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## Morphological Computation and Learning to Learn In Natural Intelligent Systems and AI

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https://www.mdh.se/en/malardalen-university/staff?id=gdc01 https://www.chalmers.se/en/staff/Pages/gordana-dodig-crnkovic.aspx http://www.es.mdh.se/staff/37-Gordana\_Dodig\_Crnkovic

#### AI, Deep Learning, System1 and System2 "Thinking" – Mapping the Territory

At present, AI in the form of machine learning is making impressive progress, especially the field of deep learning.

Deep learning algorithms have been inspired by nature, specifically by the human brain, in spite of our incomplete knowledge about brain function. However, deep-learning intelligence is lacking distribution generalization, compositionality and common-sense reasoning.

The solution recently proposed by Yoshua Bengio\* is based on agency, causality, attention and consciousness as mechanisms of learning and meta-learning (learning to learn).

They are used as the basis for deep learning to go beyond Kahneman's\*\* System 1 (fast, unconscious task solving) to System 2 (slow, conscious, reasoning, planning etc.).

\* Y. Bengio, "From System 1 Deep Learning to System 2 Deep Learning (NeurIPS 2019)," 2019. \*\* D. Kahneman, Thinking, Fast and Slow. New York: Farrar, Straus and Giroux, 2011

#### From System 1 to System 2 in Deep Learning

Step from System 1 to System 2 is proposed through two approaches, both using self-supervised learning.

One possibility is to learn by predicting missing parts in the actual input space of image, text, or audio.

Another approach is to learn by predicting in an abstract space, similar to our brains. The predicting in abstract space is based on conscious task solving that learns representations derived from a high dimensional vector space using attention.

This low dimensional vector, when learned with the right training objective, could identify a few variables capturing causal relationships and could be used for reasoning, planning etc.

[Y. Bengio, "The Consciousness Prior," arXiv:1709.08568v2, 2019.

Y. Lecun, Y. Bengio, and G. Hinton, "Deep learning," Nature. 2015.

Y. Bengio, "From System 1 Deep Learning to System 2 Deep Learning (NeurIPS 2019)," 2019.

Y. Bengio, "Scaling up deep learning," 2014. KDD '14: Proceedings of the 20th ACM SIGKDD international conference on Knowledge discovery and data mining. Pages 1966 https://doi.org/10.1145/2623330.2630802

# Learning from Nature and Testing Models on Practical Solutions/Technology – A Two-way Process

Learning from nature is a two-way process as discussed in literature\*. Computing is learning from neuroscience, while neuroscience is quickly adopting new computational/information processing models.

The question is, what can the inspiration from computational nature\*\* at this stage of the development contribute to further development of deep learning and how much models and experiments in machine learning can motivate, justify and lead research in neuroscience and cognitive science and to practical applications of artificial intelligence.

\* G. Rozenberg and L. Kari, "The many facets of natural computing," Commun. ACM, vol. 51, pp. 72–83, 2008. \*\*G. Rozenberg, T. Bäck, and J. N. Kok, Eds., Handbook of Natural Computing. Berlin Heidelberg: Springer, 2012. Learning From Nature about Cognition and Intelligence and the Development of New Models of Cognition and Computation. The Meaning of "Mapping the Territory"

"I invite readers not on a visit to an archaeological museum, but rather on an adventure in science in making"

Ilya Prigogine. The End of Certainty: Time, Chaos and New Laws of Nature, 1997

"Biology and computer science—life and computation—are related. I am confident that at their interface great discoveries await those who seek them."

Leonard Adleman. Computing with DNA. Scientific American, Aug. 1998

"In these times brimming with excitement, our task is nothing less than to discover a new, broader, notion of computation, and to understand the world around us in terms of information processing."

Lila Kari, Grzegorz Rozenberg, The Many Facets of Natural Computing. Communications of the ACM, October, Vol. 51 No. 10, Pages 72-83. 2008

Beyond Conventional Computing/Calculating: Natural Computing/Physical Computing/Morphological Computing/Unconventional Computing

The progress of computing depends on the development of hardware and software. This includes algorithms, programming languages, compilers and interpreters, operating systems, virtual machines, etc. Yet Computability Theory is still based on the Turing Machine Model of computation.

One of the ideals of computing ever since the time of Turing is *intelligent computing*, which would imply machine capable of not only executing predefined mechanical procedure, but even intelligent problem solving.

Thus the goal is a computer able to simulate behaviour of human *mathematician*, capable of intelligent insight.

A development of cognitive computing aims towards human-level abilities to process/organize/understand information.

#### Beyond Conventional Computing: Natural Computing



Natural computing is "the field of research that investigates both human-designed computing inspired by nature and computing taking place in nature." Handbook of Natural Computing

It includes, among others, areas of cellular automata and neural computation, evolutionary computation, molecular computation, quantum computation, nature-inspired algorithms and alternative models of computation.

## Learning

Learning process is central for acquiring, maintaining, and managing knowledge, both theoretical (knowledge that) and practical (knowledge how).

We explore the relationships between the present advances in understanding of learning in the sciences of the artificial (deep learning, robotics), natural sciences (neuroscience, cognitive science, biology), and philosophy (philosophy of computing, philosophy of mind, natural philosophy).

The question is, what at this stage of the development the inspiration from nature, specifically its computational models such as info-computation through morphological computing, can contribute to machine learning and artificial intelligence.

## Learning to Learn

Yoshua Bengio, (the 2018 ACM Turing Award, together with Geoffrey Hinton, and Yann LeCun) proposes to continue developing machine learning in the direction of unification between sub-symbolic and symbolic information processing\* i.e., Kahneman's System 1 and System 2.

One contribution in the development is the understanding of the mechanisms of 'learning to learn', as a step towards deep learning with symbolic layer of computation/information processing in a framework linking connectionism with symbolism.

Given that natural systems possessing intelligence are cognitive systems, we describe the evolutionary arguments for the necessity of learning to learn for a system to reach humanlevel intelligence through evolution and development.

## (Disembodied) Knowledge and Cognition

In the beginning, cognition was considered as the connection between information and knowledge, without elaboration either on the processes that precede information or those which come after knowledge is constructed.

This old view of (disembodied) cognition is directly connected with old computationalism – symbol manipulation view of mind.

#### GOFAI and Expectation of "Substrate Independence"

Both cognition and AI have been envisaged as results of logical operations, either on the information obtained directly from the perception and stored in the memory in humans, or from the data bases and online searches in the machines.

However, as the limitations of the GOFAI (good old-fashioned AI) have shown, cognition and intelligence in humans are substantially dependent on their embodiment, thus not only logical processes of reasoning, but also on their form (morphology on different levels of organization), physics and chemistry (thus details of implementation of information processing mechanisms).

Studies in simpler living beings, from the simplest ones like viruses that act like molecular machines to unicellular organisms like bacteria and up to humans, show clear connection between the physical embodiment and cognition or intelligence.

In new computational approaches to cognition and intelligence body is integral part of those processes and computation is not only symbol manipulation but also physical processes know as natural computation or morphological computation. Those new models of computation appear under variety of names such as Natural computing/ Computing nature, Unconventional computing, Morphological computing, Physical computing etc.

#### Overcoming "The Bias Of Mathematicians" (Cooper)

Embodiment is invalidating the `machine as data' and universality paradigm.

The organic linking of mechanics and emergent outcomes provides a clearer model of supervenience of mentality on brain functionality, and a connection between different levels of effectivity.

A reaffirmation of experiment and evolving hardware, for both AI and extended computing generally.

The validating of a route to creation of new information through interaction and emergence.

S. B. Cooper, "Turing's Titanic Machine?," Communications of the ACM, vol. 55, no. 3, pp. 74–83, 2012

# Natural Computing – Morphological Computing – Nonconventional Computing

Morphology studies shape, structure, pattern and material.

Structure and material are related. In the description of physical systems – material on one level of abstraction is a structure on the level below, (e.g. atom is a structure of protons, neutrons and electrons).

Morphology is described by data/information which describe a structure.

Dynamical processes on informational structure are morphological computation.

Morphological computing is a specific approach to natural computing which models nature in terms of structures and processes on those structures.

Nonconventional computing stands for all models and applications of computing that differs from the conventional ones. Natural computing, unconventional computing, cognitive computing are examples.

### Transdisciplinary-Interdisciplinary-Multidisciplinary Character of Natural Computing



Peter J. Denning. 2007. Computing is a natural science. Commun. ACM 50, 7 (July 2007), 13-18. DOI: https://doi.org/10.1145/1272516.1272529

# Digital vs. Analog, Discrete vs. Continuous and Symbolic vs. Sub-symbolic Computation

"Symbolic simulation is thus a two-stage affair: first the mapping of inference structure of the theory onto hardware states which defines symbolic computation; second, the mapping of inference structure of the theory onto hardware states which (under appropriate conditions) qualifies the processing as a symbolic simulation. Analog simulation, in contrast, is defined by a single mapping from causal relations among elements of the simulation to causal relations among elements of the simulated phenomenon."

R. Trenholme, "Analog Simulation," Philosophy of Science, vol. 61, no. 1, pp. 115–131, 1994.

#### Symbolic vs. Sub-symbolic Computation



Hofstadter in his dialogue "Prelude...Ant fugue" in "Gödel, Escher, Bach". Hofstadter, Douglas R. Gödel, Escher, Bach: An Eternal Golden Braid. Basic Books, 1999.

## Turing Machines and a Modelling of Complex Systems



After: Leonardo, Mona Lisa



Arcimboldo: Librarian

Simplified, one can say: anything can be used to model anything else – for some cognizing agent. The question is how meaningful (or applicable or adequate) the model is for a given agent.

### Turing Beyond Turing Machine Model



2012 we celebrated 100<sup>th</sup> Turing birthday

Alan Turing was:

Mathematician

Originator of the "Logical Machine" (TM) computability theory

Codebreaker

Natural philosopher

Visionary man before his time







Researchers confirm that a mathematical theory first proposed by Alan Turing in 1952 can explain the formation of fingers <a href="https://www.crg.eu/en/news/crg-researchers-confirm-mathematical-theory-first-proposed-alan-turing-1952-can-explain-formation-fingers">https://www.crg.eu/en/news/crg-researchers-confirm-mathematical-theory-first-proposed-alan-turing-1952-can-explain-formation-fingers</a>

<u>http://www.cs.usfca.edu/www.AlanTuring.net/turing\_archive/index.html</u>Jack Copeland and Diane Proudfoot <u>http://www.turing.org.uk/turing\_</u>The Alan Turing Home Page, Andrew Hodges

### System 1 and System 2 "Thinking" – Knowledge and Learning

In humans, two basic cognitive systems have been recognized,

System 1 (reflexive, non-conscious, automatic, intuitive information processing, which is fast) and

System 2 (reflective, conscious, reasoning and decision making, which is slow) (Kahneman 2011; Tjøstheim et al. 2020)

As deep learning models are inspired by the human brain information processing, recent advances in understanding of natural cognitive systems can contribute both to better explanatory models and to future developments of constructive engineered cognitive architectures.

Deep learning level corresponds to Kahneman's fast, intuitive System 1 (Kahneman 2011), and current developments in AI are continuing towards even more ambitious goals of modelling System 2 (symbolic reasoning) (Russin, O'Reilly, and Bengio 2020).

#### Cognition and Intelligence – Embodied, Embedded, Enacted

Traditionally, in philosophy, psychology and cognitive science **only humans** were seen as cognitive and intelligent agents. Cognition and Intelligence were based on abstract symbol manipulation.

Today, with increasing insights into details and mechanisms of cognition, it is emerging that human cognition and intelligence are **based not only on** activities of brain and nerve cells\*, but the body in the interaction with the environment.

Equally important is new understanding of cognitive (sensory-based) and intelligent (problem-solving) processes that regulate the state of each living cell. Cognition is characteristics of all life.

In other words, both cognition and intelligence have INCREASED IN SCOPE with increased insights in their underlying mechanisms – from the activity on the level of the human brain, to the process on the cell level.

\* We are learning about the importance of glia cells for information processing in the brain

### Cognition and Intelligence

Inspired by the models of "minimal cognition" computational and robotic cognitive systems are developed with certain degree of cognition and intelligence (in comparison to human). Certain functions of artificial intelligence surpass humans (calculation, search, memory, in some cases processing speed and even sensor power) but many other are far below human level, such as common-sense reasoning or self-preservation.

Intelligence is a capacity closely connected with cognition:

Cognition = Process of "continual being in the world" of an agent. It is based on learning/adaptation. For living organisms cognition = process of life (perception, internal process control by information, actuation/agency)

Intelligence = Problem solving\* and learning adaptive behaviours of an agent within an environment/context

\* Human intelligence is often considered to be a multidimensional capability that includes both classical Problem-solving and Decision-making (logical-mathematical reasoning), Existential (ability to survive), Visual-Spatial, Bodily-kinesthetic, Naturalist, Linguistic, Interpersonal (social), and Intra-personal (inner insight) intelligence. Those can in a broader sense be seen as optimizations of different goal-directed behaviors.

#### Natural Cognition & Intelligence. Basic Level: Cells Processing Information



http://rsfs.royalsocietypublishing.org/content/4/3/20130070

<u>https://www.youtube.com/watch?v=wJyUtbn0O5Y&list=PLXPeXawEy4EcPnecIV1FaZA6bgVDujLzm&index=7</u> Harvard University XVIVO animation showing inner world of a cell

<u>http://www.youtube.com/watch?v=NJxobgkPEAo&feature=related</u> From RNA to Protein Synthesis <u>http://www.youtube.com/watch?v=3aVT2DTbtA8&feature=related</u> Replication, Transcription, and Translation

### Some (Very Mechanistic) Details of a Molecular Machinery



<u>https://www.youtube.com/watch?v=cwDRZGj2nnY</u> The Bacterial Flagellar Motor <u>https://www.youtube.com/watch?v=X\_tYrnv\_o6A</u> Body's Molecular Machines

#### Information Processing in Life Networks



A map of protein–protein interactions in yeast cell

Bacteria Network Ben-Jacob Bacteria display various multicellular behaviors: emitting, receiving and processing a large vocabulary of chemical symbols

Human brain connectome

Internet map

http://www.nature.com/nrg/journal/v5/n2/fig\_tab/nrg1272\_F2.html http://microbes-mind.net/ben-jacob/ https://en.wikipedia.org/wiki/ Eshel\_Ben-Jacob http://eldar.cz/cognition/complexEshel Ben Jacob Learning from Bacteria about Social Networks http://www.nature.com/news/neuroscience-making-connections-1.10260 http://www.humanconnectomeproject.org https://en.wikipedia.org/wiki/Opte\_Project

#### Microorganismic cognition

Microorganisms have sensors and actuators, and use chemical signaling and transfer of genetic information as a basis for adaptation and learning.



http://phys.org/news/2009-11-conquersocial-network-cells.html



Eshel Ben Jacob bacterial colony

Bacteria sense, adapt and communicate by "chemical language"



http://www.hhmi.org/research/global-mapping-geneticnetworks A functional network for a yeast cell



http://www.cellcognition.org/ The cell cognition project

#### Plant cognition

Plants do not have nervous system, but they have information-processing systems as a basis for adaptation, and learning. Plants selectively adapt to the resources in the environment which are available for their survival and reproduction.

signals Light (quality, quantity, duration, direction)

Mechanical, constant (substrate, support) Mechanical, variable (wind, herbivores)

Atmospheric humidity tension Other plants proximity Temperature Nutrients Water  $CO_2$ Pathogenes Gravity

Exogeneous Endogeneous signals Growth regulators (cytokinin, ethylene, gibberellin, auxin, abscisic acid, brassinosteroids)

> Mechanical, growth related tissue compression and

Defence signals Jasmonic acid Salicylic acid

Developmental regulators (mobile RNA)









Signal processing and transduction in plant cells: the end of the beginning? S. Gilroy and A. Trewavas (2001) Nature Reviews Molecular Cell Biology 2, 307-314

#### Dynamics of Long-distance Signaling via Plant Vascular Tissues

Notaguchi Michitaka, Okamoto Satoru (2015) Frontiers in Plant Science. Vol. 6 No. 00161 http://journal.frontiersin.org/article/10.3389/f pls.2015.00161/full

#### Plants: Adaptive behavior, rootbrains, and minimal cognition. Garzon, Paco; Keijzer, Fred (2011). " Adaptive Behavior. 19 (3): 155–171.

Plant behaviour and communication. Karban, Richard (2008). " Ecology Letters. 11 (7): 727–739. doi:10.1111/j.1461-0248.2008.01183.x. PMID 18400016.

#### Animal cognition Rudimentary forms of language

http://www.cellcognition.org/ The cell cognition https://en.wikipedia.org/wiki/Molecular cellular cognition





http://phys.org/news/2009-11-conquer-social-network-cells.html http://www.hhmi.org/research/global-mapping-genetic-networks A functional network for a yeast cell

http://www.visualcomplexity.com/vc/images/122\_big01.jpg Protein network



Fruit fly embrio



Fruit fly larva



Fruit fly brain neurons



#### Human cognition Complex language and material culture





Human connectome http://outlook.wustl.edu/2013/jun/human-connectome-project

# Connecting **domain specific language accounts**, from molecules to human languages:



http://d1vn86fw4xmcz1.cloudfront.net/content/royptb/367/1599/2119/F1.large.jpg

#### Deconstructing the Brain

The Human Brain Project intends to create a computer simulation of the 89 billion neurons inside our skull and the 100 trillion connections that wire those cells together. A meticulous virtual copy of the human brain would potentially enable basic research on brain cells and circuits or computer-based drug trials. The project, which is seeking €1 billion in funding from the European Union, would model each level of brain function, from chemical and electrical signaling up to the cognitive traits that underlie intelligent behaviors.







http://www.nature.com/scientificamerican/journal/ v306/n6/pdf scientificamerican0612-50.pdf p. 29 The Human Brain Project

#### Molecular

A century of research, beginning with the first inspection of a brain cell under a microscope, would translate into a digital facsimile that combines component molecular parts to assemble a cell that demonstrates the essential properties of a neuron the transmission of electrical and chemical signals.

#### Cellular

A brain-in-a-box simulation will have to capture every detail of neurons and nonneuronal glial cells, including the exact geometric shapes of the dendrites and axons that receive and send information.

#### Circuits

A model of the neural connections between different brain areas and among neighboring cells may furnish clues to the origins of complex brain diseases such as autism and schizophrenia.

#### Regions

Major neural substructures the amygdala (emotions), the hippocampus (memory), the frontal lobes (executive control) can be inspected alone or as they interact with one another.

#### Whole Organ

An in silico brain might substitute for the actual organ. By removing the computer code for a "gene," the virtual system can, for instance, minic the effects of a mutation, as scientists do today by "knocking out" a gene in mice. The tool would avoid the lengthy breeding process and could simulate a multitude of experimental conditions.

#### Cognition at Different Levels of Organization of Living Organism – From Cells up

Traditional anthropogenic approach to cognition – only humans are cognitive agents.

Biogenic approaches – cognition is ability of all living organisms. (Maturana & Varela, 1980; Maturana, 1970; Stewart, 1996), argued that cognition and life are identical processes.

"A cognitive system is a system whose organization defines a domain of interactions in which it can act with relevance to the maintenance of itself, and the process of cognition is the actual (inductive) acting or behaving in this domain. Living systems are cognitive systems and living as a process is a process of cognition. This statement is valid for all organisms, with and without a nervous system." (Maturana, 1970)

New abiotic approaches to cognition assume that it is possible to construct cognitive agents starting from abiotic.

Maturana Humberto, "Biology of Cognition," Defense Technical Information Center, Illinois, 1970. Maturana, Humberto, and Francisco Varela. 1992. The Tree of Knowledge. Shambala. Stewart, John. 1996. "Cognition = Life: Implications for Higher-Level Cognition." *Behavioral Processes* 35: 311-326.

# Connecting Anthropogenic with Biogenic and Abiotic Cognition

We propose the common framework for understanding Anthropogenic, Biogenic and Abiotic Cognition.

As in the all of biology, nothing makes sense except for in the light of evolution (Dobzhansky, 1973) and the cognition as a process can only be understood in the light of evolution.

Regarding abiotic systems we will compare their "cognitive behavior" with living organisms and draw conclusions.

#### Wonders of Evolution – The Smallest Insect With Brain, Smaller Than an Amoeba



Size of the smallest wasp and two protozoans in comparison.(A) Megaphragma mymaripenne.(B) Paramecium caudatum.(C) Amoeba proteus.

Scale bar for A–C is 200  $\mu$ m.

B and C are made up of a single cell, A the wasp complete with eyes, brain, wings, muscles, guts – is actually smaller.

This wasp is the third smallest insect alive.

the smallest nervous systems of any insect, consisting of just 7,400 neurons. Housefly has 340,000 Honeybee has 850,000. 95% of the wasps' neurons have no nucleus.

http://www.sciencedirect.com/science/article/pii/S1467803911000946 The smallest insects evolve anucleate neurons Arthropod Structure & Development, Volume 41, Issue 1, January 2012, Pages 29–34

#### Machine Cognition

Machines that sense, learn, reason/think and interact with us in natural language

# **COGNITIVE COMPUTING**



MAJOR PRODUCTIVITY GAINS WILL BE UNLOCKED BY THE WAVE OF AUTONOMOUS COMPUTATIONAL SYSTEMS. THESE SYSTEMS WILL RESPOND TO THE ENVIRONMENT BY THEMSELVES, WITHOUT PRE-PROGRAMING.

#### THESE ARE SYSTEMS THAT CAN SENSE, LEARN, INFER AND INTERACT.

(1-)			
SENSE AND RESPOND – NETWORKS OF SMART MACHINES AND DEVICES THAT TALK TO EACH OTHER	LEARN LEVERAGE HISTORICAL DATA AND DRAW INFERENCES FROM PAST EXPERIENCE	INFER/THINK MIMIC THE BRAIN'S ABILITIES OF PERCEPTION, ACTION AND COGNITION, AND GENERATE EVIDENCE-BASED HYPOTHESIS	INTERACT SYSTEMS THAT HAVE DIALOGUE-ORIENTED NATURA LANGUAGE INTERFACES

http://www.enterrasolutions.com/media/Wipro-Cognitive-Computing-2.png

#### An Example: Developing Cognitive Computing at IBM



# Cognitive Computing

IBM have been working on a cognitive computing project called Systems of Neuromorphic Adaptive Plastic Scalable Electronics (SyNAPSE).

http://www.ibm.com/smarterplanet/us/en/business\_analytics/article/cognitive\_computing.html

http://cacm.acm.org/magazines/2011/8/114944-cognitive-computing/fulltext

Communications of the ACM , Vol. 54 No. 8, Pages 62-71

"The quest for intelligent machines ultimately requires new breakthroughs in philosophy, neuroanatomy, neurophysiology, computational neuroscience, supercomputing, and computer architecture orchestrated in a coherent, unified assault on a challenge of unprecedented magnitude." The state of today's effort in cognitive computing was best captured by Winston Churchill: "Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."



## Cognitive Computing vs. Artificial Intelligence


## Machine Learning, AI & Cognitive Computing



Intelligent Futures: Automation, AI and Cognitive Ecologies

# Machine Intelligence and Cognitive Computing as Interacting Knowledge/Research Networks



# Computing in Cognitive Systems, Connecting Data to Intelligent Agency



## Morphogenesis as Information Processing/Computation: Turing's Reaction-diffusion Model of Morphogenesis

http://cgjennings.ca/toybox/turingmorph



"Patterns resulting from the sole interplay between reaction and diffusion are probably involved in certain stages of morphogenesis in biological systems, as initially proposed by Alan Turing. Self-organization phenomena of this type can only develop in nonlinear systems (i.e. involving positive and negative feedback loops) maintained far from equilibrium." Dulos, E., Boissonade, J., Perraud, J. J.Rudovics, B., Kepper, P. (1996) Chemical morphogenesis: Turing patterns in an experimental chemical system, Acta Biotheoretica, Volume: 44, Issue: 3, pp. 249 -261 Computationalism Is Not What It Used To Be ... ... that is the thesis that persons are Turing machines

Turing Machine is a model of computation equivalent to an algorithm, and it may be used for description of different processes in living organisms.

We need computational models for the basic characteristics of life, such as the ability to differentiate and synthesize information, make a choice, adapt, evolve and learn in an unpredictable world. That requires computational mechanisms and models which are not "certainly, exactly correct" and predefined as Turing machine, "probably approximately correct " (PAC)\*.

\* L. Valiant (2013) Probably Approximately Correct. Basic Books.

Computationalism Is Not What It Used To Be ... ... that is the thesis that persons are Turing machines

Computational approaches that are capable of modelling adaptation, evolution and learning are found in the field of natural computation and computing nature.

Cognitive computing and cognitive robotics are the attempts to construct abiotic systems exhibiting cognitive characteristics of biotic systems.

It is argued that cognition comes in degrees, thus it is meaningful to talk about cognitive capabilities of artifacts, even though those are not meant to assure continuing existence, which was the evolutionary role of cognition in biotic systems.

#### Computing Nature and Nature Inspired Computation



Subatomic particles



Atoms



This image, by IBM scientists using an atomic force microscope, shows a nanographene molecule with carbon-carbon bonds





DNA molecule

Unicellular organism





Bacterial colony a multi-cellular "organism"

Bacteria collectively "collects latent information environment and from other the from organisms, process the information, develop common knowledge, and thus learn from past experience" (Ben-Jacob, 2009)

Peter J. Denning. 2007. Computing is a natural science. Commun. ACM 50, 7 (July 2007), 13-18. DOI=10.1145/1272516.1272529 http://doi.acm.org/10.1145/1272516.1272529

http://www.ted.com/talks/bonnie bassler on how bacteria communicate

#### Computing Cells: Self-generating Systems



Complex biological systems must be modeled as selfreferential, self-organizing "component-systems" (George Kampis) which are self-generating and whose behavior, though computational in a general sense, goes far beyond Turing machine model.

"a component system is a computer which, when executing its operations (software) builds a new hardware.... [W]e have a computer that re-wires itself in a hardware-software interplay: the hardware defines the software, and the software defines new hardware. Then the circle starts again." Kampis (1991) p. 223

Kampis (1991) Self-Modifying Systems in Biology and Cognitive Science. A New Framework For Dynamics, Information, and Complexity, Pergamon Press

Dodig Crnkovic, G. (2011). Significance of Models of Computation from Turing Model to Natural Computation. *Minds and Machines*, (R. Turner and A. Eden guest eds.) Volume 21, Issue 2, p.301.



C. Elegans has 302 neurons (humans have 100 billion). The pattern of connections between neurons has been mapped out decades ago using electron microscopy, but knowledge of the connections is not sufficient to understand (or replicate) the information processor they represent, for some connections are in hibitory while others are excitatory.

#### Reality for an Agent – An Observer-dependent Reality

Reality for an agent is an informational structure with which agent interacts. As systems able to act on their own behalf and make sense (use) of information, cognitive agents are of special interest with respect to <knowledge>\* generation.

This relates to the idea of **participatory universe**, (Wheeler, 1990) "it from bit" as well as to **endophysics** or "physics from within" where an observer is being within the universe, unlike the "god-eye-perspective" from the outside of the universe. (Rössler, 1998)

\*<knowledge> for a very simple agent can be the ability to optimize gains and minimize risks. (Popper, 1999) p. 61 ascribes the ability to know to all living: "Obviously, in the biological and evolutionary sense in which I speak of knowledge, not only animals and men have expectations and therefore (unconscious) knowledge, but also plants; and, indeed, all organisms."

#### Info-computational Framework and Levels

The question of levels of organization/levels of abstraction for an agent is analyzed within the framework of info-computational constructivism, with natural phenomena modeled as computational processes on informational structures.

Info-computationalism is a synthesis of **informational structuralism** (nature is an informational structure for an agent) (Floridi, Sayre) and **natural computationalism/pancomputationalism** (nature computes its future states from its earlier states) (Zuse, Fredkin, Wolfram, Chaitin, Lloyd).

Adriaans P. and van Benthem J. eds. 2008. Philosophy of Information (Handbook of the Philosophy of Science) North Holland.

Rozenberg, G., T. Bäck, and J.N. Kok, eds. 2012. Handbook of Natural Computing. Berlin Heidelberg: Springer.

#### Living Agents – Basic Levels of Cognition

A living agent is an entity acting on its own behalf, with autopoietic properties that is capable of *undergoing at least one thermodynamic work cycle*. (Kauffman, 2000)

This definition differs from the common view that (living) *agency* requires beliefs and desires, unless we ascribe some primitive form of <belief> and <desire> even to a very simple living agents such as bacteria.

The fact is that bacteria act on some kind of <anticipation> and according to some <preferences> which might be automatic in a sense that they directly derive from the organism's morphology.

Even the simplest living beings act on their own behalf.

#### Living Agents – Basic Levels of Cognition

Although a detailed physical/energetic account of the agent's capacity to perform work cycles and so persist\* in the world is central for understanding of life/cognition, as (Kauffman, 2000) (Deacon, 2007) have argued in detail, present argument is primarily focused on the info-computational aspects of life.

Given that there is no information without physical implementation (Landauer, 1991), computation as the dynamics of information is the execution of physical laws.

\*Contragrade processes (that require energy and do not spontaneously appear in nature) become possible by connecting with the orthograde (spontaneous) processes which provide source of energy.

#### Living Agents – Basic Levels of Cognition

Kauffman's concept of agency (also adopted by Deacon) suggests the possibility that life can be derived from physics. That is not the same as to claim that life can be reduced to physics that is obviously false.

However, in deriving life from physics one may expect that both our understanding of life as well as physics will change.

We witness the emergence of information physics (Goyal, 2012) (Chiribella, G.; D'Ariano, G.M.; Perinotti, 2012) as a possible reformulation of physics that may bring physics and life/cognition closer to each other.

#### Levels of Organization of Life/Cognition

The origin of <cognition> in first living agents is not well researched, as the idea still prevails that only humans possess cognition and knowledge.

However, there are different types of <cognition> and we have good reasons to ascribe simpler kinds of <cognition> to other living beings.

Bacteria collectively "collects latent information from the

environment and from other organisms, process the information, develop common knowledge, and thus learn from past experience" (Ben-Jacob, 2009)

Plants can be said to possess **memory** (in their bodily structures) and **ability to learn** (adapt, change their morphology) and can be argued to possess **simple forms of cognition**.

Ben-Jacob, E. (2009). Learning from Bacteria about Natural Information Processing. *Annals of the New York Academy of Sciences*, *1178*, 78–90.

#### **Evolution of the Nervous System**



(d) The fish forebrain is small compared to remainder of brain.

(e) The goose forebrain is larger.

(f) The human forebrain (cerebrum) dominates the brain.

#### Information Processing in the Brain

http://www.neuroinformatics2013.org Neuroinformatics

Modular and hierarchically modular organization of brain networks D. Meunie, R. Lambiotte and E. T. Bullmore Frontiers of Neuroscience



http://www.frontiersin.org/neuroscience/10.3389/fnins.2010.00200/full http://www.scienceprog.com/ecccerobot-embodied-cognition-in-a-compliantly-engineered-robot/

#### Learning and Evolution of "The Sensitive Soul" Ginsburg & Jablonka Proposal

What characterizes the evolutionary transition from organisms without consciousness to those with consciousness (with minimal subjective experiencing, or, as Aristotle described it, "the sensitive soul")? [for Aristotle, soul = life]

Based on the historical, neurobiological, and philosophical grounds they propose that the evolutionary marker of basic/minimal consciousness is a complex form of associative learning, which they term "unlimited associative learning" (UAL).

UAL enables an organism to find motivational value in a novel, compound, stimulus or action, and use it as the basis for future learning.

Associative learning powered the Cambrian explosion and its massive variation of organisms.

In humans, symbolic language plays a role of marker for the evolutionary transition to human rationality, to Aristotle's "rational soul."

### Literature, Further Reading – Mapping Territory Through Various Disciplines

#### **Computing Universe**



#### Self-organizing Nature

#### INCOMPLETE NATURE



How Mind Emerged from Matter



The Origins of Order



Stuart A. Kauffman

SELF-MODIFYING SYSTEMS IN BIOLOGY AND COGNITIVE SCIENCE

A New Framework for Dynamics, Information and Complexity

**GEORGE KAMPIS** 

IFSR International Series on Systems Science and Engineering

PERGAMON PRESS

#### **Computational Frameworks**



PROBABLY APPROXIMATELY CORRECT

Nature's Algorithms for Learning and Prospering in a Complex World

#### 

LESLIE VALIANT

#### Nature, Information & Computation



World Scientific, 2019



INFORMATION IN THE WORLD

World Scientific

Burgin M. and Dodig-Crnkovic M. World Scientific, 2020 Studies in Applied Philosophy, Epistemology and Rational Ethics SAPERE

Gordana Dodig-Crnkovic Raffaela Giovagnoli *Editors* 

Representation and Reality in Humans, Other Living Organisms and Intelligent Machines

🖄 Springer

REPRESENTATION AND REALITY Dodig Crnkovic G. and Giovagnoli, R. Springer, 2017

## Computation, Information, Cognition



Computation, Information, Cognition Gordana Dodig Crnkovic and Susan Stuart, Edts. Cambridge Scholars Publishing, 2007 Information and Computation Gordana Dodig Crnkovic and Mark Burgin, Edts. World Scientific, 2011

**Computing Nature** Gordana Dodig Crnkovic and Raffaela Giovagnoli, Edts. Springer, 2013

D Springer

STUDIES

AND

IN APPLIED PHILOSOPHY,

RATIONAL

EPISTEMOLOG

#### The Extended Mind in Nature



SIMONA GINSBURG AND EVA JABLONKA

ILLUSTRATIONS BY ANNA ZELIGOWSKI



SUPERSIZING THE MIND EMBODIMENT, ACTION, AND COGNITIVE EXTENSION

• • •

ANDY CLARK



## Evolution and The Extended Mind in Nature

#### Evolution in Four Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life Dimensions

Eva Jablonka, and Marion J. Lamb illustrated by Anna Zeligowski



Lecture Notes in Morphogenesis Series Editor: Alessandro Sarti

Giuseppe Longo Maël Montévil

Perspectives on Organisms

Biological Time, Symmetries and Singularities

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Chaos, Fractals, Selforganization and Disorder: Concepts and Tools

SPRINGER SERIES Springer: IN SYNERGETICS COMPLEXITY

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#### Natural/Unconventional/Morphological Computing



#### Natural/Unconventional/Morphological Computing



#### Contemporary Natural Philosophy





#### Schroeder M. and Dodig Crnkovic, G. (2020) <u>CONTEMPORARY NATURAL PHILOSOPHY</u> <u>AND PHILOSOPHIES - PART 2</u>

ISBN 978-3-03943-535-7 (Hbk); ISBN 978-3-03943-536-4 (PDF) Download PDF Dodig Crnkovic, G. and Marcin Schroeder (2019) <u>CONTEMPORARY NATURAL PHILOSOPHY</u> <u>AND PHILOSOPHIES - PART 1</u>

ISBN 978-3-03897-822-0 (Pbk); ISBN 978-3-03897-823-7 (PDF) Download PDF

#### Summary: AI, Deep Learning from System1 to System2 Information Processing (Computation)

At present, AI in the form of machine learning is making impressive progress, especially the field of deep learning.

Deep learning (DL) algorithms have been inspired by nature, specifically by the human brain, and its neural networks. However, deep-learning intelligence is lacking distribution generalization, compositionality and common-sense reasoning.

The solution proposed by Yoshua Bengio\* is based on agency, causality, attention and consciousness as mechanisms of learning and meta-learning (learning to learn).

They are used as the basis for deep learning to go beyond Kahneman's\*\* System 1 (fast, unconscious task solving of current DL) to System 2 (slow, conscious, reasoning, planning etc.) for the future machine learning.

\* Y. Bengio, "From System 1 Deep Learning to System 2 Deep Learning (NeurIPS 2019)," 2019. \*\* D. Kahneman, Thinking, Fast and Slow. New York: Farrar, Straus and Giroux, 2011

#### Summary: AI, Deep Learning from System1 to System2 Information Processing (Computation)

Continuing learning from nature, we explored different aspects and mechanisms of natural cognition and intelligence. Connecting data to intelligent agency is done by modelling cognitive systems (natural and artifactual) as information processors, equipped with physical information sensors and physical actuators acting upon information.

#### Underlying assumptions

- 1. Nature can be modelled as a network of networks of computational processes on several levels of abstraction (organization)
- 2. There is no information without physical implementation (Landauer)
- 3. Dynamics of natural information = physical /natural/morphological computation
- 4. Cognition/Intelligence = Natural computation in cognitive agents

## Summary: AI, Deep Learning from System1 to System2 Information Processing (Computation)

Implications

- 1. Cognition and intelligence are abilities of all living beings and they come in degrees
- 2. Cognition and intelligence are both EEEE (Embodied, Embedded, Enactive, Extended)
- 3. For living organisms COGNITION=LIFE. For artifacts COGNITION = ARTIFACTUAL SURROGATE OF LIFE
- 4. INTELLIGENCE = PROBLEM SOLVING ABILITY for both living organisms and artifacts. Its basic precondition is ability to learn (biological or machine learning)
- 5. All cognizing systems (organisms and artifacts) are essentially dependent on information input from the surrounding
- 5. Biological cognition and intelligence can only be understood in the context of evolution\*
- 6. Evolution in the computing nature is the result of morphological computation on succession of levels of organization
- 7. Interdisciplinary, Cross-disciplinary and Trans-disciplinary research is necessary

\* That results in genetic, epigenetic, behavioral, and symbolic variation Eva Jablonka and Marion J. Lamb (2019) Evolution in Four Dimensions. Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life (EXTENDED EVOLUTIONARY SYNTHESIS) 67

#### **Open Questions**

- How close to natural (biological) systems do we have to be to get artifactual intelligent agents with "minimal" consciousness\*?
- The role of embodiment (including timing) for learning and learning to learn
- Understanding of fundamental properties of information as a structure, fabric of reality for a cognizing, intelligent agent, and understanding of computation as a process (a hierarchical network of processes) over informational structures.
- Relate to existing models of computation such as Turing model and actor models of concurrent distributed computation and resource-aware computing
- New kinds of models, such as executable biology, new kinds of dynamic logics suitable for intelligent adaptive systems

Following authors argue against "minimal cognition" and consider cognition as a binary state, yes or no.

Lyon, Pamela, Fred Keijzer, Detlev Arendt, and Michael Levin. 2021. "Reframing Cognition: Getting down to Biological Basics." *Phil. Trans. R. Soc. B* 376: 20190750.

Lyon, Pamela, and Franz Kuchling. 2021. "Valuing What Happens: A Biogenic Approach to Valence and (Potentially) Affect." *Phil. Trans. R. Soc. B* 376: 2019075220190752. 68

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- Lyon, Pamela, and Franz Kuchling. 2021. "Valuing What Happens: A Biogenic Approach to Valence and (Potentially) Affect." *Phil. Trans. R. Soc. B* 376: 2019075220190752.

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- CÉDRIC VILLANI (2018) For A Meaningful Artificial Intelligence
  <u>https://www.aiforhumanity.fr/pdfs/MissionVillani\_Report\_ENG-VF.pdf</u>
- Eva Jablonka and Marion J. Lamb (2019) Evolution in Four Dimensions, Revised Edition. Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life. The MIT Press

## Events organized on this topic

Embodied Cognition: Constructivist and Computationalist Perspectives IACAP 2016, Ferrara. <u>http://www.iacap.org/conferences/iacap-2016/symposium-robert-lowe-gordana-dodig-crnkovic-embodied-cognition-constructivist-and-computationalist-perspectives/</u>Co-organized with: Robert Lowe, Alexander Almér, Rickard von Haugwitz

Morphological Computing and Cognitive Agency @Gothenburg summit of International Society for the Study of Information, is4si <u>http://is4si-2017.org/</u> Co-organized with: Robert Lowe, Alexander Almér

Foundations of Cyberphysical Computation: Morphological and Embodied Computing, Theory and Applications, Marcus Wallenberg Symposium. May 7th-9th, 2018 <u>https://sites.google.com/view/morphologicalcomputing</u> Co-organized with: Robert Lowe

Workshop on Software Engineering for Cognitive Services. <u>https://www.se4cog2018.com</u> 27/5–3/6 @ICSE 2018 Gothenburg <u>https://sites.google.com/view/se4cog2018</u> Co-organized with: Rao Mikkilineni
# ADDITIONAL MATERIALS

# A mathematical model for Info-computationalism A. C. Ehresmann



Open peer commentary on the article "Info-computational Constructivism and Cognition" by Gordana Dodig-Crnkovic.

Ehresmann proposes a mathematical approach to the framework developed by Dodig-Crnkovic. Based on the Property of natural computation, called the multiplicity principle development of increasingly complex cognitive processes and knowledge is described. "Local dynamics are classically computable, a consequence of the MP is that the global dynamics is not, thus raising the problem of developing more elaborate computation models."

http://www.idt.mdh.se/~gdc/work/Constructivist%20Foundations%209%282%29.pdf

# An Info-Computational Model for (Neuro-)cognitive Systems Capable of Creativity - Andrée C. Ehresmann



Ehresmann's model is based on a Dynamic Category Theory, accounting for the functioning of the neural, cognitive and mental systems at different levels of description and across different timescales.

Andrée C. Ehresmann http://www.mdpi.com/1099-4300/14/9/1703

#### Knowledge as Network of Natural Processes

Naturalized epistemology\* (Feldman, Kornblith, Stich) is, in general, an idea that knowledge may be studied as a natural phenomenon -- that the subject matter of epistemology is not our concept of knowledge, but the knowledge itself.

"The stimulation of his sensory receptors is all the evidence anybody has had to go on, ultimately, in arriving at his picture of the world. Why not just see how this construction really proceeds? Why not settle for psychology? "("Epistemology Naturalized", Quine 1969; emphasis mine)

We can re-phrase the question to be: Why not settle for computing?

\*Epistemology is the branch of philosophy that studies the nature, methods, limitations, and validity of knowledge and belief.

Actor Model Of Computation Suitable To Support The Relational Concept Of Information and Networked Agent Models - Concurrent Distributed Computation



"In the Actor Model [Hewitt, Bishop and Steiger 1973; Hewitt 2010], computation is conceived as distributed in space, where computational devices communicate asynchronously, and the entire computation is not in any well-defined state.

(An Actor can have information about other Actors that it has received in a message about what it was like when the message was sent.) Turing's Model is a special case of the Actor Model." (Hewitt, 2012)

Hewitt's "computational devices" are conceived as computational agents – informational structures capable of acting on their own behalf.

#### Actor Model of Concurrent Distributed Computation

Actors are the universal primitives of concurrent distributed digital computation. In response to a message that it receives, an Actor can make local <decisions>, create more Actors, send more messages, and designate how to respond to the next message received.

For Hewitt, Actors become Agents only when they are able to process expressions for commitments including the following: *Contracts, Announcements, Beliefs, Goals, Intentions, Plans, Policies, Procedures, Requests, Queries.* 

In other words, Hewitt's Agents are human-like or if we broadly interpret the above capacities, life-like Actors.

#### Morphological Computing

The essential property of morphological computing is that it is defined on a structure of nodes (agents) that exchange (communication) of information. Unicellular organisms such as bacteria communicate and build swarms or films with far more advanced capabilities compared to individual organisms, through social (distributed) cognition. In general, groups of smaller organisms (cells) in nature cluster into bigger ones (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.

#### Morphological Computation Connecting Body, Brain, and Environment - Rolf Pfeifer

(Brain and body roboticists learn from sometimes belongs to an octopus)

soft robotics / self-assembly systems and molecular robotics/ self-assembly systems at all scales / embodied robotics / reservoir computing / physical reservoir computing/ real neural systems systems medicine / functional architecture / organization / process management / computation based on spatio-temporal dynamics/ information theoretical approach to embodiment mechatronics / amorphous computing / molecular computing

http://morphcomp.org/2nd International Conference on Morphological Computation ICMC2011. http://www.eucognition.org/index.php?page=theoretical-scheme Tutorial on Embodiment: R Pfeifer

# Problems We Want to Model and Manage\* Computationally

- Cognitive behavior of living organisms
- Natural Intelligence/Intelligence in Nature
- Computational neuroscience & neuroinformatics
- Artificial (general) intelligence
- Cognitive robotics
- Intelligent cities
- Intelligent homes
- Big data
- Internet of everything
- Semantic web
- ...

All above problems depend on the adequate models of computation and they depend on the computational architecture.

#### Construction of Knowledge from Data by Computation

We construct knowledge from the data as pieces of information we get directly from the world via interrelation and combination of information from memory or indirectly via other people (either exchanging information personally or from the stored information found in diverse kinds of documents.)

Cognition\* for an agent is process of acquiring knowledge and understanding through thought, experience, and the senses and physical interactions with the environment and other cognitive agents.

\*The term cognition (Latin: cognoscere, "to know", "to conceptualize" or "to recognize") refers to a faculty for the processing of information, applying knowledge, and changing preferences. Cognition, or cognitive processes, can be natural or artificial, conscious or unconscious. (Wikipedia)

https://link.springer.com/chapter/10.1007/978-3-642-15223-8\_20 Dodig-Crnkovic, Constructivist Research and Info-Computational Knowledge Generation

## Good Old-Fashioned Artificial Intelligence

GOFAI\* ("Good Old-Fashioned Artificial Intelligence") i.e. symbolic AI built on human as model of intelligence (humans as symbolic species).

- Focus on language, both human and programming languages
- No interest in embodiment, embeddedness and enaction
- Denial of intelligence in any other living beings but humans
- Especially in the field of robotics rising awareness of intelligence coming in degrees
  & being dependent on the body of an agent
- Al is constructed as separate from the living world, even though human species is a result of evolution and cannot be understand without understanding its evolution

#### Evolution and Development of Cognition

Evolution and development can be understood as the processes of self-organisation of living agents in the world, and their constant reality construction/adaptation.

Cognition in this framework is capacity possessed in different forms and degrees of complexity by every living organism and the same framework can be applied to artificial agents.

All physico-chemical processes in a cognizing agent depend on its morphology (form, structure and material).

Morphological computing is defined on a structure of nodes (agents) that exchange (communicate) information.

## Computation as Information (Data) Processing

Computation is generally defined as information (data) processing. (See Burgin, M., Super-Recursive Algorithms, Springer Monographs in Computer Science, 2005)

The definition of computation is widely debated, and an entire issue of the journal **Minds and Machines** (1994, 4, 4) was devoted to the question **"What is Computation?"** Even: Theoretical Computer Science 317 (2004)

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

## Cognition as Restructuring of an Agent Through Interaction with the Environment

As a result of evolution, increasingly complex living organisms arise that are able to survive and adapt to their environment. It means they are able to register inputs (data) from the environment, to structure those into information, and in more developed organisms into knowledge.

The evolutionary advantage of using structured, component-based approaches is improving response-time and efficiency of cognitive processes of an organism.

# Intelligent Information Processing: Blurring the Boundary Between Perception and Memory



The constant stream of data from our sensory inputs gets checked against memorized data and corrected for missing parts based on memorized data.

For the interpretation of input data memory is used. In that way perception and memory are connected.

#### Design and Construction of a Brain-like Computer



"A New Class of Frequency-Fractal Computing Using Wireless Communication in a Supramolecular Organic, Inorganic System " Subrata Ghosh, Krishna Aswani, Surabhi Singh, Satyajit Sahu, Daisuke Fujita and Anirban Bandyopadhyay

Information **2014**, *5*, 28-100; doi:10.3390/info5010028

http://www.mdpi.com/2078-2489/5/1/28