbolic representation accounts of cognitive function, construed "in abstracto". Embodied cognition is conceived in opposition to "computational cognition" where both cognition and computation are modeled on human "thinking" or "mentality", taken as abstract symbol manipulation. However, modern computational perspectives on cognition such as natural computation (with its different representations, info-computation, and morphological computation) account for embodiment in a natural way, whereby cognitive processes are considered to emerge from interactions (implemented as information exchanges/computations) of the agents in the world.

This event enabled an open and constructive debate on the perceived differences in the various perspectives of constructivist and computationalist accounts of computation, regarding the dynamics of information in its natural and artifactual realizations.

MORCOM 2021 brought together perspectives of morphological, physical, natural and embodied cognitive and intelligent computation, as well as other forms of unconventional conceptualization of computing, cognition and intelligence. We, as organizers, encouraged an open and constructive debate on the perceived differences in the various perspectives of constructivist and computationalist accounts of the dynamics of information in its natural and artefactual realizations. The contributed presentations gave diverse and complementary perspectives on these relevant subjects.

It is difficult to report or summarize the multiple, multi-level discussions that followed the presentations. In the following, a very brief account of the subjects of presented works provides a basic overview of the MORCOM Conference and its contributions.

2. MORCOM 2021 Contributions

2.1. Plenary Keynotes

Two contributors to MORCOM, **Aaron Sloman and Michael Levin**, two of the most original and creative researchers within this field, presented their talks as plenary keynote speakers of the summit in the form of a dialogue searching deep into the roots of cognition and intelligence in their substrate, as well as the mechanisms that lead to advanced behaviors that are difficult to explain within the framework of our conventional models. They addressed computation as morphogenesis (the origin and development of morphological characteristics, such as shape, form, and material composition in material bodies) on different levels of organization: physical, chemical, biological, cognitive, and the virtual-machine computation built on top of these levels. The idea of the keynote dialogue started in the context of the MORCOM conference with a focus on morphological computing, that is natural (unconventional) computing based on morphological properties of a computing substrate. However, it was soon clear that the topic and the dialogue was of general interest to the IS4SI community, and it was made a plenary keynote event.

This dialogue was indeed a meeting of two extraordinary minds, with a clear scientific agenda rooted in philosophical understanding, transcending the boundaries of diverse knowledge domains and practical applications. Just a few research fields that were involved in the keynote included: computing; biology; chemistry; physics; cognitive science; intelligence science, including biological and artificial intelligence; robotics; medicine; philosophy and more. Aaron Sloman and Michael Levin are opening new research avenues and anticipate future developments that will be relevant for multiple knowledge communities and practical applications.

Aaron Sloman's keynote "**Why Don't Hatching Alligator Eggs Ever Produce Chicks**?" addressed the spatial reasoning, as well as chemistry-based mechanisms, required for biological assembly, which also underpin these complex, species-specific, forms of intelligence. "Different hatchlings, such as baby alligators or turtles, have very different physical forms and very different capabilities. What chemical processes in eggs can determine both complex physical forms (including intricate internal physiology) and complex physical behaviors, unmatched by current robots? Production, within each individual, of bones, tendons, muscles, glands, nerve fibers, skin, hair, scales, or feathers, and also intricate networks of blood vessels, nerve-fibers and other physiological structures, are clearly chemistry-based, and far more complex than chemistry-based behaviors of shape changing organisms, such as slime molds. The combination of complexity, compactness, energy-efficiency, and speed of production of processes in an egg are also unmatched by human designed assembly lines. Early stages of gene expression are well understood, but not the later processes producing species-specific forms of intelligence in eggs. How are these extraordinarily complex assembly processes controlled?" Sloman suggests that they use virtual machines with "hitherto unknown, non-space occupying mechanisms, whose construction needs to be boot-strapped via multi-layered assembly processes far more complex than anything achieved in human designed assembly plants yet using far less matter and energy in their operation". For more details see [1].

Michael Levin's keynote "**Morphogenesis as a model for computation and basal cognition**" presented empirical and theoretical work that shows how "Embryos and regenerating systems produce very complex, robust anatomical structures and stop growth and remodeling when those structures are complete. One of the most remarkable things about morphogenesis is that it is not simply a feed-forward emergent process, but one that has massive plasticity: even when disrupted by manipulations such as damage or changing the sizes of cells, the system often manages to achieve its morphogenetic goal. How do cell collectives know what to build and when to stop?" He highlighted some important knowledge gaps in this process of anatomical homeostasis, which remain despite progress in molecular genetics, offering a perspective on morphogenesis as an example of a goal-directed collective intelligence that "solves problems in morphospace and physiological space and sketching the outlines of a framework in which evolution pivots strategies to solve problems in these spaces and adapts them to behavioral space via brains". He argued that "Neurons evolved from far more ancient cell types that were already using bioelectrical network to coordinate morphogenesis long before brains appeared" and showed "examples of work to read and write the bioelectric information that serves as the computational medium of cellular collective intelligences, enabling significant control over growth and form". Levin presented synthetic living proto-organisms known as xenobots as "a new example that sheds light on anatomic plasticity and the relationship between genomically specified hardware and the software that guides morphogenesis". He argued for "A new perspective on morphogenesis as an example of unconventional basal cognition that unifies several fields (evolutionary biology, cell biology, cognitive science, computer science) and has many implications for practical advances in regenerative medicine, synthetic bioengineering, and AI".

Video recordings of Sloman's talk and Levin's talk can be found in [2,3], respectively.

2.2. MORCOM Keynote

Jordi Vallverdú argued in his MORCOM keynote speech "**Cross-Embodied Cognitive Morphologies: Decentralizing Cognitive Computation Across Variable-Exchangable, Distributed, or Updated Morphologies**" that we have a human-centric view of morphological computing, while "there are other bioinspired examples or even technical possibilities that go beyond biological capabilities (like constant morphological updating and reshaping, which asks for remapping cognitive performances).", Vallverdú suggests "the necessity of thinking about cross-embodied cognitive morphologies, more dynamical and challenging than any other existing cognitive system already studied or created".

2.3. Invited Speakers

This year, the following invited speakers attended the conference: **Susan Stepney**, University of York, UK; **Vincent C. Müller**, The Technical University of Eindhoven, The Netherlands; **Lorenzo Magnani**, University of Pavia, Italy; **Rao Mikkilineni**, Golden Gate University, US; and **Zoran Konkoli**, Chalmers Technical University, Sweden.

Susan Stepney, in her invited speech "Designing Physical Reservoir Computers", argued that computation is often conceived of as a branch of discrete mathematics, using the Turing model, which works well for conventional applications. However, for embedded devices, "sensing and controlling complex physical processes in the real world. Other computational models and paradigms might be better suited to such tasks. For example, is the reservoir computing model, which exploits the dynamics of a material to perform computation directly, and can be instantiated in a range of different material substrates. This approach can support smart processing 'at the edge', allow a close integration of sensing and computing in a single conceptual model and physical package". However, "In order to ensure that these novel materials are indeed computing, rather than simply acting as physical objects, we need a definition of physical computing. I describe one such definition, called Abstraction-Representation Theory, and show how this framework can then be exploited to help design correctly functioning physical computing devices".

Our next invited speaker, **Vincent C. Müller** gave a talk "**The Aims of AI: Artificial and Intelligent**" in which he addressed the "Explanation of what 'artificial' means, especially in contrast to 'living'. First approximation of what 'intelligent' means, especially in contrast to a discussion of the Turing Test". He pointed out the importance of "not focusing on 'intellectual intelligence'; and on the human case; not relying on behaviour alone". He discussed "intelligence vs. rational behaviour, e.g., instrumental vs. general intelligence". Müller also presented "an aim for full-blown AI—a computing system with the ability to successfully pursue its goals". According to him, this ability "will include perception, movement, representation, rational choice, learning, as well as evaluation and revision of goals—thus morphology will contribute to the orchestration of intelligent behaviour in many but not all these cognitive functions".

Lorenzo Magnani's talk "**Cognition Through Organic Computerized Bodies. The Eco-Cognitive Perspective**" elaborated: "Eco-cognitive computationalism sees computation in context, exploiting the ideas developed in those projects that have originated the recent views on embodied, situated, and distributed cognition. Turing's original intellectual perspective has already clearly depicted the evolutionary emergence in humans of information, meaning, and the first rudimentary forms of cognition, as the result of a complex interplay and simultaneous coevolution, in time, of the states of brain/mind, body, and external environment". According to Magnani, "It is by extending this eco-cognitive perspective that we can see that the recent emphasis on the simplification of cognitive and motor tasks generated in organic agents by morphological aspects implies the construction of appropriate mimetic bodies, able to render the accompanied computation simpler, according to a general appeal to the "simplexity" of animal embodied cognition".

Rao Mikkilineni in his talk "**Digital Consciousness and the Business of Sensing, Modeling, Analyzing, Predicting, and Taking Action**" argued that "Recent advances in genomics, neuroscience and general theory of information are pointing to a new understanding of how information processing structures in nature operate. Living organisms use autopoietic and cognitive behaviors to manage the business of sensing, modeling, analyzing, predicting, and taking action to maintain stability in the face of non-deterministic and rapid fluctuations while dealing with finite resources. Autopoiesis provides self-management of the organism with an identity, and the ability to reconfigure its structure to maintain stability. Cognition allows sensing, analyzing, predicting, and acting to mitigate risk. This paper examines the key ingredients required to infuse autopoietic and cognitive behaviors into digital automata and make them self-managing to maintain stability in the face of fluctuations and mitigate risk in dealing with the external world".

Zoran Konkoli presented the work in collaboration with **Ignacio Del Amo** "**On Leveraging Topological Features of Memristor Networks for Maximum Computing Capacity**" claiming that "Memristor networks have been suggested as a promising candidate for achieving efficient computation for embedded low-power information processing solutions. The goal of the study was to determine the topological features that control the computing capacity of large memristor networks. As an overarching computing paradigm, we have use reservoir computing approach". In this study, "The reservoir was implemented using a cellular automata model of a memristor network. The ideas were tested on a binary classification problem with the goal of determining whether a protein sequence is toxic or not".

2.4. Contributing Authors

The contributing authors at MORCOM 2021 were **Guillermo Rodriguez-Navas**, Nokia Bell Labs—IL/Kfar Sava; **Ana Teixeira de Melo**, University of Coimbra, Portugal; **Gordana Dodig-Crnkovic**, Chalmers University of Technology, Sweden and **Marcin J. Schroeder**, Tohoku University, Sendai, Japan.

Guillermo Rodriguez-Navas contributed a paper "**A morphogenesis perspective on deterministic communication networks: time to overcome the positional information paradigm**?" pointing out that "a fundamental challenge in real-time deterministic communication networks which are basic components of current distributed critical systems" is to "integrate the notions of adaptability/resilience and determinism". In this paper he argues that "theoretical biology gives a new perspective into these problems and helps us to identify the limitations of the existing paradigm and how it can be combined with other mechanisms found in nature". Given that the "traditional techniques for real-time communication do not scale well and are not sufficiently resilient" because of "heavy computation required for analyzing and guaranteeing schedulability in uncertain conditions, which leads to reconfiguration solutions that are fast but too constrained or flexible but too slow".

Rodriguez-Navasargues argued "that a more profound revision of the architectural principles of real-time communication networks is required to build systems that can satisfy both determinism and resilience in efficient ways. Based on our experience, which we are sharing in this paper, a deeper study of theoretical biology, and specifically *morphogenesis* and *biosemiotics*, helps to understand some limitations of the current approaches and can also lead towards novel design strategies".

It is not surprising that "the study of *pattern formation* in living organisms sheds light on the possible methods to create predictable communication/computation patterns between computers".

Moreover, importantly, it is pointed out that "the engineers have been using only one of the reigning theories for morphogenesis: the Positional Information mechanism. Other mechanisms existing in nature, which are based on Reaction-Diffusion patterns (as originally stated by Alan Turing in his seminal paper), have not been investigated. This is definitely a direction to explore in order to achieve self-generation of patterns as a way to implement self-healing, self-configuration, etc. The main challenge, as pointed out by theoretical biologists, is to identify and understand the role of the *morphogens*; it is, the substances responsible for activation and inhibition of the pattern. The embodiment of these functions as signs (messages) exchanged between nodes is not intuitive, but we hope that current investigations on cellular communication will inspire us. At present, we are trying to express an existing algorithm for distributed Self-Healing of real-time networks as a RD mechanism".

Ana Teixeira de Melo's contribution, "**Conceptualising and designing (co)augmented intelligence(s) enacting complex thinking: reflections on the morphological constraints, challenges and implications**" is based on "a recent proposal of a pragmatically oriented framework of 'Complex Thinking' (CT)(Melo, 2020) which is grounded in an enactive approach and a relational worldview". Melo discusses applications for the "design of human and computer-guided tools and strategies, or 'Other' cognitive systems (e.g.,) which, coupled with a given human observer would support and augment the enactment of key properties of CT in its own coupling with a target system of interest".

This presentation calls for "new interdisciplinary dialogues and projects to explore the theoretical, methodological, pragmatic and ethical challenges and implications of conceptualizing and designing the tools, strategies and morphological constraints of systems of (Co)Augmenting Intelligences oriented to scaffold the enactment of Complex Thinking".

Gordana Dodig-Crnkovic in her work on "Morphological Computation as Natural Ecosystem Service for Intelligent Technology" presented the basic idea of a naturalist approach to computing as learning from nature. She emphasized that "Naturalist framework provides info-computational architecture for cognizing agents, modelling living organisms as informational structures with computational dynamics. Intrinsic natural information processes can be used as natural ecosystem services to perform resource-efficient computation, instead of explicitly controlling every step of computational process. In robotics, morphological computing is using inherent material properties to produce behavior like passive walking or grasping. In general, morphology (structure, shape, form, material) is self-organizing into dynamic structures resulting in growth, development, and decision-making that represent processes of embodied cognition and constitute naturalized basis of intelligent behavior".

Marcin J. Schroeder presented "Morphological computation as morphogenesis: from Leibniz and Goethe to René Thom and beyond". The paper is "intended as an exploration of the potential methodology for hypercomputing using the long intellectual experience of the study of morphology and morphogenesis. The first part of the paper shows that the missing element of the process of computation in the studies searching for the generalization of computation is encoding. Turing Machines can work only on information encoded in a very specific way. When we look for ways to generalize computation, the analysis of encoding is the most likely source of ideas for the extension of this concept. The second part of the paper is an exploration of the history of morphogenesis from the perspective of the search for a method of unconventional encoding information".

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