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NATURAL INFORMATION, MORPHOLOGICAL COMPUTATION, COGNITION, AND INTELLIGENCE

Towards common framework for natural and artificial cognition and intelligence

GORDANA DODIG-CRNKOVIC

CHALMERS UNIVERSITY OF TECHNOLOGY

GOTHENBURG, SWEDEN

dodig@chalmers.se

http://www.gordana.se

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HIGHLIGHTS OF THE TALK

An info-computational framework for analysis of cognition and intelligence, natural and artificial, is a foundation for the study of information processing/computational phenomena.

It enables two-way learning: from nature to constructive study of artifacts (such as deep neural networks, machine learning and robots) and from increasingly sophisticated artifacts back to models and theories of natural systems (such as brains, swarms, or unicellular organisms).

At the time when the first models of cognitive architectures have been proposed, some forty years ago, understanding of cognition, embodiment and evolution was substantially different from todays.

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The state of the art of information physics, information chemistry, bioinformatics, neuroinformatics, computational neuroscience, complexity theory, self-organization, theory of evolution, as well as the basic concepts of information and computation made a substantial progress in past 40 years.

Novel developments in those sciences support a constructive interdisciplinary framework for cognitive architectures based on natural morphological computing, where interactions between constituents at different levels of organization of matter-energy and their corresponding time-dependent dynamics, lead to complexification of agency and increased cognitive capacities of living organisms that unfold through evolution.

Proposed info-computational framework for naturalizing cognition considers present updates (generalizations) of the concepts of information, computation, cognition, and evolution in order to attain an alignment with the current state of the art in corresponding research fields.

LEARNING FROM BIOLOGY REQUIRES UPDATE OF DEFINITIONS

Information = structure - means not only news and artifacts in our human civilization that are used to transmit data and knowledge, but similar structures utilized by other living organisms, even the simplest ones like bacteria.

Computation = dynamics of information - is taken to be any process of information transformation, that leads to behavior, and not only those processes that we currently use to calculate, manually or with machinery.

Cognition is ability to learn from environment and adapt so to survive as individual and species, for which organisms use information and its processing/computation. Intelligence as capacity for problem-solving can be found in all organisms as they all possess cognition. Finally, understanding cognition and intelligence because of biological mechanisms is only possible if we see it in the context of evolution.

Evolution understood as *extended evolutionary synthesis* formulation of evolutionary theory, which is the interpretation of the theory of evolution based on the newest scientific knowledge about life and its changes, emphasizing fundamental mechanisms of constructive development and reciprocal causation with environment.

LEARNING ABOUT COGNITION FROM BIOLOGY

Understanding of cognition is typically based on Cognitive science with roots in psychology and philosophy of mind, historically focused on the *human as cognizing agent*.

Recently (Piccinini 2020) presented his view of cognition as a result of *neurocomputation in organisms with nervous systems, thus acknowledging neural processes as computation.*

Even though Piccinini goes a step beyond anthropocentric understanding of cognition, he retains neurocentrism.

BASAL COGNITION AND INTELLIGENCE

However, recent research finds 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.*" (Levin et al. 2021). Thus, we generalize cognition a step further, to include all living forms, not only those with nervous systems.

It can be useful for artificial systems that need level of intelligence but not human level, such as nano-bots or different elements of IoT.

LEARNING FROM NATURE TO COGNITIVELY/ INTELLIGENTLY COMPUTE REQUIRES UNDERSTANDING EVOLUTION

In the info-computational approach to cognition and intelligence, evolution is understood in the sense of extended evolutionary synthesis (Laland et al. 2015; Ginsburg and Jablonka 2019; Jablonka and Lamb 2014) and it is a result of interactions between natural agents, cells and their groups on variety of levels of organization as Jablonka and Lamb argue in their "Evolution in Four Dimensions: Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life". These dimensions can be found on different level of organization of life.

BACTERIAL COGNITION AND CHEMICAL LANGUAGE

For example, symbolic information processing can be found both on the level of human languages, but also on the level of chemical languages used by bacteria, as Bassler (Bacterial quorum sensing) and Ben-Jacob (Bacterial Know How: From Physics to Cybernetics) have described.

A framework of natural cognition based on info-computation in living agents enables unification of natural and artificial cognition and intelligence. Cognition in nature is a manifestation of biological processes in all living beings, that subsume chemical and physical levels.

Intelligence is considered a problem-solving ability on different levels of organization.

*https://www.ted.com/talks/bonnie_bassler_how_bacteria_talk

EVOLUTION PROVIDES GENERATIVE MECHANISM

New insights about cognition and its evolution and development in nature from cellular to human cognition can be modelled as natural information processing/ natural computation/ morphological computation. In the info-computational approach, evolution in the sense of extended evolutionary synthesis is a result of interactions between natural agents, cells, and their groups.

Evolution provides generative mechanism for the emergence of increasingly more competent living organisms with increasingly complex natural cognition and intelligence which are used as a template for the artificial/computational counterparts.

CONTINUUM OF NATURAL COGNITIVE ARCHITECTURES

Recent comprehensive overview of 40 years of research in cognitive architectures, (Kotseruba and Tsotsos 2020), evaluates modelling of the core cognitive abilities in humans, but only briefly mentions biologically plausible approaches.

However, there is an important new development of biologically inspired computational models that can lead to biologically more realistic cognitive architectures.

Unlike vast majority of artificial cognitive architectures, that target human-level cognition, we would like to focus on the development and evolution of the continuum of natural cognitive architectures, from basal cellular up, as studied by (Levin, 2021).

NATURAL COMPUTATION BEHIND EVOLUTION

"And how about the entire universe, can it be considered to be a computer? Yes, it certainly can, it is constantly computing its future state from its current state, it's constantly computing its own time-evolution!

And as I believe Tom Toffoli pointed out, actual computers like your PC just hitch a ride on this universal computation!" (Chaitin, 2006)

https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.414.4009&rep=rep1&type=pdf What is Computation?

(How) Does Nature Compute? David Deutsch in A Computable Universe by Hector Zenil

*http://www.gordana.se/work/PUBLICATIONS-files/2007-Epistemology%20Naturalized.pdf

COMPUTING NATURE

Computing Nature (Naturalist computationalism) framework makes it possible to describe all cognizing agents (living organisms and artificial cognitive systems) as informational structures with computational dynamics [Dodig-Crnkovic, 2006-2020].

Morphological computation in this framework is a process of creation of new informational structures, as it appears in nature, living as non-living. It is a process of morphogenesis, which in biological systems is driven by development and evolution.

COGNITION = LIFE*

Cognitive architectures generated by natural (morphological) computation are realized in a specific substrate of matter/energy self-organized in living cells [Dodig-Crnkovic, 2012].

Cognition in living systems/agents constitutes life-organizing, life-sustaining goal-directed processes, while in artifactual systems, cognition is engineered process based on sensors, actuators and computing units designed to mimic biological cognition (bio-mimetic design).

Currently, cognitive computing mimics human-level cognition such as in:

D. S. Modha, R. Ananthanarayanan, S. K. Esser, A. Ndirango, A. J. Sherbondy, R. Singh (2011) Cognitive Computing. Communications of the ACM, Vol. 54 No. 8, pp 62-71

* Stewart, John. 1996. "Cognition = Life: Implications for Higher-Level Cognition." Behavioral Processes 35: 311-326.

Maturana, Humberto, and Francisco Varela. 1992. The Tree of Knowledge. Shambala.

BASAL BIO-COGNITION

Work of Michael Levin suggests broad range of applications for nature-inspired cognitive architectures based on biological cognition connecting genetic networks, cytoskeleton, neural networks, tissue/organ, organism with the group (social) levels of information processing.

Levin shows how biology has been computing through *somatic memory* (information storage) and *biocomputation/decision making* in *pre-neural bioelectric networks*, before the development of neurons and brains.

Insights from bio-cognition can help the development of new AI platforms, applications in targeted drug delivery, regenerative medicine and cancer therapy, nano-technology, synthetic biology, artificial life, and much more.

LEARNING FROM BASAL BIO-COGNITION

Unlike self-organized natural cognitive agents, engineered cognitive computational agents are essentially dependent on human-made infrastructure for their existence and maintenance.

Types of physical/morphological computation in solid-state inanimate matter used for computers today are *not capable of self-organizing cognitive agency that is fundamental feature of living organisms*. Their cognition is governed by language-based information processing without ‘8real-time) intrinsic connection with autonomous agency which all living creatures have.

Engineered cognitive systems can still learn a lot from living agents, even from the simple ones like unicellular organisms.

IMPORTANCE OF EMBODIMENT FOR COGNITION

Mechanisms of cognition, based on natural computation/ morphological computation are far more sophisticated than the machine-like classical computationalist models based on abstract symbol manipulation [Kampis, 1991].

They conform to the view expressed by [Witzany, 2000] and [Witzany and Baluska, 2012] that *the rule-based machines are not good enough models of natural cognition of highly complex living organisms*.

Embodiment is the fundamental characteristics of cognition, which implies that senses, feelings and emotions must be considered as constitutive of cognition [Dodig-Crnkovic, 2017a].

COMPUTING THE FOURTH SCIENTIFIC DOMAIN

Info-computational approach incorporates our best current scientific knowledge about the processes in nature, translating them into language of natural info-computation.

The aim of this approach to cognition is to increase understanding of cognitive processes in diverse types of agents, biological and synthetic, including their ability of learning, and learning to learn (meta-learning) [Dodig-Crnkovic, 2020], as well as their communications and mutual interactions.

Peter J. Denning (2010) Computing Science: The Great Principles of Computing. American Scientist, Vol. 98, No. 5, pp. 369-372

"Computing may be the fourth great domain of science along with the physical, life and social sciences"

Paul S. Rosenbloom (2015) "On Computing: The Fourth Great Scientific Domain" (The MIT Press)

BIOMIMETIC DESIGN

- Biomimetic Design of Cognitive Architectures. *What does it mean "Biologically Plausible"?*
- Cognitive Behaviors and their Simulation, Emulation and Engineering
- Two open questions that run in parallel, providing an opportunity for two-way learning between computing and neuroscience (Rozenberg and Kari 2008).

  - *How cognition works and develops in nature, and*
  - *How we can simulate, emulate and engineer it.*

CHARACTERISTICS OF ORGANIC NEUROMORPHIC SYSTEMS*

- Involvement of the same elements for memorizing and processing of the information
- Variation of electrical properties according to the Hebbian (or alternative) learning rule (electronic synapse)
- Possibility of working in the auto-oscillation generation mode
- Formation of stable chains of the signal transfer (balance between plasticity and stable long-term connections)
- Materials used for electronic compounds must allow self-organisation into 3D systems mimicking intrinsic brain functions

* (Human)Brain-like computing

Victor Erokhin (2022) “Fundamentals of Organic Neuromorphic Systems”. Springer
Johan Åkermans group Gothenburg University, https://www.gu.se/en/news/an-oscillator-chip-inspired-by-the-brain An oscillator chip inspired by the brain

CONTINUUM OF BIOLOGICAL COMPUTATIONAL MECHANISMS

"We have previously argued that the deep evolutionary conservation of ion channel and neurotransmitter mechanisms highlights a fundamental isomorphism between developmental and behavioral processes. Consistent with this, membrane excitability has been suggested to be the ancestral basis for psychology (). Thus, it is likely that the cognitive capacities of advanced brains lie on a continuum with, and evolve from, much simpler computational processes that are widely conserved at both the functional and mechanism (molecular) levels. The information processing and spatio-temporal integration needed to construct and regenerate complex bodies arises from the capabilities of single cells, which evolution exapted and scaled up as behavioral repertoires of complex nervous systems that underlie familiar examples of Selves."

Michael Levin (2019) The Computational Boundary of a "Self": Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition. Front. Psychol., 13 December 2019 |
https://doi.org/10.3389/fpsyg.2019.02688 https://www.frontiersin.org/articles/10.3389/fpsyg.2019.02688/full

LEARNING FROM BASAL BIOLOGICAL COMPUTING

- The concept of biological computation proposes that living organisms perform computations, and that as such, abstract ideas of information and computation may be key to understanding biology.[1][2]*
- *Apart from human brain with nervous system, somatic cells, non-human organisms with nervous system, non –neuronal subsystems in humans such as immune system*

Gordana Dodig-Crnkovic (2021) Cognition as a Result of Information Processing in Living Agent's Morphology. Species-specific Cognition and Intelligence. Proceedings of SweCog 2021 Conference. file:///Users/dodig/gordana.se-httpd.www/work/PUBLICATIONS-files/2021-11.10-SWECOG-2021-GDC.pdf

https://en.wikipedia.org/wiki/Biological_computation#searchInput
Mitchell M (2010-09-21). "Biological Computation". Computer Science Faculty Publications and Presentations,

LEARNING FROM BASAL BIOLOGICAL COMPUTING

- *Computational Efficiency* of Natural Computing. The Turing Machine model of computation is not resource-aware, unlike living systems are constantly optimizing their resource use.
- Von Neumann architecture has bottlenecks, processor and memory are separate. Memristors biomimetic solution combines memory and processor and avoids von Neumann bottlenecks.

Ihor Lubashevsky (2017) "Physics of the Human Mind", Springer

Kevin M. Passino (2005) Biomimicry for Optimization, Control, and Automation, Springer

Bernard Baars, Nicole Gag (2010) Cognition , brain, and consciousness : introduction to cognitive neuroscience

LEARNING FROM BIOLOGICAL COMPUTING

- *Temporal aspects of Cognitive Architectures/Intelligent systems* are central for living systems that adjust their behavior to the events in the environment. The Turing Machine has no real time, only consecutive steps in calculation, so it is not well suited for modelling of complex scheduling and time-dependences characteristic of biological systems. For that end interactive computation (Wegner, Goldin) and morphological computation as type of interactive computation can be used.

Subrata Ghosh, Krishna Aswani, Surabhi Singh, Satyajit Sahu, Daisuke Fujita and Anirban BandyopadhyayInformation (2014), 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 5, 28-100; doi:10.3390/info5010028, https://www.mdpi.com/2078-2489/5/1/28

IN WHAT WAY IS MORPHOLOGICAL COMPUTATION/PHYSICAL COMPUTATION/ ANALOG COMPUTATION (PHYSICAL INFORMATION PROCESSING) COMPUTATION AT ALL?

Burgin, M. and Dodig-Crnkovic, G., A Taxonomy of Computation and Information Architecture. ECSA 2015 ASDS Workshop. In Proceedings of the 2015 European Conference on Software Architecture Workshops (ECSAW '15). ACM, New York, NY, USA. DOI=10.1145/2797433.2797440

http://www.gordana.se/work/PRESENTATIONS-files/ComputationTaxonomyArchitecture-ASDS-ECSA-20150907.pdf

1. Physical or embodied (object-based) computations
2. Abstract or structural (sign-based) computations
3. Cognitive or Mental (interpretant-based) computations

The above constitutes layered computational architecture in cognitive agents. *So we could also call it architectural taxonomy of computation.*

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The author will be happy to discuss any questions.

Also by email: dodig@chalmers.se

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