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TENTATIVE SCHEDULE OF PRESENTATIONS AND DISCUSSIONS IS BELOW (PLEASE CHECK THE WEBSITE FOR POSSIBLE UPDATES)

KEYNOTE

CROSS-EMBODIED COGNITIVE MORPHOLOGIES: DECENTRALIZING COGNITIVE COMPUTATION ACROSS VARIABLE-EXCHANGEABLE, DISTRIBUTED, OR UPDATED MORPHOLOGIES

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Abstract: Most of the bioinspired morphological computing studies have departed from a human analysis bias: to consider cognitive morphology as encapsulated by one body, which of course can have enactive connections with other bodies, but that is defined by clear bodily boundaries. Such complex biological inspiration has been directing the research agenda of a huge number of labs and institutions during the last decades. Nevertheless, 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). And despite the interest of swarm cognition (which includes superorganisms of flocks, swarms, packs, schools, crowds, or societies) in such non-human-centered approaches, there is still a biological constraint: such cognitive systems have permanent bodily morphologies and only interact between similar entities. In all cases, and even considering amazing possibilities, such as the largest living organism on Earth, specific honey fungus *Armillaria solidipes* measuring 3.8 km across in the Blue Mountains in Oregon, it hasn't been put over the table the possibility of thinking about cross-morphological cognitive systems. Nests of intelligent drones as a single part of AI systems with other co-working morphologies, for example. I am therefore suggesting the necessity of thinking about cross-embodied cognitive morphologies, more dynamical and challenging than any other existing cognitive system already studied or created.

INVITED SPEAKERS

DESIGNING PHYSICAL RESERVOIR COMPUTERS

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Abstract: Computation is often thought of as a branch of discrete mathematics, using the Turing model. That model works well for conventional applications such as word processing, database transactions, and other discrete data processing applications. But much of the world's computer power resides in 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 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.

As an example, consider an audio-controlled embedded device: it needs to sense sound input, compute an appropriate response, and direct that response to some actuator such as an electrical motor. We can have an unconventional solution using reservoir computing, which exploits the dynamics of a material to perform computation directly. One form of MEMS (micro-electromechanical system) device is a microscopic beam that oscillates when it is accelerated and outputs an electrical signal. This kind of device is used in a car's airbag as an accelerometer to detect crashes. Such a device might be used in an audio-controlled system as follows. The incident sound waves make the beam vibrate (in an analogous way to how they make a microphone's diaphragm vibrate). This vibrating beam can be configured as a reservoir computer, where the non-linear dynamics of the complex vibrations are used directly to compute and classify the audio input. The electrical output from the device is this classified

response, sent directly to the motor. Here, the sensor and the computer are the very same physical device, which also performs signal transduction (from sound input to electrical output), with no power-hungry conversion between analogue and digital signals, and no digital computing.

Such systems, implementable in a wide range of materials, offer huge potential for novel applications, of smart sensors, edge computing, and other such devices, reducing, and in some cases potentially eliminating, the need for classical digital central resources. Many novel materials are being suggested for such uses, leading to interdisciplinary collaborations between materials scientists, physicists, electronic engineers, and computer scientists. Before such systems can become commonplace, multiple technical and theoretical issues need to be addressed.

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.

THE AIMS OF AI: ARTIFICIAL AND INTELLIGENT

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Abstract: Explanation of what 'artificial' means, esp. in contrast to 'living'. First approximation of what 'intelligent' means, esp. in contrast to a discussion of the Turing Test: Do not focus on 'intellectual intelligence'; do not focus on the human case; do not rely on behaviour alone. Intelligence vs. rational behaviour, e.g. instrumental vs. general intelligence. Formulation of an aim for full-blown AI – a computing system with the ability to successfully pursue its goals. 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.

COGNITION THROUGH ORGANIC COMPUTERIZED BODIES. THE ECO-COGNITIVE PERSPECTIVE

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Abstract: *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 of 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. This cognitive process played a fundamental heuristic role in Turing's invention of the universal logical computing machine. 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.

Hence, in computation the morphological features are relevant. It is important to note that, in the case of morphological computation, a physical computer does not need to be intelligently conceived: it can be naturally evolved. This means that living organisms or parts of organisms (and their artefactual copies) can potentially execute information processing and can potentially be exploited to execute their computations for us. It is by further deepening and analyzing the perspective opened by these novel fascinating approaches that we see ignorant bodies as domesticated to become useful "mimetic bodies" from a computational point of view, capable to carry cognition and intelligence. This new perspective shows how the computational domestication of ignorant entities can originate new variegated unconventional cognitive embodiments, so joining the new research field of the so-called natural computing. Finally, I hope it will become clear that eco-cognitive computationalism does not aim at furnishing a final and fixed definition of the concept of computation but stresses the historical and dynamical character of the concept.

DIGITAL CONSCIOUSNESS AND THE BUSINESS OF SENSING, MODELING, ANALYZING, PREDICTING AND TAKING ACTION

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Abstract:
"In brief, neither qualia nor free will seems to pose a serious philosophical problem for the concept of a conscious machine. .... The richness of information processing that an evolved network of sixteen billion cortical neurons provides lies beyond our current imagination. Our neuronal states ceaselessly fluctuate in a particularly autonomous manner, creating an inner world of personal thoughts. Even when confronted with identical sensory inputs, they react differently depending on our mood, goals, and memories."
Stanislas Dehaene (2014) "Consciousness and the Brain: Deciphering How the Brain Codes our Thoughts" Penguin Books, New York. P 265

Preamble:

Recent advances in various disciplines of learning are all pointing to a new understanding of how information processing structures in nature operate and not only this knowledge may yet help us to solve the age-old philosophical question of "mind-body dualism" but also pave a path to design and build self-regulating automata with a high degree of sentience, resilience and intelligence.

Classical computer science with its origins from the John von Neumann's stored program implementation of the Tring machine has given us tools to decipher the mysteries of physical, chemical, and biological systems in nature. Both symbolic computing and neural network implementations have allowed us to model and analyze various observations (including both mental and physical processes) and use information to optimize our interactions with each other and with our environment. In turn, our understanding of the nature of information processing structures in nature using both physical and computer experiments is pointing us to a new direction in computer science going beyond the current Church Turing thesis boundaries of classical computer science.

Our understanding of information processing structures and their internal and external behaviors causing their evolution in all physical, chemical and biological systems in nature are suggesting the need for a common framework where function, structure and fluctuations of these systems composed of many autonomous components interacting with each other under the influence of physical, chemical and biological forces. As Stanislas Dehaene (Stanislas Dehaene (2014*) "Consciousness and the Brain: Deciphering How the Brain Codes our Thoughts"* Penguin Books, New York. P 162) points out "What is required is an overreaching theoretical framework, a set of bridging laws that thoroughly explain how mental events relate to brain activity patterns. The enigmas that baffle contemporary neuroscientists are not so different from the ones that physicists resolved in the nineteenth and twentieth centuries. How, they wondered, do the macroscopic properties of ordinary matter arise from a mere arrangement of atoms? Whence the solidity of a table, if it consists almost entirely of a void, sparsely populated by a few atoms of carbon, oxygen, and hydrogen? What is a liquid? A solid? A crystal? A gas? A burning flame? How do their shapes and other tangible features arise from a loose cloth of atoms? Answering these questions required an acute dissection of the components of matter, but this bottom-up analysis was not enough; a synthetic mathematical theory was needed."

Fortunately, our understanding of the theory of structures and information processing processes in nature points a way for a theoretical frame work that allows us to:

1. Explain the information processing architecture gleamed from our studies of physical, chemical and biological systems to articulate how to model and represent cognitive processes that bind the brain-mind-body behaviors and also,
2. Design and develop a new class of digital information processing systems that are autopoietic. An autopoietic machine is capable of "of regenerating, reproducing and maintaining itself by production, transformation and destruction of its components and the networks of processes downstream contained in them."

All living systems are autopoietic and have figured out a way to create information processing structures that exploit physical and chemical processes to manage not only their own internal behaviors but also their interactions with their environment to assure their survival in the face of constantly changing circumstances. Cognition is an important part of living systems and is the ability to process information through perception using different sensors. Cognitive neuroscience has progressed in "cracking open the black box of consciousness " to discern how cognition works in managing information with neuronal activity. Functional magnetic resonance imaging used very cleverly to understand the "function of consciousness, its cortical architecture, its molecular basis, and even its diseases" allows us now to model the information processing structures that relate cognitive behaviors and consciousness.

In parallel, our understanding of the genome provides insight into information processing structures with autopoietic behavior. The gene encodes the processes of "life" in an executable form, and a neural network encodes various processes to interact with the environment in real time. Together, they provide a variety of complex adaptive structures. All of these advances throw different light on the information processing architectures in nature.

Fortunately, a major advance in new mathematical framework allows us to model information processing structures and push the boundaries of classical computer science just as relativity physics pushed the boundary of classical Newtonian physics and statistical mechanics pushed the boundaries of boundaries of thermodynamics by addressing function, structure and fluctuations in the components constituting the physical and chemical systems. Here are some of the questions we need to answer in the pursuit of designing and implementing an autopoietic machine with digital consciousness:

- What is Classical Computer Science?
- What are the Boundaries of Classical Computer Science?
- What do We learn from Cognitive Neuroscience about The Brain and Consciousness?
- What do we Learn from the Mathematics of Named Sets, Knowledge Structures, Cognizing Oracles and Structural Machines?
- What are Autopoietic Machines and How do they Help in Modeling Information Processing Structures in Nature?
- What are the Applications of Autopoietic Digital Automata and how are they different from the Classical Digital Automata?
- Why do we need to go beyond classical computer science to address autopoietic digital automata?
- What are knowledge structures and how are they different from data structures in classical computer science?
- How are the operations on the schema representing the data structures and knowledge structures differ?
- How do "Triadic Automata" help us implement hierarchical intelligence?
- How does an Autopoietic Machine move us to Go Beyond Deep Learning to Deep Reasoning Based on Experience and Model-based Reasoning?
- What is the relationship between information processing structures in nature and the digital information processing structures?
- What are the limitations of digital autopoietic automata in developing same capabilities of learning and reasoning as biological information processing structures?
- How do the information processing structures explain consciousness in living systems and can we infuse similar processes in the digital autopoietic automata?

In a series of blogs, we will attempt to search the answers for these questions and in the process, we hope to understand the new science of information processing structures, which will help us build a new class of autopoietic machines with digital consciousness.

However, as interesting as the new science is, more interesting is the new understanding and the opportunity to transform current generation information technologies without disturbing them with an overlay architecture just like the biological systems evolved an overlay cognitive structure to provide global regulation while keeping local component autonomy intact while coping with rapid fluctuations in real-time. We need to address following questions:

- How are the knowledge structure different from current data structures and how will database technologies will benefit from autopoiesis to create a higher degree of sentience, resilience, and hierarchical intelligence at scale?
- Will the operations on knowledge structure schemas improve the current database schema operations and provide higher degree of flexibility and efficiency?
- Today, most databases manage their own resources (memory management, network performance management, availability constraints etc.) which increase complexity and lower efficiency. Will autopoiesis simplify the distributed database resource management complexity

and allow application workloads become PaaS and IaaS agnostic and provide location independence?
- Can we implement autopoiesis without disturbing current operation and management of information processing structures?

ON LEVERAGING TOPOLOGICAL FEATURES OF MEMRISTOR NETWORKS FOR MAXIMUM COMPUTING CAPACITY

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Abstract: 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. A typical reservoir computer consists of two parts. First, a reservoir transforms a time-series data into the state of the network. This constitutes the act of computation. Second, a readout layer is used to label the state of the network which produces the final output of the computation. The reservoir was implement 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.

CONTRIBUTED PAPERS

A MORPHOGENESIS PERSPECTIVE ON DETERMINISTIC COMMUNICATION NETWORKS: TIME TO OVERCOME THE POSITIONAL INFORMATION PARADIGM?

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Abstract: Real-time deterministic communication networks are basic components of current distributed critical systems. A fundamental challenge in these systems is to integrate the notions of adaptability/resilience and determinism. In this paper we argue 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.

Computing devices are responsible for an ever-increasing number of crucial services, such as transportation, healthcare, manufacturing, energy management, etc. The complexity of these systems is driven by their large size and heterogeneity, their dynamic operation in unknown/uncertain conditions, and their criticality. The developers of such systems are faced with the challenge of reconciling the notions of flexibility and predictability in their designs, to achieve determinism, adaptability, and resilience.

Both scientists and practitioners have turned towards natural computing as a source of inspiration for taming complexity, and methods such as neural networks, swarm-based algorithms and evolutionary algorithms (e.g., genetic algorithms) are commonly applied. It is interesting to note that these methods are mostly concerned about adaptability and resilience, and determinism has not received the same attention, probably because the field of real-time systems had proper tools and abstractions to guarantee the required service. Nevertheless, many researchers have already noted that traditional techniques for real-time communication do not scale well and are not sufficiently resilient. One of the reasons of this limitation is the 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.

We believe 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.
One of the conclusions of our study is that 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.

1.1 Positional Information and the TT paradigm

To illustrate our findings, we focus on the Time-Triggered (TT) paradigm, which is one of the most widespread approaches for real-time communication. TT is fundamentally a static way to share computation/communication bandwidth between tasks/nodes such that a predefined response time is enforced with little variability.

We can reformulate the TT paradigm using the notions from Positional Information. First, we noted that the TT paradigm is embodied at three different levels by means of cyclic structures:

(1) Global clock
(2) Time slots
(3) Schedule

Note that the Global clock constitutes a fundamental signal that governs the rest of the mechanisms. In particular, this clock is the axis on which the gradients that form the other PI patterns are formed. A division into slots can be seen as one particular case of the *French Flag* problem, in which the threshold to change from one color to another (i.e. to start a new slot) is a time mark over the global clock.

The schedule is a function that maps a certain slot with a certain message/task. Therefore, it also uses a particular case of PI, where the slot number is the gradient that triggers the change in the output. The main difficulty or this approach is the generation/synthesis of the schedule function over the slot. It is performed computationally using constraint programming or SMT solvers. However, these PI schedules are not adaptive and need to be regenerated in case of system change or failure.

1.2 TT vs. other, biosemiotics forms of synchronization

Even if TT systems are based on the existence of a global synchronized clock, some studies about the biosemiosis of synchronization have shown that living organisms do not require this type of global reference and that they can rely exclusively on inter-subject clock synchronization (coupling) implemented via punctuations. In the terms discussed in [1], Positional Information is equivalent to the C-series Time, a type of external, static time refence, whereas living beings rely on the E-series time.

The possibility of embodying synchronization as a form of E-series time scheme would represent a revolution for real-time communication, where the concept of global synchronization is paramount. In fact, this perspective contradicts the opinion of some scholars who believe that the way to achieve more determinism is to guarantee model fidelity at the architecture (refer to Prof. Edward Lee).

One challenge for the implementation of E-series time is understanding what should be the embodiment of punctuation signs and of proper semiotic scaffolding, which can be seen as a form of clock synchronization but has never analyzed on the light of these concepts.

1.3 A discussion on symbolic vs. embodied computation for deterministic communication

Determinism represents very well the dichotomy between symbolic and embodied representations of a system. A system is deterministic if its temporal behavior can be known in advance with great accuracy.

The flow is as follows: a real problem is transformed (abstracted) into a symbolic representation. The problem is solved symbolically via computation. The symbolic solution is transformed into a real implementation; we can say that the symbolic solution is embodied on a certain system. When applying this approach, the notion of fidelity becomes paramount. How much trust can be placed

on the symbolic representation of the problem? How much trust can be placed on the embodiment of the solution?
The way to guarantee the correctness (fidelity) of these steps is to have a very tight relation between the symbolic system/solution and the real system. The Time-triggered paradigm, ideated by Herman Kopetz is an exemplary case of this approach. The solution the TT paradigm proposes is to divide time into slots of fixed duration and use a static plan, the schedule, to execute the tasks/transmit the messages. It requires global clock synchronization and the ability of each node to follow a predefined static pattern.

The main consequence of using TT is that the platform becomes predictable. Even if this somehow artificial organization of the communication reduces the actual solution space, it is still possible to find valid solutions (in the symbolic space) in reasonable time. Additionally, once the solution is found, the embodiment into the system becomes straightforward (easy to implement and easy to verify).
However, there are many cases in which the embodiment is too rigid. Examples: tolerance to link failure, merging different clock domains, etc.
The main criticism of the TT approach is its lack of flexibility. Adaptability has been investigated and several approaches have been proposed. However, none of these extensions really changes the philosophy of the paradigm, which is the division between a symbolic space in which the solution is found and a simple embodiment of said solution onto a predictable system.
For instance, the notion of active replication is realized by introducing new requirements in the symbolic representation of the problem, which are not part of the real problem. For example, that critical messages must be replicated and transmitted through disjoint paths becomes a new requirement, because the specification only says that *each message must reach its destination before a certain deadline*. Replication is an artificial requirement, which does not emerge naturally from the specification, but is forced upon the specification by the designer. (Interestingly, this resonates with the difference between Science and Philosophy as discussed by H. Maturana, who described Philosophy as dogmatic and rigid, whereas Science is flexible and self-correcting).

Other solutions to achieve adaptability also rely on introduction of multiplicity at the symbolic level. One option is to generate symbolic variations of the system, for instance assuming that a certain component may fail, and obtain a multiplicity of symbolic solutions, which then need to be embodied into the real system. Some additional complexity introduced by such an approach is that the solution should also cater for the detection of which instance of the symbolic representation is "happening" and be able to switch between the corresponding solutions. This is one of most common strategies in classical fault tolerance, which relies on error detection and error compensation. The challenge of this approach is the ability to predict all potential faults and the capacity to generate all suitable countermeasures at design time. This is very difficult for open systems or systems that work in very flexible environments.
We claim that the use of Positional Information is fundamentally the same as computing the solutions symbolically and then embedding them by means of a static embodiment of the solution.
A different approach is to fragment the symbolic problem into smaller symbolic problems that can be embodied separately. This is the approach we applied in SHP, the Self-Healing Protocol for time-triggered networks. At present, we are working on the definition of our SHP using Reaction-Diffusion patterns.

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CONCEPTUALISING AND DESIGNING (CO)AUGMENTED INTELLIGENCE(S) ENACTING COMPLEX THINKING: REFLECTIONS ON THE MORPHOLOGICAL CONSTRAINTS, CHALLENGES AND IMPLICATIONS

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Abstract: In this paper, we build upon 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. We discuss new possibilities of its application in terms of 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 (e.g. structural complexity- variety and dimensionality; relationality; recursiveness); dynamic and process complexity (multiple timescales; dynamic processes; relativity, ambiguity and uncertainty; causal and explanatory complexity (modes and finalities; historicity; complex circularity; emergence); dialogic complexity (dualities and complementary pairs; trinities and levels) and the observer's complexity (multipositioning; reflexivity; intentionalities), among others. It is hypothesised that, under given conditions, the coordinated enactment of these properties may lead to the emergence of novel critical information, in the form of 'complex intuitions' or abduction. These emergent outcomes may then the actions of an observer in their relation with 'real-world' complex systems and in dealing with 'wicked' problems (e.g. for affecting and managing change), under conditions of uncertainty, ambiguity and partial and incomplete information.

In this paper, we advance with the conceptualisation of CT, in terms of process and outcome, as a meta-landscape or meta-conversational emergent pattern (Varela, 1976): a complex (differentiated, integrated, recursive, emergent) form of Know-ing which, enacting a set of key organisational principles of complex systems (complex thinking as a process) (Melo, 2020), explores and intentionally manipulates the dynamic relationship between an observers' Landscape of Be-ing (direct, intuitive, fast, pre-reflexive, embodied, iconic) and a Landscape of Symbolic Meaning or Know-what (Varela, 1976, 1999; Kahneman, 2011) (indirect, slow, abstracted constructions, narrative, discursive). Complex Thinking could be constructed as a Star cybernetic complementary (Varela, 1976, 1999): both an emergent product of the dialectic relationship Be-Ing and Know-that and, simultaneously, the process underlying their interaction.

We propose that, in attempting to engage in more effective actions in complex situations, the human cognitive agent needs to be able to manage their own contributions to the coupling relationship with a target system of interest. Through a complex process of coupling and management (of the enactment of key properties of complex thinking) of the observer's own embodied experiences and higher-order constructions, those landscapes may mutually perturb each other, resulting in variations and innovations or even undergoing deeper transformations (Stepney, 2021). This process may lead to the emergence of critical information for guiding action: complex (experiential) intuitions, as perturbations in the landscape of Be-ing (guiding action directly), and, indirectly, abduction (Shook & Paavola, 2021) (e.g., in the form of hypotheses) as perturbations in the coupled landscape of Know-what.

However, the contributions of the observer to the complexity of the coupling relationship with a target system of interest may not be complex enough to support emergence, given constraints of its own structural determination. Nevertheless, we expect it to be possible to scaffold (Vygotsky, 1978) the complexity of a target cognitive agent through systems of (Co)Augmenting Intelligence(s), involving both human-to-human and human-to-human-to-computer interactions, organised, recursively, according to principles of CT.

In this presentation, we open a call for new interdisciplinary dialogues and projects to explore the theoretical, methodological, pragmatic and ethical challenges and implications of conceptualising and designing the tools, strategies and morphological constraints of systems of (Co)Augumenting Intelligences oriented to scaffold the enactment of Complex Thinking.

MORPHOLOGICAL COMPUTATION AS NATURAL ECOSYSTEM SERVICE

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Abstract: The basic idea of naturalist info-computational framework for cognition in living organisms [Dodig-Crnkovic, 2006-2020] is learning from nature. Morphological computation in this approach is a process of creation of new informational structures, as it appears in nature. Relationships defining information and computation are always realized/embodied in matter/energy [Dodig-Crnkovic, 2012]. Cognition in living systems/agents is constituting life-organizing, life-sustaining goal-directed process, (Maturana and Varela, 1992), or as (Stewart, 1996) puts it, "Cognition = Life". In artifactual systems, cognition is engineered based on sensors, actuators and computing units. Unlike self-organized natural cognitive agents, engineered cognitive computational agents are essentially dependent on human-made infrastructure for their existence and maintenance. Engineered cognitive systems can still learn a lot from living agents, about adaptability, adequacy of response and resource efficiency - among others.

Computation is information processing (Burgin, 2005). It is natural information dynamics [Rozenberg, Back, Kok, 2012] [Stepney et al., 2005, 2006; Stepney, 2008] [MacLennan, 2004] as it is always implemented in material substrate. It can be observed at different levels of organization (physics, chemistry, biology, cognition) [Dodig-Crnkovic, 2017a-c] [Burgin and Dodig-Crnkovic, 2015). Evolutionary process in living organisms, best described as extended evolutionary synthesis [Jablonka, Lamb, Zeligowski, 2014], [Laland et al. 2015], is unfolding as a result of interactions of living agents with the environment, including other living agents. Morphological computing programs/algorithms accelerate evolution, as not every change comes at random but activates a sequence of sequences of computations. Evolution starts with the first simplest pre-biotic structures and leads to more complex forms such as viruses and bacteria, continuing up in complexity to humans and human networks [Dennett, 2018] [Dodig-Crnkovic, 2015]. Evolution evolves computationally (Sloman 2013).

This 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].

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 rule-based machines are not good enough models of natural cognition of highly complex living organisms. 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. 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 in nature. For the development of increasingly sophisticated intelligent cognitive computational systems nature provides one more ecological service – information ecosystem service of morphological computation.

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MORPHOLOGICAL COMPUTATION AS MORPHOGENESIS: FROM LEIBNIZ AND GOETHE TO RENÉ THOM AND BEYOND

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Abstract: The pairs of adjectives "analog" - "digital" and "qualitative" - "quantitative" entered everyday language and in the common belief the latter in each pair is better, more progressive, and future oriented. There is another belief, this time among those who at least know the theoretical model of computing introduced by Alan Turing called now Turing Machine that this model sets the boundaries for computing which cannot be crossed. This belief is not universal and there is continuous effort to design hypercomputing, i.e. computing free from the limits set in the orthodox model. Turing himself challenged the limits, first with his oracle machines, later by exploration of chemical morphogenesis.

To go beyond Turing's model of computation requires a generalization of the concept of computing. Of course, computing understood as a process modeled by Turing Machine excludes hypercomputing. On the other hand, without having any idea about the process which could have the orthodox computing as a special case, but which exceeds its boundaries the task is formidable. Thus far, the attempts were made to engage some elements of analog computing within the orthodox digital paradigm.

Von Neumann described analog computing as based on the idea that the representation of numbers in the processing units is not digital (i.e. is not based on the finite number of classes of states of the physical processor associated with digits and their combination into numerals), but analog (numbers are represented directly by the physical magnitudes characterizing the states of processor). Its disadvantage in comparison to digital computing is in the lack of universality and the need for reconfiguration for different tasks. My own distinction between the analog and digital computing can be formulated in terms of the distinction between states and observables introduced in physics after influence of quantum mechanics. Analog computing is performed directly and exclusively on the states of the processing unit without the mediation of observables, i.e. numbers. Digital computing involves the mediation of observables, i.e. numbers. Of course, this distinction is slightly different from von Neumann's in which processing is in both cases of the numbers which are represented in the analog or digital forms.

In order to avoid the mediation of numbers we can explore information systems based on morphology. However, this tells us about the information systems, but it does not answer the question about the generalization of computing. My own choice is to define computing as a construction of information structures in the interaction of two or more information systems (as defined in my earlier publications) carrying information. The crucial point is that computing is understood as a dynamical process involving more than one information system and that the outcome of the process is information which is a nontrivial function of information from the interacting systems. This prevents the overgeneralization in which every process, such as motion of a stone could be considered computation. On the other hand it is clear that the work of Turing Machine is a form of computing understood this general way and because the function describing the interaction of the component systems does not have to be Turing computable we may achieve hypercomputing.

The next question is about a nontrivial model of such computing. Here we can use the long tradition of philosophical and scientific studies of morphogenesis starting from Leibniz (*On the Art of Combination, 1690*) before the term morphology was introduced by Goethe (*On Morphology*, *1817*) through the influential work of D'Arcy Thompson (*On Growth and Form, 1917*) to Turing (*The Chemical Basis of Morphogenesis*, 1952), to Stephen Smale (*Differentiable Dynamical Systems, 1967*) and René Thom (*Structural Stability and Morphogenesis*, *1972*).

Now, the question is how this intellectual experience of more than 300 years can help us to design morphological computing. The work of Thom is of special value. He showed that we can investigate dynamic processes from the point of view of differential topology. These processes of morphogenesis and the study of their structural stability provide the tools for the design of morphological computing. On the other hand, we also get a warning in the fact that Thom did not achieve any breakthrough in his study of semiosis (information processing!) His failure (which he himself admitted) was the result of not being able to reject traditional principles of the quantitative methodology. It seems that we should follow the dream of Leibniz to develop an entirely new structure of human thought based on a general form of algebra (as expressed in his own words). The outline of a general algebraic description of information and of its dynamic has been already proposed in my earlier work.

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TENTATIVE SCHEDULE OF PRESENTATIONS AND DISCUSSIONS (PLEASE CHECK THE WEBSITE FOR POSSIBLE UPDATES)

MORCOM 2021, Thursday, September 16

4:00-5:00 UTC Jordi, Susan, Vincent (keynote/invited speakers, 20 min each)
5:00-5:10 UTC 10 min coffee/tea break
5:10-6:10 UTC Lorenzo, Rao, Zoran
6:10-6:20 UTC 10 min coffee/tea break
6:20-7:20 UTC Discussion
7:20-7:30 UTC 10 min coffee/tea break
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7:30-8:30 UTC Guillermo, Ana, Gordana & Marcin (contributed talks, 15 min each)
8:30-8:40 UTC 10 min coffee/tea break
8:40-9:40 UTC Discussion
9:40-10:00 UTC Conference wrap-up