Natural Information Processes, Cognition, and Intelligence

Conceptual Analysis in the Search of Common Framework for Natural and Artificial Cognition and Intelligence

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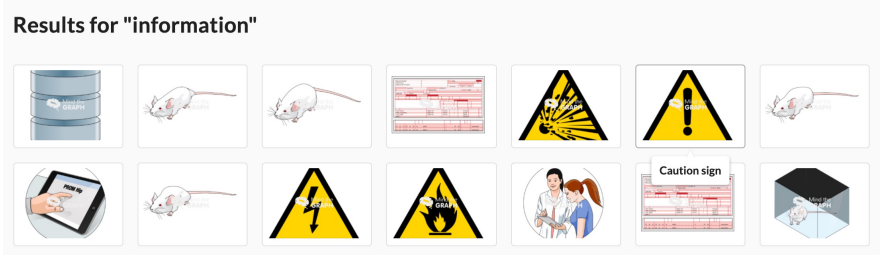
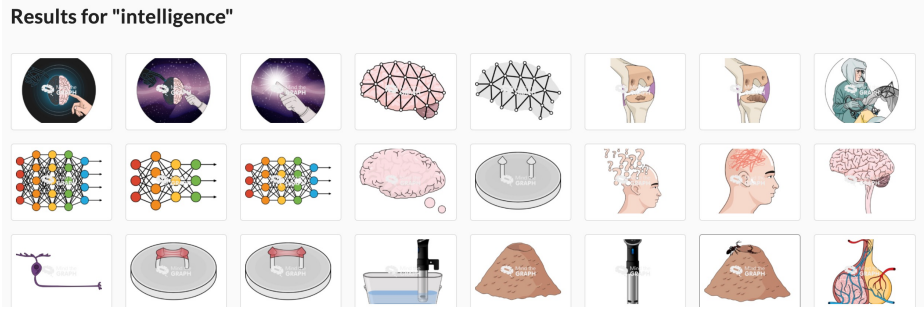
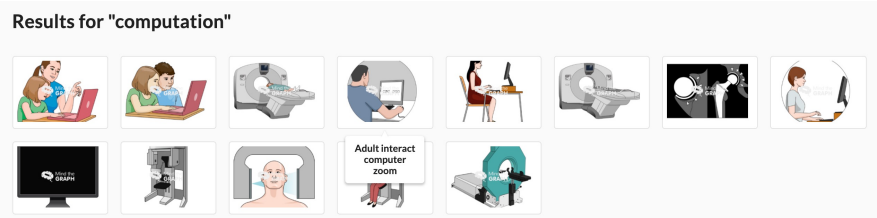
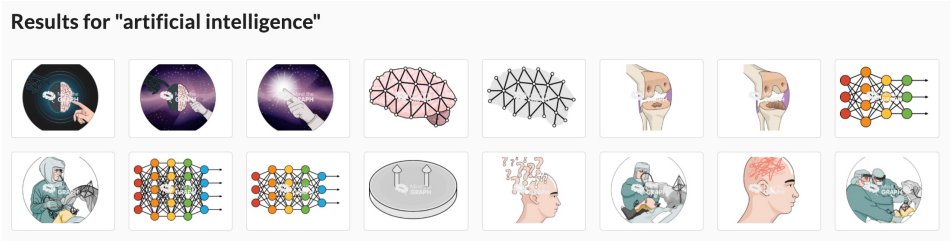
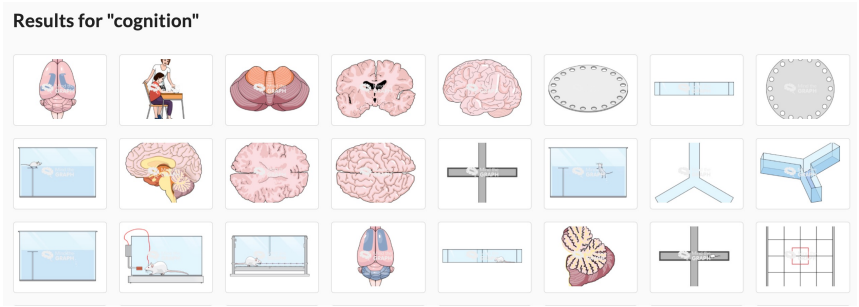
Information, Computation, Cognition, and Intelligence: Searching for relationships in graphical representation - Graphical abstract











https://mindthegraph.com

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Abstract: A common framework for conceptual analysis of cognition and intelligence, natural and artificial, enables study of information processing/computational phenomena based on the up-to date knowledge of underlying scientific fields. 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) and back. Building such an info-computational framework requires generalization of involved concepts:

information -to mean 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 is taken to be any process of information transformation, that leads to decision-making and 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. We adopt 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.

Keywords: Information, Computation, Cognition, Intelligence, Extended Evolutionary Synthesis

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New concepts introduced in this framework

Information is the fabric of the universe/nature. For a cognitive agent, information is the basis or reality on which decisions are made and behavior is based.

Computation in this context is *information processing that enables decision making.*

Cognition is generalized to include characteristics of all living forms, not only humans or organisms with nervous systems. Cognition is a network of life-sustaining processes that enables every living organism to perceive its environment, react adequately and adapt so to survive as individuals and species.

Evolution is seen as Extended evolutionary synthesis, which considers that not only random mutations, but also sequences of changes caused by laws of physics and chemistry (that can be described as morphological computation) leads to the development of new structures which are then exposed to natura lselection.

https://extendedevolutionarysynthesis.com/about-the-ees/

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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.

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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.

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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.

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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

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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.

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

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Cognitive Architectures: Core Cognitive Abilities and Practical Applications

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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 based on natural computation.

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

Unlike vast majority of artificial cognitive architectures, that target huma-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).

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Cognitive Architectures in a Continuum from Unicellular to Human-level Social Cognition

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We use evolutionary info-computational framework, where natural/ physical/ morphological computation leads to evolution of increasingly complex cognitive systems, from abiotic to simplest unicellular biotic, and from there to increasingly complex multicellular organisms.

Forty years ago, when the first artificial cognitive architectures have been proposed, understanding of cognition, embodiment and evolution in nature was very different from today. Important new insight have been made in 40 years.

Similar is the case for information physics, bioinformatics, information chemistry, computational neuroscience, complexity theory, self-organization, theory of evolution, information and computation that experienced explosive development during past forty years.

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Computing Nature – Natural Computationalism – The Universe that Computes

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"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

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Information as a Substrate of Natural Computation

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If Nature computes, what is the substrate on which computation is performed?

It is INFORMATION (as developed in Floridi's Informational Structural Realism)

Here we distinguish two kinds of information:

- Ontological (information as the case, what universe is)
- Epistemological (information as the basis of knowing)

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Cognitive Architectures Based on Natural Info-Computation

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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.

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Cognitive Architectures Based on Natural Info-Computation

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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).

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Pre-neural Biocomputation

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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 biocognition 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.

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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.

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Natural info-computational model of reality for an agent includes agent itself and the world as it appears for the agent (Umwelt).

Computation is information processing (Burgin, 2005).

In other words, in general, *computation is natural information transformation* [Rozenberg, Back, Kok, 2012] [Stepney et al., 2005, 2006; Stepney, 2008] and [MacLennan, 2004], *on different levels of organization* (physics, chemistry, biology, cognition) [Dodig-Crnkovic, 2017a-c] [Burgin and Dodig-Crnkovic, 2015).

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Evolutionary process in living organisms, in the sense of extended evolutionary synthesis [Jablonka, Lamb, Zeligowski, 2014], [Laland et al. 2015] unfolds as a result of interactions of living agents with the environment, including other living agents.

It starts with the first simplest pre-biotic structures and leads to more complex forms such as viruses and bacteria, continuing up in complexity through the evolution of species, from single cells to humans, [Dennett, 2018] [Dodig-Crnkovic, 2015].

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Info-computational framework is treating *cognition as an open-ended process of self-organization where computation for the most part proceeds as signal processing in natural systems, and only under special circumstances it takes form of symbol manipulation and language-based communication* [Ehresmann, 2012].

Both living and engineered info-computational artifacts possess various degrees of cognitive capacities [Dodig-Crnkovic, 2018; 2017a-c].

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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].

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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.

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Cognitive Architectures Based on Natural Info-Computation

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The focus is on the understanding of the fundamental mechanisms of cognitive processes based on natural information and morphological computation, which boils down to the study of the structures and their dynamics at different levels of organization.

As the development of increasingly sophisticated artificial intelligent cognitive computational systems rapidly progresses, a framework that can seamlessly connect the natural with the artificial is useful for learning in both directions – from the natural system to the model and back.

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Conclusions: Some Open Questions of Cognitive Architectures and Natural Info-Computation

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- Biomimetic Design of Cognitive Architectures. *How "Biologically Plausible" is Enough?*
- 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.

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Conclusions: Some Open Questions of Cognitive Architectures and Natural Info-Computation

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- *Computational Efficiency* of Natural Computing. The Turing Machine model of computation is not resource-aware, unlike living systems are constantly optimizing their resource use.
- *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.

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