Info-computational Constructivism and Cognition

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> Context • At present, we lack a common understanding of both the process of cognition in living organisms and the construction of knowledge in embodied, embedded cognizing agents in general, including future artifactual cognitive agents under development, such as cognitive robots and softbots. **> Purpose** • This paper aims to show how the info-computational approach (IC) can reinforce constructivist ideas about the nature of cognition and knowledge and, conversely, how constructivist insights (such as that the process of cognition is the process of life) can inspire new models of computing. **> Method** • The info-computational constructive framework is presented for the modeling of cognitive processes in cognizing agents. Parallels are drawn with other constructivist approaches to cognition and knowledge generation. We describe how cognition as a process of life itself functions based on info-computation and how the process of knowledge generation proceeds through interactions with the environment and among agents. **> Results** • Cognition and knowledge generation in a cognizing agent is understood as interaction with the world (potential information), which by processes of natural computation becomes actual information. That actual information after integration becomes knowledge for the agent. Heinz von Foerster is identified as a precursor of natural computing, in particular bio computing. **> Implications** • IC provides a framework for unified study of cognition in living organisms (from the simplest ones, such as bacteria, to the most complex ones) as well as in artifactual cognitive systems. **> Constructivist content** • It supports the constructivist view that knowledge is actively constructed by cognizing agents and shared in a process of social cognition. IC argues that this process can be modeled as info-computation. **> Key words** • **Constructivism, info-computationalism, computing nature, morphological computing, self-organization, autopoiesis.**

1 Introduction

« 1 » Info-computationalism (IC) is a variety of natural computationalism, which understands *the whole of nature as a computational process*. It asserts that, as living organisms, we humans are cognizing agents who construct knowledge through interactions with their environment, processing information within our cognitive apparatus and through information communication with other humans. Therefore, the epistemology of info-computationalism is *info-computational constructivism*, and it describes the ways agents process information and generate new information that steadily changes and evolves by natural computation.

« 2 » Processes of cognition, together with other processes in the info-computational model of nature, are computational processes. This is a generalized type of computation, natural computation, which is defined as information self-structuring. Information is also a generalized concept in the context of IC, and it is always agent-dependent: *information is a difference (identified in the world) that makes a difference for an agent*, to paraphrase Gregory Bateson (1972). For different types of agents, the same data input (where data are atoms of information) will result in different information. A light presents a source of energy for a plant; for a human, the same light enables navigation in the environment, while it brings no information at all to a bat, which is not sensitive to light. Hence the same world for different agents appears differently. We want to understand mechanisms that relate an agent with its environment as a source of information.

« 3 » The historical roots of info-computational constructivism can be traced back to cybernetics, which evolved through three main periods, according to Umpleby (2002): the first period, *engineering cybernetics*, or *first order cybernetics* spanned the 1950s to 1960s, and was dedicated to the design of control systems and machines to emulate human reasoning (in the sense of Norbert Wiener); the second period, *biological cybernetics,* or *second-order cybernetics,* developed during the 1970s and 1980s, and was dominated by biology of cognition and constructivist philosophy (notably by Humberto Maturana, Heinz von Foerster, and Ernst von Glasersfeld); and the most recent, third period, *social cybernetics*, or *third order cybernetics*, concerns modeling of social systems (Niklas Luhmann and Stuart Umpleby).

« 4 » During the engineering period, the *object* of observation, *the observed* was central. In the second phase, with research in biology of cognition, the core interest shifted from what is observed to the *observer*. In the third phase, the domain of social cybernetics focus moved further to models of *groups of observers* (Umpleby 2001, 2002). The achievements of the first period have been largely assimilated into engineering, automation, robotics, artificial intelligence (AI), artificial life (ALife), and related fields, while the second period influenced cognitive science and AI. The third period is still under development, labeled as, among other names, social cognition, social computing or multi-agent systems.

« 5 » Info-computational constructivism builds on insights gained in all three phases of the development of cybernetics, combined with results from AI, ALife, theory of computation (especially from the nascent field of natural computation), science of information, information physics, neuroscience, bioinformatics, and more. This article concentrates on connections between IC and biology of cognition and the constructivist approaches, with Maturana, von Foerster, and von Glasersfeld as the main representatives. Based on arguments developed in my earlier work, I will examine how info-computational constructivism relates to other constructivist approaches.[1]

« 6 » In what follows, the next chapter on "Natural information and Natural computation" presents the basic tenets of IC. It expounds two basic concepts of IC and explains how they differ from common, everyday notions of information as a message and computation as symbol-manipulation. In the third chapter, I address information and computation in cognizing agents, and argue that IC provides a common framework for biological and artifactual cognition. Chapter 4 addresses self-organization and autopoiesis in relation to IC and the construction of the reality for an agent. In Chapter 5 I discuss several criticisms of info-computationalism.

2 Natural information and natural computation

« 7 » In 1967, computer pioneer Konrad Zuse was the first to suggest that the physical behavior of the entire universe is being computed on a basic level by the universe itself, which he referred to as *Rechnender Raum* ["Computing Space"] (Zuse 1969). Consequently, Zuse was the first *pancomputationalist*, or natural computationalist, followed by many others such as Ed Fredkin, Stephen Wolfram and Seth Lloyd. According to the idea of natural computation, one can view the dynamics of physical states in nature as information processing. Such processes include self-assembly, developmental processes, gene regulation networks, gene assembly in unicellular organisms, protein-protein interaction networks, biological transport networks, processes of individual and social cognition, etc. (Dodig-Crnkovic & Giovagnoli 2013; Zenil 2012).

« 8 » The traditional theoretical model of computation corresponds to symbol manipulation in a form of the Turing machine model. It is a theoretical device for the execution of an algorithm. However, if we want to model adequately natural computation, including biological structures and processes understood as embodied physical information processing, highly interactive and networked computing models beyond Turing machines are needed, as argued in (Dodig-Crnkovic 2011a; Dodig-Crnkovic & Giovagnoli 2013). Besides physical, chemical, and biological processes in nature, there are also concurrent computational devices today (such as the Internet) for which the Turing machine as a sequential model of computation is not adequate (Sloman 1996; Burgin 2005).[2]

« 9 » Physical processes observed in nature and described as different forms of natural computation can be understood as *morphological computing*, i.e., computation governed by underlying physical laws, leading to change and growth of form. The first ideas of morphological computing can be found in Alan Turing's work on morphogenesis (Turing 1952). Turing moved towards exploration of natural forms of computing at the end of his life, and his *unorganized machines* were forerunners of neural networks.

« 10 » Based on the same physical substrate, different computations can be performed and those can appear at different levels of organization. That is how the same conventional digital computer can run the Windows operating system and, on top of that, a Unix virtual machine. Each virtual machine always relies on the basic physical computation. Aaron Sloman (2002) developed interesting ideas about the computation of virtual machines and about the mind as a virtual machine running on the brain substrate. Computation observed in the brain is based on the physical computation of its molecules, cell organelles, cells, and neural circuits, as neurons are organized into ensembles/circuits that process specific types of information (Purves, Augustine & Fitzpatrick 2001).[3]

« 11 » The difference between morphological computation and our conventional computers (artificial symbol manipulators implemented in specific types of physical systems and governed by an executing program) is that morphological computation takes place spontaneously in nature through physical/chemical/biological processes. Our conventional computers are designed to use physical (fundamentally computational) processes (intrinsic computation) to manipulate symbols (designed computation).

« 12 » The current understanding of morphological computation on the neural level is expressed in the following passage:

> "Neuroscience studies cell types, tissues, and organs *that ostensibly evolved to store, transmit, and process information*. That is, the behavior and organization of neural systems support computation in the service of adaptation and intelligence." (Crutchfield, Ditto & Sinha 2010: 037101-1)

1 | The description of the conceptual framework of info-computationalism can be found in (Dodig-Crnkovic & Müller 2011; Dodig-Crnkovic 2006, 2009). The relationship between natural computing (such as biocomputing, DNA-computing, social computing, quantum computing, etc.) and the traditional Turing machine model of computation is elaborated in (Dodig-Crnkovic 2010a, 2011a, 2011b, 2012). Construction/generation of knowledge within info-computational framework is discussed in (Dodig-Crnkovic 2008, 2010b, 2010c).

2 | The Universal Turing Machine (UTM) is sometimes thought of as a universal model of computation. However, the UTM can only compute what any other TM can compute, and no more.

3 | In his new research program, which addresses the evolution of organic forms, Sloman (2013) goes a step further by studying *meta-morphogenesis,* which is the morphogenesis of morphogenesis – a way of thinking that is in the spirit of second-order cybernetics, i.e., the cybernetics of cybernetics.

The central question that arises from this is: How are the intricate physical, biochemical, and biological components structured and coordinated to support natural, intrinsic neural computation? Currently, huge research projects in Europe (Human Brain Project), the USA (the BRAIN initiative, Allen Brain Atlas), and Japan have been launched with the aim of addressing this question.

« 13 » Von Foerster was an early representative of natural computation through his work at the Biological Computer Lab at the University of Illinois between 1958 and 1975, where he studied ideas of self-reference, feedback, and adaptive behavior found in computational implementations of second-order cybernetics (Asaro 2007). He differentiated between symbol manipulation and physical computation, which is evident from his definition of computation, as:

"any operation (not necessarily numerical) that transforms, modifies, rearranges, orders, and so on, observed physical entities ('objects') or their representations ('symbols')." (Foerster 2003c: 216).

« 14 » In IC, everything that exists for an agent is interpreted as *potential information* (see also the next chapter), while representations actualized in an agent are informational structures. If we compare von Foerster's above definition of computation with the basic definition of computation used within the IC approach:

"*Computation is information processing.*" (Burgin 2010: xiii)

we see that *information processing* corresponds to von Foerster's *operation on "'objects,' or their representations, 'symbols'."* In the next chapter we will say more about this connection between what are considered "physical objects" and information.

« 15 » Von Foerster also emphasizes the important difference between his *general notion of computation* and computation performed by a conventional computer:

"Computation takes place in the nervous system. Therefore, we can say the nervous system is a computer or computing system. But this is correct only if one understands the general notion of computation." (Segal 2001: 74)

Often arguments have been made against computational models of cognition, based on the idea that cognitive processes are computational in the conventional sense. Scheutz (2002) argues against this misconception and for the idea of *new computationalism,* based on the general notion of computation.

« 16 » In order to specify the models of computation that may be more general in their information processing capabilities than the Turing machine, IC adopts Carl Hewitt's Actor Model of computation (Hewitt, Bishop & Steiger 1973; Hewitt 2010), as described in the following:

"*In the Actor Model,* 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: 161, my emphasis)

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

« 17 » Within the info-computational framework, the definition of information is adopted from informational structural realism[4] (Floridi 2003). According to this definition, for an agent, information is the fabric of the universe. This definition may cause misunderstandings and deserves clarification. Information that is the fabric of the universe is *potential information* before any interaction with an (observing) agent. IC characterizes this kind of potential information[5] as *proto information* (or *proto data*). One might insist that for information to actualize, some agent must be there to relate to it. An additional complication is that the terms *information* and *data* (as atoms of information) are used interchangeably. So the world can be characterized either as a potential informational structure or as a potential data structure for an agent.

« 18 » The process of dynamical changes of structures as (potential) information makes the universe a huge computational network where computation is information processing. The computational universe is, by its construction, necessarily both discrete and continuous, and exists on both a symbolic and a sub-symbolic level. Information is structure, which exists either potentially outside of the agent (as the structures of its environment) or inside an agent (in the agent's own bodily structures, which contain memories of previous experiences with its environment). Messages are just a very special kind of information that is exchanged between communicating agents. They can be carried by chemical molecules, pictures, sounds, written symbols or similar. An agent can be as simple as a molecule (Matsuno & Salthe 2011) or the simplest living organism (a bacterium) (Ben-Jacob, Shapira & Tauber 2006).

« 19 » Physicists Anton Zeilinger (2005) and Vlatko Vedral (2010) suggest the possibility of *seeing information and reality as one.*[6] This agrees with informational structural realism, which says that the world is made of proto informational structures that

4| "Informational structural realism" is a variant of epistemic structural realism, which is defined as follows: "(Epistemic) Structural realism is often characterized as the view that scientific theories tell us only about the form or structure of the unobservable world and not about its nature" (Ladyman 2013). A constructivist reconciliation with structural realism would see "realist structure" as the best available model. Thanks are given to an anonymous reviewer for this observation.

5| It would be more correct to say (potential) data. Von Foerster rightly pointed out that computers do not process information but data. However, this term is already widely used. Data are atoms of information. Information is obtained when data becomes integrated into structure (correlated), which happens in the interaction with a cognizing agent.

6| This of course does not imply that potential information from the world moves intact into an agent. This potential (proto) information is accessed by an agent through interactions and it is processed by the agents' cognitive apparatus. It is dynamically integrated and linked to other informational structures (in the memory). What is important and new about this view from physicists is that they do not talk about matter and energy as the primary stuff of the universe (which is traditionally objectivized within the sciences). They talk about information, thus returning an agent into the picture of the world.

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agents use to construct their own reality through interactions with the world (Floridi 2008a, 2009; Sayre 1976). Reality for an agent is thus informational and agent-dependent. Being agent dependent and given that every observer is also an agent, reality is observer-dependent.[7]

« 20 » Reality for an agent consists of structural objects (informational structures, data structures) with computational dynamics (information processes) that are adjusted to the shared reality of the agent's community of practice. This brings together the metaphysical view of Wiener (according to whom "information is information, not matter or energy") and John Wheeler ("it from bit")[8] with the view of natural computation shared by others such as Zuse, Fredkin, Lloyd, and Wolfram (Dodig-Crnkovic & Giovagnoli 2013).

« 21 » The world as proto information presents the potential form of existence corresponding to Immanuel Kant's *Ding an sich* (thing in itself).[9] That proto information becomes information, "a difference that makes a difference," (Bateson 1972) *for a cognizing agent* in a process of interaction.

« 22 » Besides Gregory Bateson's definition, there is a more general definition of information by Carl Hewitt that makes the fact that *information is relational* even more explicit, and subsumes Bateson's definition:

"Information expresses the fact that *a system is in a certain configuration that is correlated to the configuration of another system*. Any physical system may contain information about another physical system." (Hewitt 2007: 293, my emphasis)

« 23 » Combining Bateson and Hewitt's insights, on a basic level we can state:

Information is the difference in one physical system that makes a difference in another physical system.

« 24 » The reality for an observer is informational and information is relational:

"A message's effect on a receiver can be construed to include its capacity to cause a functional or adaptive response in an organism." (Terzis & Arp 2011: xviii)
"The receiver of information can be so-called only if it can relate what is received to what was emitted." (ibid: 63)

What is called message or information can be as simple as, for example, an electron that is a difference that makes a difference in the receiver molecule.

« 25 » This relational character of information has profound consequences for epistemology and relates to ideas of a participatory universe (Wheeler 1990) and endophysics (Rössler 1998), with observer-dependent knowledge production as understood in second-order cybernetics. All information exists in relation to an observer, or for an agent. In the words of von Foerster, observer-dependence is described as the truism that an observation implies one who observes:

"(i) Observations are not absolute but relative to an observer's point of view (i.e., his coordinate system: Einstein); (ii) Observations affect the observed so as to obliterate the observer's hope for prediction (i.e., his uncertainty is absolute: Heisenberg) […] What we need now is the description of the 'describer' or, in other words, we need a theory of the observer." (Foerster 2003b: 247)

« 26 » Even though there are attempts to define the observer, especially in the theory of measurement in quantum mechanics, the common understanding of the central importance of observer dependence in cognition and knowledge production is still missing. It is interesting to notice that information-based accounts of quantum mechanics emphasize the necessity of explicating the observer, as earlier expressed by physicists Niels Bohr and Wolfgang Pauli of the Copenhagen School of quantum mechanics. In the words of Christopher Fuchs:

7| This does not imply that reality is subjective. Observers form shared reality through processes of social cognition, as explained in third-order cybernetics (Johannessen & Hauan 1994).

8| "Wheeler (1990) has suggested that information is fundamental to the physics of the universe. According to this 'it from bit' doctrine, the laws of physics can be cast in terms of information" (Chalmers 1995: 215).

9| Here I interpret Kant not as saying that noumenon is something abstract without properties, but as saying it is something infinitely rich that we learn successively more and more about (the way we can reach the world through interactions – our senses and our reasoning). The world exists, but changes as we interact with it. It is different in itself (unperturbed) and in interaction with us. In quantum mechanics, in chaos theory, and in relativity we see what it means. We interact and disturb the physical system; we send a probe and wave function collapses, chaotic system changes regime.

"The world in some very real sense is a construct and creation of thinking beings simply because its properties are so severely tied to the particular questions we ask of it. *But on the other hand, the world is not completely unreal as a result of this; we generally cannot control the outcomes of our measurements.*" (Fuchs 2011: 151)

« 27 » Among new information-based quantum theories, QBism takes an observer into account when modeling physical system, based on the Bayesian approach to probabilities. They argue that "the distinction between classical and quantum probabilities lies not in their definition, but in the nature of the information they encode" (Caves, Fuchs & Schack 2002). It is instructive to see how new epistemic ideas take form in quantum physics based on quantum information theory. In the years to come we can expect interesting discussions in terms of realism vs. antirealism and the role of observer in the quantum physical realm – discussions for which ideas of constructivism are highly relevant.

3 Information, computation, and cognition

« 28 » The advantage of computational approaches is their testability. Cognitive robotics research, for example, presents us with a sort of laboratory where our understanding of cognition can be tested in a rigorous manner. From cognitive robotics it is becoming evident that *cognition and intelligence (and especially learning) are closely related to agency (ability to act and explore the environment)* (Pfeifer & Bongard 2006; Pfeifer & Gomez 2009). Anticipation, planning, and control are essential features of intelligent agency. Studies by Pfeifer et al. show that there is a similarity between the generation of behavior in living organisms and the formation of control sequences in artificial systems (Pfeifer & Bongard 2006; Pfeifer, Lungarella & Iida 2007).

« 29 » Information produced from sensory data processed by an agent is a result of the process of perception. From the point of view of data processing, perception can be seen as an *interface*[10] between the proto information in the environment and an agent's behavior in the environment. This interface is an information-processing device, which means that information input for an agent gets restructured and integrated with the existing information (memory). Perception is agent-dependent. This is illustrated by Donald Hoffman's critique of the view of perception as a true picture of the world:

"[O]*ur perceptions constitute a species-specific user interface that guides behavior in a niche.* Just as the icons of a PC's interface hide the complexity of the computer, so our perceptions usefully hide the complexity of the world, and guide adaptive behavior. This interface theory of perception offers a framework, motivated by evolution, to guide research in object categorization." (Hoffman 2009: 148)

« 30 » Thus, perception produces interrelated informational structures that connect inside cognitive informational structures with outside informational structures through dynamic information processing. Cognition cannot be decoupled from the other side of the interface (the environment) and isolated inside an agent and its brain. Patterns of potential information (potential data) are both in the world and in the structures of the agent, which are connected through dynamical processes of self-structuring (self-organization) of information. The computational mechanism of self-structuring of information is presented in Bonsignorio (2013), Lungarella & Sporns (2005), and Dodig-Crnkovic (2012).

« 31 » Perception has co-evolved with the sensorimotor skills of an organism. The enactive approach to perception (Noë 2004) emphasizes the role of sensorimotor abilities, which can be connected with the changing informational interface between an agent and the world, increasing information exchange. The enactivism of Francisco Varela, Evan Thompson, and Eleanor Rosch (1991) underlines that *cognizing agents self-organize through interaction with their environment*. It is an approach closely related to situated cognition and embodied cognition, and is supported by the current research in robotics (Pfeifer & Bongard 2006; Pfeifer, Lungarella & Iida 2007; Pfeifer & Gomez 2009).

« 32 » Traditionally, symbolic AI was an attempt to model cognition and intelligence as symbol manipulation, which turned out to be insufficient (Clark 1989). In order to improve and complement symbolic approaches to animal cognition, Paul Smolensky proposed the mechanism of an *intuitive processor* inaccessible to symbolic intuition as a program for a conscious rule interpreter and basis for…

"all of animal behavior and a huge proportion of human behavior: Perception, practiced motor behavior, fluent linguistic behavior, intuition in problem-solving and game-playing – in short, practically all skilled performance." (Smolensky 1988: 5)

This non-symbolic processor is a neural network type of computation.

« 33 » In natural computation, cognition and *knowledge are studied as natural processes in biological agents*. That is the main idea of naturalized epistemology (Harms 2006), where the subject matter is not *our concept of knowledge (or how we talk and reason about knowledge)*, but knowledge as physically existing in a cognizing agent as specific biological informational structures.[11]

« 34 » We know little about the origin of knowledge in first living agents, and the still dominant idea is that knowledge is possessed only by humans. However, there are different types of knowledge and we have good reasons to ascribe "knowledge how" and even simpler kinds of "knowledge that" to other living beings. Plants can be said to possess memory (in their bodily structures) and the

10 | It is important to note that this "interface" is a complex program that transforms and re-structures information entering an agent's sensory apparatus and gets connected with the rest of cognitive architecture. It is not just direct one-to one mapping. The claim that patterns of information must be on both sides of the "interface" comes from enactivism. I should make it clear that this "interface" is an active one. In computing it is a program that rearranges input information so that it can be accepted on the other side of the interface. It is absolutely not an identity relation. In other words, this is simply the statement that an agent and its niche, or environment, mutually form each other. If we adopt structuralism, then structures are on both sides and they affect each other.

11 | Maturana (1970) was the first to suggest that *knowledge is a biological phenomenon*.

ability to learn (adapt, change their morphology) and can be argued to possess rudimentary forms of knowledge.[12] In his book *Anticipatory Systems*, Robert Rosen claims:

> “I cast about for possible biological instances of control of behavior through the utilization of predictive models. To my astonishment I found them everywhere […] the tree possesses a model, which *anticipates* low temperature on the basis of shortening days.” (Rosen 1985: 7)

« 35 » Karl Popper ascribes the ability to know to all living things:

> “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.” (Popper 1999: 61)

And similarly Maturana and Varela:

> “Living systems are cognitive systems, and living as a process is a process of cognition. This statement is valid for all organisms, with or without a nervous system.” (Maturana & Varela 1980: 13)

« 36 » The above understanding of cognition is adopted by info-computational constructivism as it provides a notion of cognition in degrees, which bridges from human-level cognition to minimal cognition in the simplest biological forms and intelligent machines. For a cognizing agent, information is meaningful data, which can be turned into knowledge by interactive computational process. Information is always embedded in a physical substrate: signal, molecule, particle or event (Landauer 1991), which will induce a change in a structure or a behavior of an agent. For IC this is important: we must know how to construct cognitive artificial agents that are able to function adequately in their environment, so we must know how to treat information acquired, stored, processed or used by an agent.

« 37 » The information-processing view should be identified neither with classical cognitive science, nor with the related notions of input–output and symbolic representations. It is important to recognize that *connectionist models are also computational* as they are based on information processing (Scheutz 2002; Dodig-Crnkovic 2009; Clark 1989). The basis for the capacity to acquire knowledge is in the specific morphology of organisms that enables perception, memory, and adequate information processing. That morphology is a result of the evolution of living organisms in the interaction with the environment.

« 38 » William Harms (2004) proved a theorem showing that under certain conditions, by nature, the total amount of information in the living system will always increase, which will always lead a population to accumulate information, and so to “learn” about its environment. Samir Okasha summarizes Harms’ results:

> “any evolving population ‘learns’ about its environment, in Harms’ sense, even if the population is composed of organisms that lack minds entirely, hence lack the ability to have representations of the external world at all.” (Okasha 2005: §10)

4 Construction of “reality” as info-computation in an agent via “structural coupling”

« 39 » In order to understand cognition and knowledge as a natural phenomenon, the process of re-construction of the origins, development and present forms and existence of life, processes of evolution, and development based on self-organization are central. The work of Maturana and Varela on the constructivist understanding of life is of fundamental importance. They define autopoiesis as a network of processes in the “autopoietic machine” (a unity in space constituted by its components) that govern production, transformation, and destruction of those components and so enable incessant regeneration and maintenance of the autopoietic machine as a whole (Maturana & Varela 1980: 78). Or, in the words of Milan Zeleny:

> “A *cell* produces cell-forming molecules, an *organism* keeps renewing its defining *organs*, a social *group* ‘produces’ *group*-maintaining individuals, etc. Such autopoietic systems are *organizationally closed* and structurally *state*-determined…” (Zeleny 1977: 13)

« 40 » What does it mean that an autopoietic system is *organizationally closed*? It means that it conserves its organization. However, this applies only to the snapshot of an organism’s inner operation. In the course of evolution, organisms change their structure through interactions with the environment and successively, as they evolve, even change their organization. In other words, organisms tend to preserve their organization, but that organization evolves on an evolutionary time scale. That is what Maturana calls “ontogenic structural drift” (Maturana 2002: 17).

« 41 » The information-processing picture of organisms incorporates basic ideas of autopoiesis and life, from the sub-cellular to the multi-cellular level. Being processes of cognition, life processes are different sorts of morphological computing that, on evolutionary time scales, affect even the structures and organization of living beings in the sense of meta-morphogenesis. In Sloman’s work on meta-morphogenesis, understood as “evolution and development of information-processing machinery,” he presents…

> “a first-draft rudimentary theory of ‘meta-morphogenesis’ that may one day show how, over generations, interactions between changing environments, changing animal morphologies, and previously evolved information-processing capabilities might combine to produce increasingly complex forms of ‘informed control,’ starting with control of various kinds of physical behaviour, then later also informed control of information processing.” (Sloman 2013: 849)

The ideas of morphogenesis and meta-morphogenesis are attempts at computational modeling of cognitive processes and their evolution in all living organisms within the same computational framework, where the computational model is not a simple Turing machine computing function but morphological computation that represents biological information processing.

« 42 » In the process of living, interaction between an organism and its environment is a source of new information that results in learning and adaptation. Maturana

12 | On the topic of plant cognition, see Garzón (2012: 121–137).

explains the relationship between an autopoietic system and its environment in the following:

> I have called the dynamics of congruent structural changes that take place spontaneously between systems in recurrent (in fact recursive) interactions, as well as the coherent structural dynamics that result, structural coupling. (Maturana 2002:16)

« 43 » Autopoietic processes with *structural coupling* can be described within the IC model as changes of structures in the biological system resulting from the exchange of information with the environment and thus the information processing patterns in a self-reflective, recursive computation. Self-organization with natural selection of organisms is responsible for information that living systems have built up in their genotypes and phenotypes, as a simple but costly method to develop knowledge capacities. Higher organisms (which are "more expensive" to evolve[13]) have grown learning and reasoning capabilities as a more efficient way to accumulate knowledge. The step from "genetic + epigenetic learning" (typical of more primitive forms of life, Ben-Jacob, Shapira & Tauber 2006) to the acquisition of cognitive skills on higher levels of organisation of the nervous system (behavioral and symbolic) are the next topic to explore in the project of cognitive info-computation, following the ideas of Eva Jablonka & Marion Lamb (2005), who distinguish *genetic, epigenetic, behavioral, and symbolic* evolution. A study of cognitive skills of increasingly more complex organisms is the next project for naturalized epistemology in terms of info-computational constructivism. Understanding of the roots and evolution of cognition are relevant for cognitive robotics and cognitive computing, which are also useful for implementing ideas and testing hypotheses.

« 44 » As already mentioned, for Maturana & Varela, *the process of living is a process of cognition*. In the info-computational formulation, life corresponds to information processing in a hierarchy of levels of organization, from molecular networks, to cells and their organizations, to organisms and their networks/societies (Dodig-Crnkovic 2008). In that way, fundamental-level proto information (structural information) corresponding to the physical structure, is a "raw material" for cognition as a process of life with variety of self-* properties in a living system: self-reproduction, self-regeneration, self-defense, self-control/self-regulation (plants); self-movement/locomotion, and self-awareness (animals); and self-consciousness (humans).[14] Survival, homeostasis, learning, self-maintenance, and self-repair appear as a product of evolution in complex biological systems, which can be modeled computationally, as argued in (Dodig-Crnkovic & Hofkirchner 2011).

« 45 » Expressed in terms of von Foerster's notions of *eigenvalues* (stable structures) and *eigenbehaviors* (stable behaviors established in the interaction with the environment):

> Any system, cognitive or biological, which is able to relate internally, self-organized, stable structures (eigenvalues) to constant aspects of its own interaction with an environment can be said to observe eigenbehavior. Such systems are defined as organizationally closed because their stable internal states can only be defined in terms of the overall dynamic structure that supports them. (Rocha 1998: 342)

« 46 » Even though organizationally closed, living systems are *informationally open* (Pask 1992). They communicate and form emergent representations of their environment through processes of information self-organization. Rocha defines self-organization as the "spontaneous formation of well-organized structures, patterns, or behaviors, from random initial conditions." (Rocha 1998: 343). Learning, as a self-organized process, requires that the system "be informationally open, that is, for it to be able to classify its own interaction with an environment, it must be able to change its structure…" (ibid: 344).

« 47 » Observation is one of many possible ways of interacting with the environment, and von Foresters' notion of observation receives the following illuminating interpretation: "observables do not refer directly to real world objects, but are instead the result of an infinite cascade of cognitive and sensory-motor operations in some environment/subject coupling" (Rocha 1998: 341). In principle, those cascades are infinite because of self-reference, while in practice they successively die off because of energy dissipation. Thus von Foerster's eigenvalues represent the externally observable manifestations of cognitive operations.

« 48 » Von Foerster's insight that identifies the ability of an organization to *classify* its environment as a consequence of *formation of stable structures (eigenvalues)* in the dynamics of its organization, agrees with current understanding of dynamic systems (Smolensky & Legendre 2006; Crutchfield, Ditto & Sinha 2010; Juarrero 2002). Dynamical system theory establishes the connection between the brain as a dynamical system and the environment, while the details of the connection of the body of an agent and the environment are modeled as morphological computation.

« 49 » Von Foerster's view of observables casts doubts on the belief that we humans can directly interact with the "real world as it is." One of the reasons is that it takes time for an agent to integrate information. Dana Ballard explains: 229

> Our seamless perception of the world depends very much on the slow time scales used by conscious perception. Time scales longer than one second are needed to assemble conscious experience. At time scales shorter than one second, this seamlessness quickly deteriorates. Numerous experiments reveal the fragmentary nature of the visual information used to construct visual experience. (Ballard 2002: 54)

« 50 » Already Kant argued that "phenomena," or things as they appear to us, and which constitute the world of common experience, are an illusion. Consciousness provides only a rough sense of what is going on in and around us, primarily what we take to be essential for us. The world as it

13 | More expensive in this context means that they take more time and other natural resources to develop. A human compared to a bacterium is considerably more "expensive" to develop.

14 | Even though some plants possess the capacity for self-movement it is not a typical characteristic of plants. Despite animals possessing degrees of self-consciousness/self-awareness (Allen 2010), it is commonly not considered as dominant characteristic of animals.

appears for our consciousness is a sketchy simulation, which is a computational construction. The belief that we can ever experience the world "directly as it is" is an illusion (Nørretranders 1999). We change the world through interactions and, moreover, the world is always more than we can observe and interpret in any given moment. What would it mean anyway to experience the world "directly as it is," without ourselves being part of the process? Who would experience that world without us?

« 51 » The positivist optimism about observations independent of the observer proved problematic in many fields of physics such as quantum mechanics (wave function collapse after interaction), relativity (speed-dependent length contraction and time dilatation) and chaos (a minor perturbation caused by measurement sufficient to switch the system to a different attractor). In general, the observer and the systems observed are related (Foerster 2003a) and by understanding their relationship we can gain insights into limitations and power of models and simulations as knowledge generators. The interaction of an agent with the environment eliminates inadequate cognitive models. Model construction thus proceeds through variation and selection. This agrees with von Glasersfeld's second principle of constructivism:

> "The function of cognition is adaptive and serves the organization of the experiential world, not the discovery of ontological reality." (Glasersfeld 1995b: 18)

5 Some criticisms of the info-computational approach to cognition and their refutation

No information without humans?

« 52 » A typical criticism of the informational nature of reality originates from the belief that the world without cognizing agents would lose its content because there would be no one to observe it. The view is that "if all the humans in the world vanished tomorrow, all the information would vanish, too."

« 53 » In response to this criticism, let me point out that not only is information physical (Landauer 1996), but the opposite also holds: "things physical are reducible to information" *for an agent*. Quantum physics can be formulated in terms of information for an agent (Chiribella, D'Ariano & Perinotti 2012; Goyal 2012; Caves, Fuchs & Schack 2002; Baeyer 2013). Physical reality as information for an observer makes this observer-dependence of the physical model both explicit and natural.

« 54 » Clearly, if there are no cognizing agents in the world, the world remains proto information, *das Ding an sich*, and never turns into actual information for an agent. But, in the same way as the world does not disappear when we close our eyes, it does not disappear when we look back in history to when no living beings were present to observe it. Moreover, given the fact that there are cognitive agents besides humans, living beings (animals, plants, microorganisms, and even machines capable of cognitive computing, i.e., processing information and making sense of it), information for all those agents continues to exist even if no human is present.

« 55 » It is not necessary for an agent to be conscious on a human level in order to make use of the world as proto information/potential information. The fundamental insight of Maturana and Varela that not everybody has yet realized is that *life in itself is a cognitive process* (Maturana & Varela 1992). Metabolism is a basic aspect of cognition, along with sensorimotor functions and immune system processes. No nervous system or free will is needed for the information processing that goes on in all living organisms. Those processes can be understood as computational in the sense of natural computation (Ben-Jacob, Shapira & Tauber 2006).

« 56 » Koichiro Matsuno and Stanley Salthe (2011) go one step further, in a search of the origins of life, attributing *material agency* and *information processing ability* even to such simple systems as molecules. We can apply Hewitt's Actor Model to the computation found in nature and say that even elementary particles possess material agency, as they are capable of acting on their own. The step from material agency to life is a big one, and goes via chemical computing of more and more complex molecular structures, leading to the first autopoietic systems (Gánti 2003).

Can information bridge the Cartesian gap?

« 57 » Søren Brier criticizes the idea of information as used in IC, since in his view, "it is not information that is transmitted through the channel in Shannon's theory, but signals" (Brier 2013a: 242).

« 58 » As an answer to this criticism, I refer to the work of Brian Skyrms (2010) and Bateson (1972). It is possible that we should see Bateson's "differences that make a difference" as *data or signals* even though they are usually called information:

> "Kant argued long ago that this piece of chalk contains a million potential facts (Tatsachen) but that only a very few of these become truly facts by affecting the behavior of entities capable of responding to facts. For Kant's Tatsachen, *I would substitute differences and point out that the number of potential differences in this chalk is infinite but that very few of them become effective differences (i.e., items of information) in the mental process of any larger entity. Information consist of differences that make a difference.*" (Bateson 1979: 110, my emphasis)

« 59 » But those differences, "items of information" or "atoms of information," become information when they trigger an agent's inner structures and cause changes in its informational networks. Those changes may be relatively simple for relatively simple living agents such as bacteria, while they become more complex for increasingly complex living organisms.

« 60 » Brier continues his critical examination of IC, which in his view does not provide an account for…

> "how the processes of cognition and communication develop beyond their basis in the perturbation of and between closed systems and into a theory of feeling, awareness, qualia and meaning." (Brier 2013a: 243)

This criticism may be applicable to some computational approaches but not to IC based on natural computation and the idea of the world as proto informational structure. Information is not only suitable for the fundamental reformulation of physics, but even, as David Chalmers aptly noted, a natural candidate for a theory of consciousness bridging that Cartesian gap between mind and matter:

“We are led to a conception of the world on which information is truly fundamental, and on which it has two basic aspects, corresponding to the physical and the phenomenal features of the world.” (Chalmers 1995: 215)

« 61 » The phenomenal aspect of information (vs. physical aspect) can be interpreted as a version of the endogenous (within an agent) vs. exogenous (outside an agent) aspect of cognition. Endogenous information constitutes what can be identified as the agent itself/himself/herself and constitutes the inner "subjective," while exogenous information corresponds to the network of relationships with the outside world, which defines the negotiated "intersubjective/objective." This approach gets its natural formulation if we chose the *relational definition of information* proposed in the introduction.

« 62 » Von Foerster offers illuminating analysis of "intersubjective/objective" and asks what is then objective about an object seen as an eigenvalue or a result of a process of classification in the dynamic structures of a cognizing agent? His answer is *intersubjectivity* through other agents, when "eigenbehaviors of one participant generate (recursively) those for the other." Meaningful communication is a result of inter-subjectivity. The gap between inner and outer is bridged by information as the fabric of reality for cognizing agents – both "objective" and "subjective" reality.

A third-person vs. first person approach and emergence of meaning for a cognizing agent

« 63 » Brier (2013a) discusses Dennett's (1993) endeavor to explain subjective consciousness and the qualia by explaining "subjective" phenomena in "objective" terms of "the objective, materialistic, third-person world of the physical sciences" (Dennett 1978: 5). Brier's argument is that this project is not viable "since the language of physics does not include the notion of agent (agency) and meaning." (Brier 2013a: 242). This would imply that any translation between different levels of description is in principle impossible. However, there are macroscopic phenomena that can be explained by microscopic physical theories in the language of quantum mechanics, such as superconductivity, ferromagnetism, and atomic spectral lines. The macroscopic phenomenon of heat can be explained in terms of microscopic kinematics of molecules. It is not necessary that the same vocabulary be used at each level of description. At the single-neuron level there is no cognition. At different levels of organization, different vocabularies are appropriate. Vocabulary is not intrinsic to the domain, but imposed by human observers who interact with it and also construct connections between vocabularies.

« 64 » The way of interpreting Dennett's research program would be to equate objective with inter-subjective and material with physical, which makes it agree with modern cognitive science approaches, as presented, for example, in Clark (1989). Physics has no notion of meaning (more than the intrinsic meaning of its own theory), but meaning in living organisms emerges from physical substrate. Information plays a role of establishing relations.

« 65 » *Subjective experience* has no special privileged position in relation to other types of cognition. It is by no means cognitively superior and cannot replace third-person understanding of that experience (established socially). *Subjective experience* is informational like all other aspects of reality for an agent, and we have no reason to believe that it is different from the rest of cognitive processes.

« 66 » From neuroscience we learn that processes of listening/hearing/seeing/etc. all correspond to physical states of the brain (von Foerster talks about eigenstates with regard to perception). What happens at the physical level in our body, at some higher level of information processing, gets observed as subjective experience. What arrives as photons to our visual apparatus causes processes that lead to dynamically stable states in our brains (Foerster 2003b; Juarrero 1999). Those processes in our physical body give us subjective experience of the world. Without the third-person insight we would not be able to share the knowledge about the existence of other first-person experiences. To base a research program on a third-person perspective, inter-subjective knowledge and physical foundations are necessary for a scientist. Take, for example, a psychologist who deals with people and their first-person experiences by using a third person approach. Likewise, it is impossible for a physician to have a first-person experience of the pain of a patient. It is more useful if he/she can help the patient by sharing the kind of third-person knowledge about first-person pain that people typically share in similar situations. For similar reasons, info-computational constructivism builds on a scientific approach and takes a third-person approach to subjective aspects of cognition.

6 Conclusion

« 67 » No philosophical approach or scientific field can exhaust all the aspects of one phenomenon – that is why we need transdisciplinarity and collaboration in a constructive project. Constructivist approaches are important because elements of knowledge produced in specialist fields are used in the building of a common knowledge network in which elements being connected gain new meaning from their new common context. In order to understand the result of the construction it is important to understand its process.

« 68 » The IC framework needs to fill many explanatory gaps. Based on neuroscience, biology, bioinformatics, biosemiotics, cognitive computing, etc., it needs to provide computational models of phenomena of mind for which we still lack proper scientific models. The concept of natural computation as presented in Dodig-Crnkovic & Giovagnoli (2013) provides some hints on how to fill those gaps within the computational framework, proposing the concept of nature as a network of networks of concurrent information processes. Even though the first steps towards a unified understanding of natural computation have already been made (in particular the contributions in Hector Zenil's 2012 book *A Computable Universe*), a lot of work remains to be done for a full picture to emerge and connect both to its predecessors in the work of constructivists – von Foerster, Maturana and Varela, von Glasersfeld, and others – and to anticipated results from, among other disciplines, the brain sciences, cognitive computing, synthetic biology, and studies in the origins of life.

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Open Peer Commentaries

on Gordana Dodig-Crnkovic's "Info-computational Constructivism and Cognition"

IC and the Observed/Observer Duality

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> Upshot • While I agree with Gordana Dodig-Crnkovic's IC approach, I am uncertain about two points: first about whether constructivism needs yet another etiquette in order to be considered a viable conception, and second whether the focus on information and computation carries the risk of directing attention away from other crucial aspects of the approach.

« 1 » Gordana Dodig-Crnkovic's paper provides a comprehensive survey of what could be called the state of the art constructivist conception arising from the compilation of second-order-cybernetic, computational, informational, and cognitive approaches. I have no doubt that this survey indeed outlines a framework for the unified study of cognition in living organisms as well as in artificial cognitive systems.

« 2 » The one point, however, that I am a bit skeptical about is the question of whether it really is necessary to tag this compilation with yet another label, the label of "info-computationalism" (IC). I agree that information and computation are crucial aspects in this framework and definitely play an essential role. And of course, it might also be strategically gainful to establish a rather complex and controversial approach by way of using new labels. But in my opinion, this strategy also carries the risk of directing attention away from another aspect of this framework that is mentioned in the paper but not further discussed in terms of its consequences. This is the aspect of *duality* or *concurrency*, as implicitly alluded to in the sentence: "Information is the difference in one physical system that makes a difference in another physical system" (§23). In its consequences, this aspect could be more crucial for the acceptance of this framework than information and computation. It seems to stir up those objections against constructivism that, in spite of the favorable evidences gained from computation (Füllsack 2013), still render it a controversial theory in the eyes of many. In the following, I will briefly expand on this aspect.

« 3 » Information, as a difference that makes a difference, is, according to Gregory Bateson and, as emphasized in the paper (§21), always a difference *to someone* or *to something* that is able to perceive this difference as such. This definition of information hence implies – different to the definition of Claude Shannon – *observation*. It implies a *difference* of an observed and an observer, or in other words, a difference of a system that is able to change, albeit slightly, in reaction to a change in *another* system. As a philosophical minimum condition from this, *one* bit of information needs *two* entities (or systems or whatever) in order to be. A difference in one system would not be a difference (that makes a difference) without the other system *for which* this makes a difference. So if we agree with the constructivist assumption that there is no unobserved reality, we need a rather demanding theory with not just one but *two* "first" entities to start with. The info-computational approach (or however it may be called) hence implies the counter-intuitive picture of an "initially" differentiated world, or of a system that in its origins is sufficiently complex to harbor (at least) two subsystems, of which one can make a difference in reaction to the difference in the other.

« 4 » This is not to say that I consider this option less attractive than the assumption of a reality existing beyond observation – quite the opposite. But it challenges additional explanations that might not be entirely deliverable through informational and computational theory.

« 5 » Two theoretical approaches that might provide helpful building blocks in this regard seem to be, on the one hand, the differentiation theory of George Spencer Brown (1969) as interpreted by Niklas Luhmann (1995), and, on the other hand, a notion by Francesco Varela (1992) about the possibility to regard observation as a kind of capitalization of advantages that might be interpreted in terms of Kolmogorov complexity. Since I intend to elaborate on these modules and their implications for a consistent second-order science in a separate paper, I will just briefly summarize these aspects in the following.

« 6 » A consequence of defining information in the above sense can be seen in the fact that any observer – whatever basic conception one is willing to use – cannot be conceived differently than as being dependent on being observed itself. The observer hence forces its scientific explanation into circular reasoning (Foerster 1981; Luhmann 1995; Kauffman 2009), or as philosophers call it when rejecting it, into a *vicious circle*. A fundamental conception for bootstrapping the observer in this sense has been suggested with the distinction/indication dual of Spencer Brown (1969). This concept conceives observation as a formal duality of drawing a distinction and indicating one of the distinct parts as the currently relevant one, i.e., as a basic binary choice. Its circularity arises from the fact that each observation builds on (presupposed) preceding observations that cannot be observed in the current act of observation, thereby generating an "unmarked space" in each observation. Observations hence carry uncertainty with respect to their own constitution. They are built, so to speak, on the anticipation of being confirmed in the next step. In the same manner as the nodes of a network depend on other nodes, the distinction/indication-dual hence founds a procedural approach that considers potentially infinite webs of recurrent observations that cannot be reduced to any "first" (cf. Füllsack 2011). Each observation remains conditioned on observation itself, implying a process of ongoing interaction of observed and observer.

« 7 » A mathematical concept that captures the recursive interaction of observed and observer has been brought forth by Heinz von Foerster (1976), following Jean Piaget's considerations on cognitive development via ongoing sensorimotor interactions (Abraham & Shaw 1999). As this recursive interaction of observation – of a new-born baby for instance – and subsequent coordinative movement tend to render its initial value (its "first") irrelevant, it seems to offer a chance to conceive observed and observer in terms of the generation of what von Foerster (1976) called "objects as tokens for eigenbehaviors." Mathematically, these objects correspond to attractors that the "bottomless" interaction of non-linear dynamics runs up (Strogatz 1994). Seen as the expression of an asymmetric statistical tendency of dynamical systems, the concept of "strange" or "itinerant" attractors in particular seems to provide an appropriate template for scientific explanations of phenomena that emerge in the ongoing interaction of observed and observer.

« 8 » This conception of attractors combined with the formal conception of the Spencer Brownian observer might allow the observed/observer duality to be re-defined in terms of what philosophers discuss as "intentionality." This can be considered as a temporarily viable "interpretation" of an observer (an "ascription" in the sense of Ernst von Glasersfeld 1995b), in the course of which something becomes a "resource" (towards which intention is directed) if it is observed in the presence of an entity (an organism, for instance) that depends on it (Varela 1992). This generalizes the observed/observer duality, since the entity, as observed as intentionally relating to the resource, could be an organism on the search for nourishment as well as a network of catalysts forming into an autocatalytic loop (Kauffman 2000) or the Game of Life glider[1] reacting to the state of its adjacent cells.

« 9 » Conceiving the observed-observer duality in this way seems to allow Varela's notion of something "capitalizing on a resource" to be connected to the concept of algorithmic complexity (Kolmogorov 1965). Using this conception, observation (in the formal sense) can be conceived as a way of compressing regularities into some kind of viable algorithm, as for instance the rule $F_n = F_{n-1} + F_{n-2}$ (with $F_0 = 0$ and $F_1 = 1$) does with the regularities of the Fibonacci-sequence. As this compression (or model) frees computational power (i.e., reduces complexity), it counteracts entropy and thus implies (temporal) order, which in the next step itself can be capitalized on at another trophic level. From this, a "metabolic" network becomes conceivable that grows through the emergence of entities finding ways to capitalize on respective regularities (or, just as well, on regularities of irregularities by establishing control and monitoring mechanisms) – with the caveat, however, that the expression "finding ways" and the intentionality it implies has to be taken as observed itself, i.e., as *second-order observed* (Foerster 1981). While on the level of first-order observation, this network would be nothing but coincidental (i.e., unintended) – a "cut-out" (in the sense of James 1983) provided by natural selection with intentionality only retrospectively ascribed – the required second-order observation would need a network that includes concurrently operating strong-tie clusters that themselves serve as observers by compressing aspects and dynamics of the rest of the network into a concept that otherwise would remain dispersed and overly complex. Or in other words, it necessitates a modularized network of looser and tighter coupled nodes (weak and strong ties, Granovetter 1973; Csermely 2009), of which some form clusters that, by taking in the "intentional stance" (Dennett 1987), capitalize on the (perceived) order of others, thereby freeing computational power, generating order themselves and hence becoming observable (i.e., capitalizable) in their own turn. Freeing computational power in this sense could then be understood as being "productive," and a web of mutual observations could be conceived as a "food web" of some sort, with each observation reducing complexity and thereby providing "resources."

« 10 » I intend to elaborate on this conception in the near future in a more comprehensive publication. For the moment, this commentary might serve as a supportive reference to one of the directions in which the conception of Dodig-Crnkovic might be fruitfully expanded.

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1 | The cell constellation called "glider" in John Conway's Cellular automaton "Game of Life" self-replicates according to the state of its neighboring cells. It thus could be observed as "capitalizing on" the state of its neighboring cells.

Phenomenological Computation?

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> Upshot • The main problems with info-computationalism are: (1) Its basic concept of natural computing has neither been defined theoretically or implemented practically. (2). It cannot encompass human concepts of subjective experience and intersubjective meaningful communication, which prevents it from being genuinely transdisciplinary. (3) Philosophically, it does not sufficiently accept the deep ontological differences between various paradigms such as von Foerster's second- order cybernetics and Maturana and Varela's theory of autopoiesis, which are both erroneously taken to support info-computationalism.

« 1 » I have had the pleasure of discussing the info-computational (or pan-computational) paradigm several times before (Brier 2011a, 2013a, 2013b) in writing, and orally at several meetings and conferences, with my colleague Gordana Dodig-Crnkovic, and watched her paradigm develop to the present stage. See, in particular, Brier (2008), where most of my arguments present here are developed in greater detail.

« 2 » I find this article's transdisciplinary goal admirable, but also find its idea of an all-encompassing computation process for nature, society and consciousness to be too reductionist. This is first of all because the paradigm does not include first person experience or the phenomenological aspect, which I find crucial for human intersubjective production of knowledge and meaning. Secondly, because its idea of natural computation is a mere postulate based on a reductionist belief in present computers' production of what is called artificial intelligence to be the core of human cognition This paradigm gave rise to the reductionist view of cognitive science based on information processing. In latter years, the development of cognitive science has moved into brain sciences. It is now trying to model and emulate human emotions on one hand and one the other to correlate registration of neural activity with human first person experience, comparing analysis of behavior and linguistically based reports of experience – not the experience itself, which we cannot measure. But the idea of a general info-computation is a research program without any theory of what such a common denominator for all natural, social and conscious processes that have to go beyond the possibilities of a Universal Turing Machine should be, except some sort of universal concept of information processing. So far, it does not contain a theory of conscious awareness and meaning. The whole phenomenological and hermeneutical aspect of reality is not only missing, but simply not recognized and accepted as crucial to such a transdisciplinary paradigm. This is a considerable blow to its transdisciplinary aspiration in the sense of Basarab Nicolescu's (2002) *Manifesto of Transdisciplinarity*. To put it in another way, I do not think that "Messages are just a very special kind of information that is exchanged between communicating agents" (§18) but on the contrary, that information is a part of meaningful cognition and communication.

« 3 » I also find info-computationalism's blend of a sort of computational realism – even if it is only a variant of epistemic structural realism – with a declared constructivism based on, especially, second and third order cybernetics, paradoxical and confusing. This is of course because I base my views on a Peircean triadic pragmaticist semiotic realism that considers information only as a component of semiotic processes, which always include meaning.

« 4 » I am also a doubtful about the soundness of combining the idea of computation with the self-organizing paradigms of general system science and non-equilibrium thermodynamics, as long as this new conception of natural computation – call it actor-model or a general notion of computation – is not produced. It is like selling the skin before the bear is shot. After all, the concept of computation is developed on the basis of the Turing machine, which is not self-organizing but a fixed structure created and organized by the human mind. Although robots can be programmed to function with each other in self-organizing ways, the Turing machine in itself is sequential and linear; the problem is that most natural processes of the living systems are not. There is a huge gap between these two conceptual worlds. I do understand the need to bridge or merge them. But the mere talk of "if we had a model for natural computation" is not enough. It rather avoids the deep problem in my view. See, for instance, the many discussions about this in Swan (2013).

« 5 » As part of the group that has developed the idea of biosemiotics, I am inclined to believe that biosemiotics is a much better research strategy for understanding what sets the processes in living nature apart from computers and the processes in inanimate nature, namely that they are Peircean triadic semiotic. Heinz von Foerster is used as part of Dodig-Crnkovic's argument such as in §14: "…we see that information processing corresponds to von Foerster's operation on 'objects,' or their representations, 'symbols.'" However, he did not see computation as information processing either (Brier 1996). He wrote very critically against the general information concept. I therefore think he is misused here as a supporter of info-computationalism.

« 6 » From a Peircean ontology of continuity and view point of fallibility of all general knowledge, it is also worth remarking that mathematics and science are finite disciplines and are not identical with or prior to reality as such. We live in an immanent frame, which we continually expand and attempt to understand. Experience and cognizing reality is the starting point of all thought and cognition – not computation in my view.

« 7 » In the same way, I wonder how Dodig-Crnkovic uses the concept of "observer" (is a robot an observer?) and I do not think she interprets Floridi correctly here (§19) or Wheeler just after that (§20). His "it from bit" is based on a participatory universe, not a computer metaphor. Deep ontological issues seem to be treated a little superficially here. Pan- and info-computation views attempt to remove all mystery from the world by postulating computational agents without any experiential awareness. In §23 Dodig-Crnkovic claims: "Information is the difference in one physical system that makes a difference in another physical system," and a little later speaks of functional responses only. But then she returns to her inspiration from second-order cybernetics that all information is observer dependent but that observer is never an experiential phenomenological first person one. In some other places Dodig-Crnkovic writes about perception as if subjective experience is taken for granted, but it does not really exist in the implicit paradigm the whole paper is written on. It is much as in Ernesto Laclau and Chantal Mouffe's (1985) discourse analysis, where the subject is what fills out the holes in a chain of arguments (Laclau 1990). It works like a negative definition in the hope of an "intuitive processor" as a form of neural network non-symbolic processor type of computation (§32) – now introducing biological (probably cybernetic) agents. As a biosemiotician, I agree that all biological systems produce knowledge, but not from the understanding of them as autopoietic machines (Brier 1995, 2011b).

« 8 » There are some further cases in which Dodig-Crnkovic may have misquoted other scholars. Humberto Maturana does not accept an information processing view either; neither did Francisco Varela, who was influenced by phenomenology. So they are misquoted here, even though their insights fit well with von Foerster's eigen-values and eigen-behaviors, and Luis Rocha's further development of his cognitive cybernetics. In §56 Stanley Salthe's pan-semiotism is ignored and instead he is portrayed as supporting constructivist info-computationalism. In reply to my earlier criticisms, Dodig-Crnkovic uses David Chalmers informational model of consciousness but misses mentioning his doublet aspect theory of information, which is pretty different from hers (although I do not agree myself with the way he introduces the experiential aspect). She deals with the doublet aspect philosophy in §62 with the help of the concepts *exo-* and *endogenic*, thereby dodging the experiential aspect of awareness. Dodig-Crnkovic combines the endo-exo-model with Gregory Bateson's "information as a difference, which makes a difference" omitting the fact that it applies only for a cybernetic mind that does not contain first person experience and qualia (Brier 1992). In §64, subjectivity becomes a question of levels, though such a qualitative emergent ontological organismic system thinking is not introduced or argued, but is again postulated in §65.

« 9 » In §66, intersubjectivity is seen as primary to first person subjectivity, which to me is the prerequisite for intersubjectivity and language. Here, however, it is made informational. This is an interesting attempt to place first person experience and perception as well as meaningful communication in a corner of a basic physicalistic information world view. But first person experience and meaningful communication are the prerequisite for the information science from which the info-computational view is argued. It is not the other way round.

« 10 » In general, I cannot help the impression that the philosophy behind info-computation is mixing apples, pears, and bananas by arguing that no matter how their taste is experienced, they are all fruits and that is the basic fact on which we should build transdisciplinarity.

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A Mathematical Model for Info-computationalism

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> Upshot • I propose a mathematical approach to the framework developed in Dodig-Crnkovic's target article. It points to an important property of natural computation, called the multiplicity principle (MP), which allows the development of increasingly complex cognitive processes and knowledge. While 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 computations, perhaps with the help of Turing oracles.

How can a mathematical approach to info-computationalism be developed?

« 1 » Gordana Dodig-Crnkovic proposes an info-computational framework for approaching cognition in living organisms and in embodied cognitive agents of any kind: the environment affords potential information that the agent can integrate into actual information and transform into knowledge by natural computation; perception acts as an information-processing and learning device, through dynamical processes of self-organization of the agent. While the objective is clear, the article remains in an abstract setting, without illustrating it with specific situations, and it does not raise the problem of mathematical modeling, with its possible contributions to a better understanding of the situation.

« 2 » Here I propose such a mathematical approach, namely the bio-inspired *Memory Evolutive Systems* (MES) methodology, which we have been developing for 25 years (cf. Ehresmann & Vanbremeersch 2007). It is based on a "dynamic" category theory, a recent mathematical domain (introduced by Samuel Eilenberg and Saunders MacLane in 1945) that stresses the role of relations over structures. It identifies some important properties of information processing and natural computation not discussed in the article, and shows their role in the non-(Turing-)computability of the global dynamics of the system.

Memory Evolutive Systems

« 3 » An MES gives a constructive model for a self-organized multi-scale cognitive system that is able to interact with its environment through information processing, such as a living organism or an artificial cognitive system. Its dynamics is modulated by the interactions of a network of specialized internal agents called *co-regulators* (CRs). Each CR operates at its own rhythm to collect and process external and/or internal information related to its function, and possibly to select appropriate procedures. The co-regulators operate with the help of a central, flexible *memory* containing the knowledge of the system, which they contribute to develop and adapt to a changing environment.

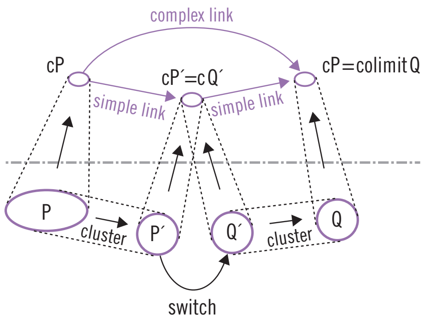

Figure 1: Complex links in MES

« 4 » In an MES, a central role is played by the following properties of information processing in living systems: (i) The system not only processes isolated information items, but also takes their interactions into account by processing *information patterns*, that is patterns of interconnected information items. (ii) The MES satisfies a *multiplicity principle* (MP), asserting that several such information patterns may play the same functional role once actualized, with the possibility of a switch between them during processing operations. This principle formalizes the *degeneracy* property that is ubiquitous in biological systems, as emphasized by Edelman (1989; Edelman & Gally 2001). It permits Gregory Bateson's sentence (§21) to be completed into "a difference that makes a difference, but also may not make a difference." The MP is at the root of the flexibility and adaptability of an MES; it will also be responsible for the non-computability of its global dynamics.

« 5 » Once actualized in the MES, an information pattern *P* will take its own identity as a new component *cP* of a higher complexity order, which "binds" the pattern, for instance as a *record* of *P* in the memory. The binding process is modeled by the categorical *colimit* operation (Kan 1958): *cP* becomes the colimit of *P* and also of each of the other functionally-equivalent information patterns; thus it acts as a multi-facetted component. Such multi-facetted components are constructed through successive *complexification processes* (Ehresmann & Vanbremeersch 2007). The complexification also constructs the links interconnecting two multi-facetted components *cP* and *cQ*. There are *simple links*, which bind together a cluster of links between the information items constituting the patterns *P* and *Q*. However, the MP makes also possible the emergence of *complex links*, composed of simple links binding non-adjacent clusters, for instance a simple link binding a cluster from *P* to *P′* and a simple link from *Q′* to *Q* if *P′* and *Q′* are functionally equivalent patterns with colimit $cQ'=cP'$ (cf. Figure 1). Complex links reflect "changes in the conditions of change" (Popper 1957). They are at the root of the *emergence theorem* (Ehresmann & Vanbremeersch 2007): the MP allows the development over time of components of increasing orders of complexity, such as more and more elaborate knowledge and cognitive processes.

The model MENS for a neuro-cognitive system

« 6 » To describe the functioning of an MES more explicitly, we restrict ourselves to a particular MES, the *memory evolutive neural system* (MENS), which models the cognitive system of an animal (up to man). MENS gives a framework comprising the neural, cognitive and mental systems at different (micro, meso, macro) levels of description and across different timescales. Its construction takes account of the following properties of the neural system: (i) as already noted by Hebb (1949), there is formation, persistence and intertwining of distributed neural patterns whose synchronous activation is associated to a specific mental process; (ii) this association is not one-to-one due to the "*degeneracy* property of the neural code," emphasized by Edelman (1989: 50). In MENS, this degeneracy is formalized by the MP, and a mental object or process is represented by the common binding (formally colimit) of the more or less different neural patterns that it can synchronously activate at different times, and that constitute its several "physical" realizations.

« 7 » MENS is a *hierarchical evolutive system* (Ehresmann & Vanbremeersch 2007) that sizes up the system "in the making," with variation over time of its configuration categories, its information processing. Its memory stores different data, knowledge, experiences and procedures in a flexible manner, to be later recalled or actualized in changing conditions. The evolutive system Neur of neurons (and synapses) constitutes the lower level of MENS. The higher levels are constructed by successive complexifications of Neur that add new components, called "category neurons," that represent mental objects or processes and are obtained from the binding (= colimit) of synchronous neural patterns. Due to the emergence theorem, these complexifications generate an "algebra of mental objects" (Changeux 1983), up to flexible higher mental and cognitive processes. Thus MENS processes more and more complex information over time (cf. §38). However, the complexifications may also destroy some existing category neurons, in particular records in the memory that are no longer adapted to the context.

Dynamics of MENS

« 8 » "Potential information" (§14) consisting of some change in the environment can be actualized in MENS only if it interacts with the system by activating some neural patterns in specialized brain areas acting as co-regulators. These co-regulators operate stepwise as an "interface" (§29) between the environment and the system's behavior. Several co-regulators "perceive" different parts of incoming information through specific patterns; for instance, a co-regulator dealing with colors will only perceive the color of an object *O*, while a shape co-regulator will only perceive the shape of *O*. At a time *t*, a co-regulator collects the different information received from its external and/or internal environment into its *landscape* at *t* (modeled by a category). Using its differential access to the memory, it processes the information and reacts to it by selecting an adequate procedure: if the color of *O* is already known, the color CR will "recognize" it and activate its record; if the color is not yet known, it will command the synchronization of the color pattern *P* (by strengthening its synapses), leading to its binding into a new category-neuron (colimit of *P*), which will memorize the color of *O*. The synchronization of an assembly of neurons is a kind of natural computation that is reducible to a classical computation in the usual Turing sense; if there was only one co-regulator, its dynamics during one step could be computed by classical means (e.g., via differential equations).

« 9 » However, there is a whole network of co-regulators that can function asynchronously (as in Hewitt's actor model, cf. §16). At *t*, the different procedures they try to implement can be conflicting, thus requiring some "interplay" among them to harmonize them. MP lends flexibility to this process, since a procedure *Pr* can be "physically" realized through the activation of any one of the neural patterns it binds. As there is no central co-regulator, this interplay may necessitate cascades of natural computation of various kinds, making it not computable in the usual sense. At the moment we do not know of any mathematical models for such a kind of natural computation, where there are possibilities for switching between different physical realizations of the same procedure. It would necessitate the use of more sophisticated methods, for instance using Turing machines with oracles (cf. Soare 2009, or the DIME method proposed by Mikkilineni 2011). The idea would be that each co-regulator acts as an oracle, possibly interrupting the local dynamics of another co-regulator, with cascades of such operations up to the attainment of a common solution.

Conclusion

« 10 » The MES methodology affords partial constructive mathematical approaches to the development of cognition in Dodig-Crnkovic's general info-computational framework. It also characterizes the multiplicity principle as the root of both the emergence of increasingly complex knowledge and of the non-computability (in a classical sense) of natural computation. The colimit (or binding) operation translates the actualization of information patterns into new components that, thanks to the multiplicity principle, take their multi-facetted individuation over time. While the local dynamics of one co-regulator during one step is classically computable, the global dynamics is not. There is a need for more elaborate mathematical models, thus opening new horizons for research.

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Information, Computation and Mind: Who Is in Charge of the Construction?

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> Upshot • Focusing on the relationship between info-computationalism and constructivism, I point out that there is a need to clarify fundamental concepts such as information, informational structures, and computation that obscure the theses regarding the relationship with constructivist thought. In particular, I wonder how we can reconcile constructivism with the view that all nature is a computational process.

Introduction

« 1 » Gordana Dodig-Crnkovic's "Info-computational Constructivism and Cognition" presents a comprehensive program of cognitive studies combining constructivist methodology with an info-computational ontological framework. The main line of thought is well documented and supported by solid argumentation, but there are some points which aroused objections or questions in the present author. Thus, although the following is not intended as a criticism of the program, it is a call for further explanation or clarification of confusing statements. The need for further explanation may be a result of the immense task of comparing and correlating the two extensive directions of thought that Dodig-Crnkovic ventured and achieved with impressive results, but that did not allow more detailed explanation to be entered into. However, in the opinion of the present author, the comparison becomes confusing without clarification of the fundamental concepts, such as information or computation.

Questions regarding the ontology of info-computationalism

« 2 » The main question regarding the program presented by Dodig-Crnkovic is about the degree to and manner in which the view of reality in terms of information and computation, at least as presented in the article, is consistent with the constructivist point of view (hence the subtitle of this commentary: Who is in charge of the construction?) Unfortunately, neither info-computationalism (IC) nor constructivism are homogeneous, uniform schools of thought, and the perception of the need for the question above can be just a matter of equivocation. But even then, it is worth attempting to clarify this issue.

« 3 » The article declares in the first paragraph that

> "It [IC] asserts that, as living organisms, we humans are cognizing agents who construct knowledge through interactions with their environment, processing information within our cognitive apparatus and through information communication with other humans." (§1)

However, this sentence is preceded by

> "Info-computationalism (IC) is a variety of natural computationalism, which understands the whole of nature as a computational process."

« 4 » I find this innocent looking juxtaposition puzzling. If we understand the constructivist position as a view that gives the active and primary role in the process of construction of knowledge to the mind, how can we reconcile it with the view that all nature is a computational process? What can be the contribution of the mind to a universal process seemingly governed by external, independent rules?

« 5 » The long tradition of constructivism, going back at least to Giambattista Vico, opposes the view of learning through observation (even when understood as exploration necessarily involving interaction), promoting the view that knowing means creation, that truth is an invention or generation, not an acquisition. After all, the constructivist tradition was intended as a way to avoid the Cartesian duality of body and mind, *res extensa* and *res cogitans*. We know something when we can construct it, not when we recognize a pattern through observation. The involvement of the mind in the construction of what we are learning dissolves the division between the mental and the physical. When we give priority to the external universal process (computational or not), in which the mind can participate in various degrees but is subject to its rules and does not contribute to it as a creator or constructor, we deviate from the main tenet of constructivism.

« 6 » The target article refers to the views of Stuart Umpleby (2002) as the historical roots of info-computational constructivism, which included the division of the development of this direction of thought into the three periods of so-called engineering, cybernetics, biological cybernetics and social cybernetics:

> “During the engineering period, the object of observation, the observed was central. In the second phase, with research in biology of cognition, the core interest shifted from what is observed to the observer. In the third phase, the domain of social cybernetics focus moved further to models of groups of observers.” (§1)

Here the use of the term “observer” is curious, in the context of the constructivist position. But the “damage” to the constructivist tradition does not seems beyond repair if we substitute the words “construction” and “constructor” for the words “observed” and “observer.” However, to include cybernetics (at least its first stage) into the main stream of constructivism, we have to redefine its philosophical foundations and interpret it as modeling the constructivist view within a very different or even opposite paradigm. The original position of cybernetics, i.e., first-order cybernetics, was rather to eliminate the mind from the Cartesian mind-body dualism by giving priority to the body (embodiment), not by elevating the mind to the role of a creator, inventor or constructor.

« 7 » The reference to first-order cybernetics, or even its later forms, as the initial source of info-computational constructivism brings out the possibility that this position should rather be considered a mirror reflection of the traditional position of constructivism, closing the gap in the dualistic view not from the side of the mind but from the side of the body. It can be seen, for instance, in the views of Humberto Maturana and Francisco Varela, whose main concept is called an “autopoietic machine,” not “autopoietic mind” (Maturana & Varela 1980: 78). Thus, the ontological foundation is built on the assumption of the existence of the “physical world” in which some structure is constructing mind out of its cognitive functions.

« 8 » Someone could look for more constructivist ontological foundations for autopoiesis, detaching it from dualistic ontology by the assumption of a shift of emphasis from the body (machine) side of the dualism to the mind side. It could do so by interpreting autopoiesis as self-organization, where organization could be made independent from its physical substratum and could assume an active, constructive role. This is how we could understand the statement from the target article:

> “In order to understand cognition and knowledge as a natural phenomenon, the process of re-construction of the origins, development and present forms and existence of life, processes of evolution, and development based on self-organization are central. The work of Maturana and Varela on the constructivist understanding of life is of fundamental importance.” (§39)

However, the interpretation of autopoiesis as self-organization is not consistent with the views of the original authors of this concept. Maturana explicitly opposed such interpretation, writing that he would “never use the notion of self-organization, because it cannot be the case … it is impossible. That is, if the organization of a thing changes, the thing changes” (Maturana 1987: 71).

« 9 » The target article also refers to Milan Zeleny’s view:

> “Such autopoietic systems are organizationally closed and state-determined… What does it mean that an autopoietic system is organizationally closed? It means it conserves its organization.” (§39)

In what sense can we say that an autopoietic system is self-organizing, which means developing (i.e., changing) its organization, and at the same time conserving its organization? This contradiction cannot be resolved by a distinction between the conservation of organization at the phenotypic level and change at the genetic level of species, as phenotype and species are two different systems.

« 10 » It seems quite clear that the expression “autopoietic machine” in the fundamental concept of autopoiesis is not accidental, and that it refers to the fact that its ontological status is clearly rooted in the body side of Cartesian dualism, with the objective of subordinating or eliminating the mind side.

Questions regarding understanding information

« 11 » Similar ontological assumptions can be found in Dodig-Crnkovic’s article regarding the fundamental concepts of IC. It starts at the most fundamental level by defining the concept of information (preceding the concept of computation) in her paraphrase of Gregory Bateson’s definition:

> “Information is also a generalized concept in the context of IC, and it is always agent-dependent: information is a difference (identified in the world) that makes a difference for an agent. […] For different types of agents, the same data input (where data are atoms of information) will result in different information.” (§2)

The concept of “atoms of information” is questionable and difficult to understand in the context of her definition (are there any indivisible differences?). But whatever the data are, this means their existence is within the world and seemingly they are independent from agents. Thus, it is just a matter of what agents do with the data (how they interpret data), and this suggests that actually Dodig-Crnkovic is writing not about the data–information relationship, but about the meaning of information.

« 12 » The dualistic (physicalistic) ontological position can be seen even more clearly in her next paraphrase of Bateson’s definition, to combine it with Hewitt’s relational view of information: “Information is the difference in one physical system that makes a difference in another physical system” (§23, emphasis in the original).The dualistic ontology is already present in the use of expression “physical world” as it requires a complement in the form of the mental world (what other complement is possible?). If not, what is the reason for using the adjective “physical”?

« 13 » The relationship with the world is described in the target article as follows:

> “The world as proto information presents the potential form of existence corresponding to Im-

manuel Kant's Ding an sich (thing in itself). That proto information becomes information, 'a difference that makes a difference,' […] for a cognizing agent in the process of interaction." (§21)

« 14 » It is difficult to find out how an agent is involved in creation of information beyond the fact that it is involved in observation through interaction, which changes proto information into information. But this was just the definition of proto information involving an "(observing) agent" as necessary for transition into information (§17). It is, of course, an expression of the view that an observer is necessary to transform potential existence into actual existence, but it hardly reflects tenets of constructivism. Once again, it seems likely that this process is actually not a transition from proto information to information, but rather interpretation that gives meaning to information; however, there is nothing in these passages regarding creation of the meaning for information (which actually could be considered a weak form of constructivism, if the role of construction is given to the mind).

Questions regarding computation

« 15 » There is a similar problem with understanding how to identify the constructivist character of the second fundamental concept of computation. The quotation of Mark Burgin's definition "*Computation is information processing*" does not make it easier (§14, emphasis in the original). To say that "computation is information processing" is to say nothing except that there is some vague relationship between computation and information (computation is doing something to information), unless someone clearly defines the term "processing."

« 16 » We can learn more from the quotation of Heinz von Foerster's definition of computation as "any operation (not necessarily numerical) that transforms, modifies, rearranges, orders, and so on, observed physical entities ('objects') or their representations ('symbols')" (§13). It seems that von Foerster means that computation is simply any change of some entities, their relations, or representations, or actually any change in general, as every change is either of entities, their relations or representations. Changes of accidental or essential properties of entities are just specifications of the types of changes of entities. This, however, is a gross over-generalization, as what would be the reason to use two different terms "change" and "computation" in the same meaning? Change is a natural candidate for the *genus* for computation, but we need a non-trivial *differentia*.

« 17 » Since the very concept of an agent has its most general meaning as something that makes changes, the reference to "computational agents" does not help much in understanding computation: "Hewitt's 'computational devices' are conceived as computational agents – informational structures capable of acting on their behalf" (§16). Here, as well as in many other places in the target article, appears the expression "informational structures." It is not clear what they are and how they relate to the constructivist view of reality. There is a short passage in a footnote, which seems to be the most important in the entire paper, which refers to the problem:

"Von Foerster rightly pointed out that computers do not process information but data. However, this term is already widely used. Data are atoms of information. Information is obtained when data becomes integrated into structure (correlated), which happens in the interaction with a cognizing agent." (Footnote 5)

« 18 » In the opinion of the present author, this is the point where we can find a connection between information, computation, and constructivism. In the target article, information integration and its structural characterization are left without more detailed description, but the recognition of the role of a cognizing agent in the integration of information seems to point at the active role of the mind in seeking knowledge. This point of view is close to the views presented by the present author in his earlier publications (Schroeder 2011). But even the footnote is confusing and apparently involves a vicious circle. We learn that data are atoms of information, but information is obtained only when data are integrated into a structure in the interaction with an agent. There is another passage that refers to informational structures: "Reality for an agent consists of structural objects (informational structures, data structures) with computational dynamics (information processes) that are adjusted to the shared reality of the agent's community of practice" (§20). However, it does not explain what these structural objects are and what kind of dynamics describes their interactions. Even worse, here we have put informational structures and data structures alongside each other.

« 19 » Thus, when the concept of morphological computing appears in the text, we can guess that it is some type of structural change involving informational structures. But it is not clear at all what these informational structures are or how they come into existence, except that it happens in the interaction (of the data?) with a cognizing agent. Then, the dynamics of informational structures is also left without explanation. Dynamics means interaction, in this case interaction between informational structures (or possibly within, but in this case between what?). At the same time we have an interaction with a cognizing agent that constitutes information, which itself requires some form of dynamics.

« 20 » Confusions regarding the concepts of information, informational structures, and computation and their relationship to constructivism make understanding the relationship between info-computationalism and constructivist thought very difficult. It is possible that it is a matter of difference in the understanding of info-computationalism. In fact, for the present author, the definition of info-computationalism as "understanding of the whole nature as a computational process" is not clear as long as a computational process (i.e., presumably computation) is just any change of unclearly defined informational structures. The way from information understood as a difference that makes a difference (notice the idiomatic character of this expression!) to informational structure to computation is too long to be left to individual interpretations if we want to have some identifiable direction of thought.

Conclusion

« 21 » Info-computationalism can be related to constructivist approaches only when its fundamental concepts are defined in a sufficiently clear philosophical framework. Otherwise, we risk inconsistency in relating constructivist epistemology to a dualistic ontology of info-computationalism. The definitions and their interpretations used in the target article are too narrow, too general, or too far removed from the philosophical background to satisfy this postulate.

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Modelling Realities

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> Upshot • Gordana Dodig-Crnkovic proposes that radical constructivism and info-computational (IC) processes have a synergy that can be productive. Two issues are proposed here: can constructivism help IC to model creative thinking, and can IC help constructivism to model conflict resolution?

« 1 » Classical introductions to constructivism are presented in human terms. Humberto Maturana's account of cognition begins with observation. More generally, cognition depends on noticing differences and we make choices based on past experience. These choices are based on decisions concerning what is best for us (Glasser 1985) and the heuristics on which these decisions are based have been studied (Gopnik et al. 2004). Ernst von Glasersfeld (1974) introduced radical constructivism (RC), emphasising that our cognitive rational ways of understanding the world did not refer to a Reality as it was always beyond our sense receptors. This implied that classical notions of truth that presumed a matching of cognition with Reality require rethinking and von Glasersfeld proposed instead that viability ensured that our understandings worked. The concepts of truth viability and certainty are linked because survival depends on knowledge. So the ways an individual and her social group understand reality are vitally important.

« 2 » Siegfried Schmidt (2011) recently proposed that constructivism should focus on processes rather than entities. Gordana Dodig-Crnkovic here makes a similar proposal that the info-computational approach (IC), which also emphasises processes, has a synergy with constructivism that can be mutually beneficial to both approaches. In her article she describes how computing agents interact with their environments in intelligent ways. Agents and robots that compute do so with a limited but effective notion of their environment. They are regulatory systems that are increasingly becoming commonplace in our experience of our worlds, from thermostats to computer assisted braking systems to apps in phones. These regulatory systems with cybernetic features use feedback from specific sensors and have been compared to cognitive processes since the time of Ross Ashby (1960) and the Macy Conferences in the middle of the last century.

« 3 » In modelling cognition with computing systems, there are two issues on which I would like to comment. One goes back to the conflicting approaches of René Descartes and Giambattista Vico. These are whether thinking is better-modelled as deductive (Descartes), or whether the creative processes involved in constructing new ways of understanding phenomena should be emphasised (Vico). This issue is one that invites comment from the IC approach. Since Charles Sanders Peirce and John Dewey, processes of deduction and induction have been accompanied by abduction as ways of explaining creative processes. So, I wonder if computing systems that use parallel computing can, or will soon, simulate this type of creativity. Dodig-Crnkovic cites the inadequacy of earlier efforts to model cognition (§32). Constructivism has a strong history of emphasising creativity in learning; in an appropriate example, the Empowering Minds Project used Lego robotics with children in schools (Butler & Gash 2003). One feature in this project that required creative problem solving for novices was the problem of changing the direction of power using gears, as in cars. Creative problem solving often requires a flash of insight and a new conceptualisation and a feature involved in such processing is non-linearity. Are such problems and processes an inspiration or a stumbling block for new IC developments, such as parallel computing processes?

« 4 » A second issue is to explain different realities. This theme seemed to preoccupy von Glasersfeld. It is a theme that since then has been a constant source of irritation (e.g., Boghossian 2006). However, it must be stated, our concept of reality is intimately associated with our notion of self and responsibility, thus it is intimately related to our identity. It is also central to so many conflicts, both intercultural and interpersonal. I want to explain this and then ask whether the IC position might offer a solution to explaining the RC position and make it less irritating.

« 5 » Taking responsibility for one's own ideas has been central to the constructivist position, and different writers give different reasons for this. Von Glasersfeld (2010) arrived at his RC position on account of both his philosophical readings and his living in more than one language. Humberto Maturana's (1988) explanation of cognition shows how taking responsibility for our acts and thoughts implied acceptance of the constructivist position. Finally, Andreas Quale's target article on ethics implies that our interactions with each other influence the forms of responsibility we adopt in our daily lives. It is clear that our ethical values arise during, and are influenced by, our experiences with others. Like our sense of self, ethical values and responsibility belong in the relational domain (Glasersfeld 1979). The problem is how to share these ideas with the wider public. Civic responsibility has received serious attention, especially in the need to promote social capital (Putnam 2000). However, these ethical implications of constructivism have a low profile in accounts of constructivism.

« 6 » A largely ignored implication of constructivist thinking is that two realities are uncomfortable and potentially dangerous. Gregory Bateson (1979) referred to this when discussing heresy. However, we do not need to discuss religious or political differences in the past or present to appreciate how two visions of how things are or should be can be divisive. Yet RC proposes that these ideas about different realities depend on the choices and past experience of their proponents, and this proposition always seems to require explanation. If this insight could be made more commonplace, perhaps negotiations between opposing groups with different views on their reality would have a sounder footing.

« 7 » Is it possible that the info-computational approach could model opposing views in ways that would facilitate negotiations between rival groups? It is well known that contact between groups has the potential to facilitate the emergence of mutual respect. If the idea that different versions of reality are what divide two groups is more generally accepted, and if this reality can be modelled with computer assisted representations, this might assist negotiations. The work done in IC seems to hold this out as a possibility, and two models seem appropriate one a simulation model (Riegler & Douven 2009) and the other theoretical (Josué Antonio Nescolarde-Selva & Josep-Lluis Usó-Doménech 2013). The latter proposed model of belief systems is mathematical, with specific properties for understanding expressions of culture, including text. This model should allow precise specification of the belief systems of two groups who are trying to negotiate. When groups differ in their visions of reality, one difficulty is to persuade each group that things can be seen differently. Is it too much to hope that the commonplace gadgets that are so useful to us can serve as models of limited realities? IC seems to hold much promise for facilitating a model of understanding constructivism. Schmidt (2011) has shown how this works cognitively. Can IC contribute? Perhaps there are computer models of negotiations that can take these ideas and develop them?

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Info-computationalism or Materialism? Neither and Both

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> Upshot • The limitations of materialism for studying cognition have motivated alternative epistemologies based on information and computation. I argue that these alternatives are also inherently limited and that these limits can only be overcome by considering materialism, info-computationalism, and cognition at the same time.

« 1 » Gordana Dodig-Crnkovic argues convincingly that materialism is insufficient for studying cognition. As an alternative, an epistemology based on information and computation is offered.

« 2 » Materialism has been successful in describing physical phenomena (matter and energy), but it cannot explain phenomena such as cognition, life, meaning, and agency, often falling into a mind/body dualism (Kauffman 2010). The problem with a dualistic perspective is that it cannot relate physics and cognition (nor life, §35); nor can it explain how cognition depends on a physical substrate or how cognition can affect the physical world.

« 3 » Instead of trying to describe information in terms of matter and energy, we can describe matter and energy in terms of information (Gershenson 2012). This allows us to explore potential laws that apply to phenomena at all observable scales, including the biological and the cognitive. I defined information as "anything that an agent can sense, perceive, or observe" (Gershenson 2012: 102), and computation as a change in information.

« 4 » IC can offer a novel perspective on cognition, but it also has its limitations. Even though in principle it encompasses materialism, physics cannot be ignored, as it can be argued that meanings are grounded in a common physical space (matter and energy), mediated by social interactions. Intersubjectivity (§63) requires a physical medium to share and change information. Moreover, there are physical constraints that limit the living and cannot be deduced from only information. Looking only at molecules, one cannot distinguish living systems from non-living ones. Take, for example, an aquarium with fish, algae, and bacteria. From the *physical* perspective there is no difference between the aquarium with its contents and another object with exactly the same molecules. The difference lies in the *organization* of the components (§39; Varela, Maturana & Uribe 1974). Considering only information, one cannot distinguish the physical from the virtual, as in a computer simulation. If we have a physical description of matter and energy, this can be also described in terms of information (Gershenson 2012), as matter and energy can be seen as particular types of information. Nevertheless, my argument is that the physical substrate of cognitive systems cannot be neglected. I claim that within a constructivist worldview, it is not enough to consider only the organization/information of systems; their substrate and their relation must also be considered, as will be expanded on below. This is not an ontological claim, but an epistemological one.

« 5 » The "conflict" between materialism and IC can be traced back to the centuries-old discussion related to the concept of *emergence*, i.e., that the whole is not the sum of its parts. If physics describes the parts, what is the "something" that makes the whole more? As I argued in Gershenson (2013), this something is information, and in particular, *interactions*.

« 6 » The concept of emergence seems to be problematic in terms of causality: can the parts cause the whole? Can the whole cause the parts? (Bar-Yam, 2004b; Heylighen, Cilliers & Gershenson 2007). Philip Anderson (1972) showed that properties of systems cannot be reduced to the properties of their components. And it is common sense to agree that even when a system can influence its components, these may have certain autonomy, such as an individual in a society. Because of this, when studying complex systems, parts and whole and their interactions should be considered at the same time in order to have a more complete description. Multiscale perspectives attempt to address this issue (Bar-Yam 2004a; Gershenson 2011).

« 7 » In a similar line of thought, Buddhist philosophy maintains that object, subject and the action of the subject perceiving the object are not separable (Nydahl 2008). This is because we cannot describe an object without a subjective observer, while subjective description is constrained by the object, and their relation is mediated by the action. Focussing only on objects we fall into materialism, with all the limitations exposed by Gordana Dodig-Crnkovic. Focussing only on the descriptions, we fall into subjectivism, which has also its drawbacks, as we know from the limitations of postmodernism (Cilliers 2002). Constructivism proposes to go beyond these limitations by relating the social construction of the descriptions, mediated by shared objects and through the action of observing.

« 8 » Materialism, IC, and cognitive science are not separable but are complementary: objects are described by materialism, subjects by IC, and action by cognitive science. The latter is not an epistemological position, but is required to link the other two, as it is cognitive systems that produce information from a material substrate and use the information to change the substrate. This also considers the social aspect of cognition, as meaning is made not only by the interaction between object and subject, but also between subjects (§22; §56; Froese, Gershenson & Rosenblueth 2013).

« 9 » Matter and energy (object, observed) cannot be studied without considering information (subject, observer), nor vice versa. Cognition (action, observing) is precisely the process that relates the physical and the mental, the material and the informational. It might not seem so, but this is actually a monist perspective, as this triadic interdependence does not allow us to study different aspects separately. "Matter" and "energy" are concepts relative to the cognitive subject, who constructs them out of her experience. Only by considering matter, information, and cognition at the same time, will we have a better understanding of them all.

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Info-computational Constructivism and Quantum Field Theory

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> Upshot • Dodig-Crnkovic's "info-computational constructivism" (IC), as an essential part of a constructivist approach, needs integration with the logical, mathematical and physical evidence coming from quantum field theory (QFT) as the fundamental physics of the emergence of "complex systems" in all realms of natural sciences.

« 1 » In this commentary I suggest how QFT, with its logic and its epistemology, can support, integrate or even correct some IC notions, always clarifying them at the fundamental levels – logical, mathematical, and physical.

A change of paradigm: From mathematical physics to physical mathematics

« 2 » In the second section (§§7–27), Gordana Dodig-Crnkovic "expounds the two basic concepts of IC" (§6). These are the notions of "natural information" and "natural computation," as far as they are based on the information approach to quantum physics, and hence distinguished from their usual notions, respectively, of symbol transmission (information) and symbol manipulation (computation).

« 3 » There are several theoretical versions of the information theoretic approach to quantum physics (cf. Fields 2012), which, for the present purpose, can be reduced to essentially two.

« 4 » The first one is related to a classical "infinitistic" approach to the *mathematical physics* of information in quantum mechanics (QM). Its proponents include Heinz-Dieter Zeh (2004, 2010) and Max Tegmark (2011). Typical of this approach is the notion of the *unitary evolution* of the *wave function,* with the connected, supposed *infinite* amount of information it "contains," "made available" in different spatio-temporal cells via the mechanism of the "decoherence" of the wave function. This approach needs to assume *an external observer* ("information for whom?" Fields 2012). It uses Claude Shannon's *purely syntactic* measure and notion of information (Rovelli 1996).

« 5 » Dodig-Crnkovic refers essentially to this infinitistic approach when she speaks about natural information/computation, equating "natural computation" with "morphological computing, i.e., computation governed by underlying physical laws, leading to change and growth of form" (§9). That is, physical/chemical/biological processes relate to the progressive emergence of ever more complex natural structures of matter, from hadrons and leptons to atoms, to molecules, to cells, tissues, organs, and organisms, up to social groups (§11).

« 6 » Assuming that the *mathematical laws* of nature "produce" the ever more complex structures characterizing our evolving universe seems in contradiction with constructivism. "Effects" are produced by "causes" not by "laws." They "rule" a causal process, making its evolution in time predictable (or, conversely, retro-dictable) to observers. Hence, it is not "kinetics," defined as the geometrical laws of mechanics, but "dynamics," defined as the different types of forces and force fields, "causally" acting on material things (processes, particles, systems, etc.), that produces the different forms of "orders." They can be "quantified" through their proper "order parameters," characterizing the emergence of ever more complex systems at all levels of matter organization in nature – and self-organization. This also holds in quantum physics and explains the epistemological difference between QM and

QFT. It justifies the *evolutionary emergence* of the same mathematical laws of nature with the processes they rule and therefore contradicts such laws' "immutability," assumed by the dualistic Platonic ontology underlying the Newtonian paradigm since the beginning of modern science. This suggests changing the *mathematical physics* of the Newtonian approach to the *physical mathematics* of constructivism.

« 7 » Such an alternative is related to QFT, which is a "finitistic" approach to the *physical mathematics* of information, taken as a fundamental physical magnitude together with energy. QFT makes it possible to span the microphysical, macrophysical, and even the cosmological realms within a single quantum theoretical framework, which is different from QM (Blasone, Jizba & Vitiello 2011).

« 8 » In contrast to QM, in QFT systems, the number of degrees of freedom is not finite, "so that infinitely many unitarily inequivalent representations of the canonical commutation (bosons) and anti-commutation (fermions) relations exist" (Blasone, Jizba & Vitiello: 18). Indeed, through the principle of *spontaneous symmetry breaking* (SSB) in the "ground state" (i.e., in the state at 0 energy of the system), infinitely (not denumerable) many quantum vacua conditions compatible with the ground state exist. Moreover, this holds not only in *the relativistic (microscopic) domain* but also applies to *non-relativistic many-body systems* in condensed matter physics, i.e., in the macroscopic domain, and even on the cosmological scale (Blasone, Jizba & Vitiello 2011: 53–96).

« 9 » Several phenomena related to what Dodig-Crnkovic calls "morphological computing" can be found in QFT, and in the SSB of quantum vacuums as their fundamental explanatory dynamic framework. This includes: the thermal field theory; the phase transitions in a variety of problems at any scale; and the process of defect formation during the process of non-equilibrium symmetry breaking in the phase transitions, characterized by an order parameter. All these phenomena and many others are fruitfully approachable by using the same principle of "nonequivalent representations" in QFT. For the same reason, and to go back to Turing's early suggestion, even though on a different basis (see below), I suggest using the notion of "morphogenetic computing" in IC.

« 10 » Another fundamental character of IC mentioned right at the beginning in §1 has its proper fundamental dynamic explanation in the QFT approach. It is the IC principle inspired by Gregory Bateson's seminal idea of the "necessary unity between a biological (and hence cognitive) system and nature" (Bateson 2002), according to which,

> "for different type of agents, the same data input […] will result in different information. […] The same world for different agents appears differently." (§2)

This principle has its proper causal and mathematical explanation in the QFT formalism of "algebra doubling" for justifying the intrinsic character of the thermal bath in QFT systems.

« 11 » In the context of QFT, the notion of non-symbolic, "morphogenetic computation," which has its proper ancestor in Alan Turing's pioneering work on "morphogenesis" (Turing 1952; see §9), has its deepest justification at the level of fundamental physics. In fact, it concerns the various different physical interpretation of the *Heisenberg uncertainty principle* and of the related particle-wave duality.

Wigner functions, quasi-probabilities and the notion of "natural information"

« 12 » QFT may also offer a rigorous pathway for a quantitative definition of the IC notion and measurement of "natural information" (§7), as distinct from the syntactic notion and measurement of Shannon information used in QM, and that cannot justify in principle any constructive, causal approach to complexity.

« 13 » Indeed, because of the intrinsic openness to the quantum vacuum fluctuations of any QFT system, and because of the associated thermal bath, it is possible in QFT to define thermodynamic operators such as "entropy" and "free energy," as well as the dynamic role they play in the different QFT systems. Schrödinger "negentropy" is indeed "*free* energy," that is energy "properly channeled" toward the "right places" where it can perform "work." The "free energy" is thus "*ordered* energy."

« 14 » The widespread applicability of QFT is claimed by Massimo Blasone and colleagues, who address an important aspect, i.e., that quantum field dynamics is not confined to the microscopic world only but rather includes the whole domain of fundamental physics, from cosmology to the physics of condensed matter, living, and neural systems:

> "[C]rystals, ferromagnets, superconductors, etc. are macroscopic quantum systems. They are quantum systems not in the trivial sense that they are made by quantum components (like any physical system), but in the sense that their macroscopic properties, accounted for by the order parameter field, cannot be explained without recourse to the underlying quantum dynamics (Blasone, Jizba & Vitiello 2011: ix).

« 15 » From the computability theory standpoint, this means that a physical system in QFT, in contrast to the Turing Machine paradigm, *is able to change dynamically the basic symbols of its computations*, since – according to the QFT uncertainty principle – new collective behaviors can emerge from individual ones, or vice versa. This justifies the definition of the information associated with a Wigner distribution as a *semantic (non-syntactic) information content*, since the system is able to change *dynamically* the codes of its computations, so to suggest a new, semantic sense of the notion of "computational dynamics."[2]

« 16 » In Basti (2014), I demonstrated that in formal logic an *inference process*, based on such a probability calculus, in which the basic symbols – and hence "truth" – between the antecedent and the consequent *are not conserved* cannot satisfy the logical connective of the material implication ($p \rightarrow q$ (1011)). On the contrary, it satisfies the logical connective of the *converse implication* ($p \leftarrow q$ (1101)), i.e., the connective of all the "form generation" or *morphogenetic* processes. However, it is the logic of

2| To avoid misunderstandings, the notion of "semantic" information and computation allowed by the QFT notion of "coherence domain constitution" has nothing to do with Tarski's truth function.

an *inductive inference,* not as a logic of the (empirical) *corroboration* of true propositions already given, but as the logic of the Aristotelian (*onto*-logical) *constitution* of new true propositions. This means that the IC notion of "morphogenetic computation" is non-symbolic in the syntactic TM sense (see §32), because it is the computational dynamics process of new *symbol dynamic generation,* and not of the syntactic *symbol manipulation.*

Conclusion: Toward a constructivist change of paradigm in modern science

« 17 » The novelty of the constructivist approach, with the support of IC and QFT, can be summarized in the slogan "from mathematical physics to physical mathematics." Paul Davies describes it in the following way:

> "In a universe limited in resources and time – for example, in a universe subject to the Lloyd's cosmic information bound – concepts such as real numbers, infinitely precise parameter values, differentiable functions and the unitary evolution of the wave function are a fiction: a useful fiction to be sure, but a fiction nevertheless." (Davies 2010: 82)

« 18 » In other words, the change of paradigm consists in turning the dualistic "Platonic" relationship, characterizing the Galilean-Newtonian beginning of the modern science:

Mathematics → Physical Laws → Information

into the QFT one, which has a greater heuristic power:

Information → Mathematics → Physical Laws

« 19 » The key problems for further research are about the notion and measure of "natural information" in QFT, in as far as it supposes:

- the notion and measure of natural information, based on the notion and measure of "quasi-probability," typical of WF, and of a QFT approach to quantum computing, and hence,
- the morphogenetic computational paradigm with its proper logic, and mathematics – set theory (meta-mathematics) included.

This is an amazing, huge, constructivist, research project for several future works.

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On the Emergence of Meaningful Information and Computing in Biology

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> Upshot • Info-computational constructivism calls attention to some of the open questions about the origins of information and computation in the living realm. It remains unclear whether both were developed and shaped by evolution by natural selection or if they appeared in living systems independently of it. If the former, it is possible to sketch a scenario with a certain degree of reasonableness and postulate some of the conditions that triggered the emergence of these biological properties.

« 1 » The evolution of the first living cells began about 3.8 billion years ago and the first multicellular organisms appeared nearly 1 billion years ago. These facts tell us that the time to evolve from simple cells to more complex cellular systems was almost three times more than that for the evolution of all the multicellular organisms (including humans). The great complexity within modern cells expresses very soundly a need for new approaches to understanding the most central properties of living systems (Riofrio 2007) and conditions for the emergence of cognition in evolution (Heyes & Huber 2000; Gontier 2010). One interesting alternative in this direction is the info-computational constructivism proposal. For instance, in §3, Gordana Dodig-Crnkovic claims that computation is information processing (a reformulation of Heinz von Foerster's physical computation). Her aim is to develop a model of natural computation that is more general than that of the information processing capabilities in the Turing machine.

« 2 » On the other hand, looking at the dynamics of microorganisms, we observe the massive acquisition of new genes through horizontal transfer[3] (Jain, Rivera & Lake 1999; Sowers & Schreier 1999). Horizontal gene transfer is an important evolutionary driving force in microorganisms. Although gene exchange is easier in closely related organisms, it is proposed that horizontal gene transfer played a central role in the evolution of archaea and bacteria (Boto 2010). Moreover, according to Carl Woese (2002), the "origin of speciation" is marked by the shift in early phylogenic adaptation from vertical to horizontal gene transfer. This picture leads to the postulate that the time of the major transition of evolutionary mechanisms was the passage from horizontal transfer to the beginnings of vertical transfer.

« 3 » Pursuing the connection between information, natural computation and cognition within a broad framework allows attention to be put on the conceptual necessity of capturing the semantic aspect of these. Clearly, if one can defend information being the base of natural computation and cognition, the following is also correct:

> "The ability to detect and respond to meaningful information is essentially a biological phenomenon, since there are no inanimate information detectors in nature. Information and energy are both fundamental properties of organized matter that reflect the complexity of its organization […]" (Reading 2011: 9)

3 | Horizontal gene transfer (HGT) refers to the transfer of genes between organisms in a manner other than traditional reproduction. It has played a major role in bacteria and archaea evolution and is fairly common in certain unicellular eukaryotes.

« 4 » The important thing is the way in which biological entities are self-organized, because inside these complex macromolecular connections certain kinds of information detectors have appeared in evolution, such that:

> "Meaningful information can thus be defined as a pattern of organized matter or energy that is detected by an animate or manufactured receptor, which then triggers a change in the behavior, functioning, or structure of the detecting entity […] If there is no effect on the detecting entity's behavior, functioning or structure, the information is considered to be meaningless […]" (Reading 2012: 638).

« 5 » Certainly, this pattern of organized matter or energy is a kind of "pattern" only to the biological entities that have the capacity to detect it. An interesting question is that of when some living components started to behave like information detectors in the course of biological evolution. It seems the answer is again related to the epoch in which the self-organization of intertwined macromolecular connections reached a sufficient degree of complexity such that this new entity started to behave as an autonomous agent (Kauffman 2000).

« 6 » In order to integrate these aspects into a possible scenario, it is important to establish a relationship between meaningful information, natural computation and evolution as follows.

« 7 » If one claims the hypothesis that the emergence of cellularity was earlier in evolution than previously thought (Morowitz 1992), then my proposal of a kind of dynamic self-organization originating at the dawn of the prebiotic world is feasible. It could contain the most basic properties of living systems: information, function and autonomy (Riofrio 2007). If this is correct, it is rational to contend that what is mentioned above could signal the beginnings of a kind of prebiotic evolution that led, very much later, to the first horizontal gene transfer dynamics (Riofrio 2010).

« 8 » Furthermore, sharing certain components and structures acquired and transmitted through these sources was possibly the way that the most ancient populations of protocells evolved. Maybe this was also the way that novel structures, components, molecular networks, characteristics, properties and the like were generated by the first dynamic protocells (Riofrio 2011).

« 9 » Moreover, in agreement with Dodig-Crnkovic and Anthony Reading's quote above with respect to meaningful information, my proposal of biological information as a relational notion will depend on biological processes and is related to whatever kind of energy variation might occur in a biological system. If this kind of energy variation is incorporated into the system – as a variation – with the capacity to become part of the system's processes, the system will have the capability to react accordingly. On the other hand, if an energy variation does not have the capacity to be incorporated in the form of a variation in the system, the system cannot develop a response. This is the way that information emerges in the biological world as meaningful information, as information with biological meaning or "bio-meaning" (Riofrio 2008: 365–366).

« 10 » The minimum complexity discussed above would be necessary for conditions to be ripe for the emergence of the most fundamental properties of life. It would have to be possible to contend the existence of two very interconnected processes behaving as the first prebiotic constraints: (1) a container made of amphiphilic molecules[4] and (2) a micro cycle, driving the protocell far away from thermodynamic equilibrium. This latter constraint would then cause a change in the system's free energy, i.e., a trend towards negative values, and turn into an unavoidable checkpoint along the pathway of creating a future set of responses that are generated in another part of the interconnected and interdependent processing network. In consequence, it would have provided the conditions for the emergence of the first small world structures as core characteristics of the way in which the biological realm computes. And some kind of "horizontal-like" evolution may have been the rule in those remote epochs (Riofrio 2012).

« 11 » Taking into account the above-mentioned sketch of my proposal, together with the info-computational approach, it is possible to discern some directions in future research in the growing field of biological information. This field is visualized as the structure in which biological computation is defined as its dynamics, inside the biological realm. Firstly, it seems important to study the character of biological processes understood as non-algorithmic computation and the nature of some kind of efficient formalization able to represent the major points of this dynamic in order to reproduce it in simulations. Secondly, it is important clarify to what extent biological computation could show us the central aspects of a universal model underlying all natural computation. Thirdly, it is the idea that the info-computational model includes open systems in communication with the environment. In other words, the proposal that the environment is constitutive to an open, complex, info-computational system could shed more light on certain important problems in biology, for example, the elaboration of a theoretical biology and the origin of a signaling network (Dodig-Crnkovic 2010a). Finally, focusing on the study of evolutionary dynamics in prebiotic systems may widen the framework and application of some notions involved in the combinatorial optimization problem such as evolutionary computation (Riofrio 2013).

4| I.e., molecules having a polar water-soluble group (hydrophilic) attached to a water-insoluble hydrocarbon non-polar part (hydrophobic).

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Author's Response

Why We Need Info-computational Constructivism

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> Upshot • The variety of commentaries has shown that IC impacts on many disciplines, from physics to biology, to cognitive science, to ethics. Given its young age, IC still needs to fill in many gaps, some of which were pointed out by the commentators. My goal is both to illuminate some general topics of info-computationalism, and to answer specific questions in that context.

« 1 » It is my first and pleasant duty to thank all commentators for their attentive and insightful contributions. I learned a lot following their arguments and numerous instructive references. No doubt many of the topics addressed by the commentators are fundamental and would deserve a full article of their own. Here, I can just focus on the main criticisms and sketch future lines of research for info-computational constructivism (IC).

Why IC and what makes it constructivist?

« 2 » The probably most fundamental question was raised by **Manfred Füllsack**: Why a new framework, a new variety of constructivism? For me, IC is not so much a new theory but rather a *theoretical framework* constructed such as to accommodate *upgrades*. Our (scientific) knowledge is rapidly changing. So we have to make updates to keep various pieces of knowledge in a well-connected system. In the context of IC, this addresses, in particular, theories of information and computation, communication, computability theory, neuroscience, new branches of physics (including the question of the observer in physics[1]), theory of knowledge, and cognitive science, among others. IC tries to integrate all this new knowledge in a coherent epistemological framework. It is constructed from two basic concepts, information and computation, representing two complementary phenomena: structure and process, being and becoming. As a bottom-up synthetic process, IC aims at *reconstructing* knowledge production, starting from physics, via chemistry then biology, up to cognition in terms of info-computation. It connects matter/energy with agency and biology/cognition with consciousness as the highest level of information integration in living agents with nervous systems. Connections are based on processes of natural computation on structures of natural information on a variety of levels of organization.

« 3 » **Søren Brier** is critical when it comes to placing IC among constructivist approaches. He argues that

> "Philosophically, it does not sufficiently accept the deep ontological differences between various paradigms such as von Foerster's second- order cybernetics and Maturana and Varela's theory of autopoiesis, which are both erroneously taken to support info-computationalism." (Upshot)

« 4 » I am aware that using elements from different approaches and incorporating them into IC results in new contexts in which those elements acquire different meanings. For example, Maturana's reluctance to base his theory of autopoiesis on the concept of information may be related to the fact that in the time of first-order cybernetics and the early days of artificial intelligence, "information" meant "symbolic information" and computation was conceived as symbolic program execution. IC, on the other hand, is built upon *natural information* and *natural computation*, which are much broader concepts that allow us to develop models of biological systems. This clearly relates to Heinz von Foerster's research in biological computing in the 1960s and 1970s, which opposed symbolic artificial intelligence. However, I must add that IC is in its beginnings, and is still far from being able to model autopoietic systems in detail. Nevertheless, the work of **Andrée C. Ehresmann** presented in this issue as well as in Ehresmann (2012) shows the direction for how this can be done mathematically.

« 5 » The constructivist character of IC can be characterized as follows. It *assumes* the existence of *potential information*. This potential information actualizes through interaction with an agent. An agent is an entity that can act on its own behalf. It is also an informational structure for other agents. Living agents are agents characterized with self-* properties (self-organizing, self-adaptive, self- optimizing, self-protecting, self-managing, self-healing). All agents use differences that make a difference in their environment (Bateson 1972) to construct their realities and to act based on that. Through interaction with the environment, living agents modify their morphology based on self-organization and autopoiesis and evolve through constructive processes. Networks of data form information, and networks of data networks (i.e., networks of information) self-organize as knowledge for an agent.

« 6 » For **Marcin Schroeder**, such a characterization seems in contradiction with the constructivist position, which "gives the active and primary role in the process of construction of knowledge to the mind" (§4). He wonders how this position can be reconciled with the view that all nature is a computational process: "What can be the contribution of the mind to a universal process seemingly governed by external, independent rules?" (ibid.)

« 7 » Whatever mind is, in the computing nature *mind is computational process*. However, computation does not refer to "a universal process seemingly governed by external, independent rules." Rules are not external but internal to the mind and its substrate. I make a distinction between cognition as a property of any living organism and mind as a specific info-computational process that is essential for living beings with nervous systems. Mind is a result of active engagement of an agent with the environment. It is evolutionary, morphological process of intrinsic, natural computation of a kind that **Ehresmann** describes in her commentary.

« 8 » Schroeder continues that we deviate from the main tenet of constructivism when "we give priority to the external universal process (computational or not), in which the mind can participate in various degrees but is subject to its rules and does not contribute to it as a creator or constructor" (§5).

1 | Cf. the subjective Bayesian account of quantum probability (Baeyer 2013) and Otto Rössler's Endophysics (Rössler 1998).

« 9 » Here an assumption is made that I did not make, namely that "we give the priority to the external universal process." Info-computationalism is constructed as a way to dissolve the problem of the matter/mind duality. This assumes that for a cognizing agent, reality is an informational structure. However, an important point is that *there is no information without physical implementation* (Floridi 2008b), which means that beneath all the informational layers there is a physical substrate that makes it "tick." That applies to a qubit, which is the most fundamental level of quantum information. A qubit is a manifestation of an underlying physical reality. We do not know anything more about that layer than what we can derive from information itself. In Dodig-Crnkovic (2014), I present mechanisms of agency "in the world," where "world" is an agent's "reality" resulting from learning process. A cognizing agent actively constructs its reality from its experiences. The fact that processes of construction are understood as (still theory-less, in the terminology of Leslie Valiant 2013) computation processes does not change anything; they are the same processes of construction that Ernst von Glasersfeld refers to in relation to the concept of reality: "It is made up of the network of things and relationships that we rely on in our living, and on which, we believe, others rely, too" (Glasersfeld 1995a: 7) and "To the constructivist, concepts, models, theories, and so on are viable if they prove adequate in the contexts in which they were created" (ibid). According to von Glasersfeld, "knowledge does not reflect an objective, ontological reality but exclusively an ordering and organization of a world constituted by our experience" (Glasersfeld 1984: 24). Von Glasersfeld also emphasizes:

> "When I make this point it is often assumed that I deny reality. In fact, this is not so. I merely deny that we can know reality, if by 'reality' we intend something that 'exists' and has a structure independent of the human knower." (Glasersfeld 1991: 32)

According to IC, natural information that is the fabric of reality for an agent is not independent from an agent; it is a result of an agent's interactions with its environment and self-organization of information intrinsic to the agent.

« 10 » In §8, **Schroeder** rightly criticizes my use of the *mechanism of self-organization* instead *of autopoiesis*. I should have spent more time explaining the difference. My position is that the basic generative process is that of self-organization (Kauffman et al. 2008). Autopoiesis is the result of self-organization in which closure has been obtained. A cell, even though the result of self-organization, is a very special system with an autopoietic process that not only sustains pattern-formation but also organization-formation and maintenance.

« 11 » Schroeder also sees a contradiction between saying that "an autopoietic system is self-organizing […] and at the same time conserving its organization?" (§9). The contradiction is resolved if we recall that cells are dying and being replaced all the time. Skin cells live about two or three weeks, red blood cells live some four months, while white blood cells live on average about a year. Similar processes are going on inside the cell. In the huge dynamical machinery of a cell, molecules are transmitted, re-combined, degraded, expelled etc. And yet, dynamically, a cell keeps its organization. So it is actually form that is preserved while "matter" is in flow.

Agents' realities

« 12 » **Füllsack** identifies an important modelling detail of IC – the origin of observers: "if […] there is no unobserved reality, we need a rather demanding theory with not just one but two 'first' entities to start with" (§3). There are two comments on this.

« 13 » Firstly, we can say that there is no unobserved reality in the sense that *remembered reality* is *previously observed reality*, while *anticipated reality* is a *projection of the previously observed reality* to the imagined potential future circumstances (scenarios).

« 14 » Secondly, IC starts with the existing physical world in which different physical structures function as each other's observers. The living world encompasses a multitude of living agents who interact and thus engage in mutual "observation." In what sense can we say that *there is no unobserved reality* for humans? So I agree with the claim that nothing can be real for humans, which have never been observed by anybody or anything else, even though we can reconstruct reality that no humans have (directly) observed – such as the life dinosaurs may have lived. All of history has the character of reconstructed knowledge, not only observed but also memorized, forgotten, glued together from pieces of pottery and bones. The basis of knowledge is obviously not only direct observation. Huge parts of modern physics are non-observable – they are inferred from observable data with the help of theoretical models. Can inferences be seen as inevitable results of observed reality? In a sense, yes; they reflect observed regularities in one's experiential reality.

« 15 » According to **Füllsack**, IC

> "implies the counter-intuitive picture of an 'initially' differentiated world, or of a system that in its origins is sufficiently complex to harbor (at least) two subsystems, of which one can make a difference in reaction to the difference in the other." (§3)

Do we have to assume more than we actually can observe today? As we have multitude of different "observers," we do not need to postulate them. Reconstruction of the origin of observer assumes a lot of reasoning that goes beyond observation, and will need some elaboration that I leave for the future development of IC.

« 16 » **Hugh Gash** wonders "whether the IC position might offer a solution to explaining the RC position [on different realities] and make it less irritating" (§4). The answer is, yes. First, understanding similarities of mechanisms of reality construction in different kinds of cognitive agents such as animals, plants and machines can help to grasp *the necessity of different realities for different agents*. This has nothing to do with *subjectivity* but with *different cognitive architectures*. Those architectures decide what information is possible for an agent to perceive and process. An isolated neuron or an isolated bacterium is cognitively very different from a brain or a bacterial colony. The essential information processing takes place through interaction in the distributed system. IC sees cognitive processes in different cognitive architectures as natural computational processes on a variety of levels of organisation of natural information. We have still a long way to go before we understand exactly how the process of knowledge generation leads to higher cognition. However, it is just a matter of time and further study to understand how such a complex system as the human brain handles information from the molecular to the cellular level, in neural circuits, brain regions and on the whole brain level. Ehresmann's work points in that direction.

Physical aspects

« 17 » Physics has often been criticized for its reductionism. However, sheer reductionism as an epistemology would be unfortunate for modern developments that increasingly deal with complexity and emergency. So Carlos Gershenson's statement "[f]rom the physical perspective there is no difference between the aquarium with its contents and another object with exactly the same molecules" (§4) may be a gross simplification. It should be admitted that even physics makes the difference between different aggregate states of the same molecules. Water, H_2O, in the form of a vapour, a liquid or ice will behave differently as a *physical* system. Maybe we could say that a *molecular physicist* is not interested in the organization of matter on the supramolecular level. But then again, physicists who study molecules differentiate between molecules bound in a crystal lattice from those moving freely in a gas. It may not be accurate to present physics as insensitive to the organization of matter. Besides biophysics, a current example of physics dealing with biological phenomena is cancer physics (see Gravitz 2012). Traditionally, physics may not have been involved in the study of living systems; however, with the development of complexity field physicists are starting to address even complex biological systems, thus moving from sheer reduction to reduction + construction.

« 18 » I agree with Gershenson's claim that "the physical substrate of cognitive systems cannot be neglected" (§4). Indeed, IC emphasizes the necessity of a physical grounding of information and its dynamics. IC relies, at the fundamental level, on informational formulation of quantum physics, which is the basic level of organisation of the physical world. If we de-construct the intricate construction of physical reality, we will find the basic building blocks for a quantum-mechanical agent, qubits. These stand for the relation of an agent with the quantum physics level, having underlying physical reality from which the whole of the physical world is constructed through processes of self-organization.

« 19 » Reflecting on the physical basis of IC, Gershenson claims that "[m]aterialism, IC, and cognitive science are not separable but complementary: objects are described by materialism, subjects by IC, and action by cognitive science" (§8). The point of IC is to provide a coherent framework for cognition (as biological agency), based on information (structure) and computation (process). Computation stands for physical behaviour in time (thus a temporal physical aspect) while information stands for structure, morphology. What we call "mass" in physics is related to the behaviour of a physical object with respect to acceleration. An info-computational description of a physical system describing moving mass would use an informational structure (with respect to some agent) and computational behaviour that will depend on what kind of "matter" there is behind that informational structure.

« 20 » Regarding Gershenson's statement that "[m]atter and energy (object, observed) cannot be studied without considering information (subject, observer), nor vice versa." (§9), I should point out that I do not consider matter and energy only *object* and *observed*; matter-energy is a *substrate* and a *vehicle/driver* [source of change] of a *subject* and *cognition*. The three are genuinely entangled. Cognition is not only agency in general ("action" can be ascribed non-living, i.e., non-cognitive, entities), but cognition is self-organization of information powered by matter-energy in the process of autopoiesis. Information is always relative to the agent. The essential mechanism that enables information to act in the world is *memory*, which is the re-configuration of matter as a result of past events – like Hebbian learning or other adaptive changes in the morphology of organisms that act as *constraints* for their future behaviour. Sebastian Deffner and Christopher Jarzynski illustrate the importance of memory in the generalization of the second law of thermodynamics, which allows transfer of heat from cold to hot, with "emphasis on the limits and assumptions under which cyclic motion of the device of interest emerges from its interactions with work, heat, and information reservoirs" (Deffner & Jarzynski 2013: 1). This research can contribute better understanding of how living beings are capable of autopoiesis, in spite of the second law of thermodynamics.

« 21 » Gianfranco Basti also draws our attention towards the physical aspects of IC, more specifically to the question of physics of emergence. Given the layered computational architecture of IC, it is important to understand the process of emergence of higher levels from the lower ones. In his Upshot, Basti suggests for IC the…

> "integration with the logical, mathematical and physical evidence coming from quantum field theory (QFT) as the fundamental physics of the emergence of 'complex systems' in all realms of natural sciences."

« 22 » I also agree with him, pointing out that in my target article I have described quantum physics as quantum mechanics. This should actually be replaced by quantum field theory, which has a constructive character, as shown by Basti as well as Xiao-Gang Wen (2004, 2012).

Biological aspects

« 23 » In his commentary, Walter Riofrio quotes Anthony Reading on the topic of "meaningful information": "The ability to detect and respond to meaningful information is essentially a biological phenomenon, since there are no inanimate information detectors in nature" (Reading 2011: 9). In contrast to this, I should emphasize, in agreement with Terrance Deacon (2011) and Stuart Kauffman (1993), that it is rather living agents that make sense of information they find in the environment. There is no meaningful information in the world as such, just potential information. That potential information actualizes and becomes meaningful in different ways for different cognizing agents. Meaning for an agent is use of information.

« 24 » In §5 Riofrio wonders "when some living components started to behave like information detectors in the course of biological evolution." In my view the question could also be the opposite: When did some information detectors start to behave like living components in the course of (biological) evolution of matter? In an info-computational universe, simple systems are "information detectors" in Reading's sense above. If a quant of energy (photon) hits an atom, this atom detects the photon and changes its behaviour accordingly. Molecules can be said to act as information detectors, even if they are not a part of an organism.

Natural information

« 25 » In §11, Schroeder rightfully points at my ambiguous use of the expression "atoms of information" for data. In order to avoid the connotation of indivisibility, I should have better used "chunks of information." Thinking in terms of zeros and ones as atoms is possible, but likely inadequate. What I meant to express is that for an agent, that which makes "the difference that makes the difference" depends on the agent's architecture and sensors/receptors, which typically register signals/data. The next step is that data/signal be transmitted further in the system until it reaches memory, in which it will get related to and incorporated into existing information structures.

« 26 » IC is monistic because information and computation are two inseparable aspects of the same phenomenon. However, Schroeder claims:

> "The dualistic ontology is already present in the use of expression 'physical world,' as it requires a complement in the form of the mental world (what other complement is possible?). If not, what is the reason for using the adjective 'physical'?" (§12)

That is an interesting observation. Usually "physical" is contrasted with "chemical," sometimes with "logical," and sometimes with "biological." In data modeling there are conceptual, logical, and physical data models. By emphasizing "physical world," I want to draw attention to the physical substrate. Within the framework of IC, "mental" is a *process* in the physical and, as such, inseparable *manifestation* of physical. "Mental" is *not a substance* different from physical.

Even §18 in Schroeder's commentary addresses informational structures mentioned in my article as "Reality for an agent consists of structural objects (informational structures, data structures) with computational dynamics (information processes)" (§20). Schroeder points out "it does not explain what these structural objects are and what kind of dynamics describes their interactions. Even worse, we have here put informational structures and data structures alongside each other."

« 27 » When I refer to "objects," I use this notion in the sense of von Foerster (2003b): *objects as tokens of eigenbehaviors*. Regarding informational *structures* or data *structures* – they can coexist. If data structures are elements for building informational structures (while informational structures are elements for building knowledge) – the result is a structure with different granularity. We can have a system consisting of different *objects* – molecules, atoms and electrons; there should not be a problem. In a description of reality for an agent, different chunks of information naturally coexist.

IC as a field of research

« 28 » According to Brier, one of the main problems with IC is that "[i]ts basic concept of natural computing has neither been defined theoretically or implemented practically" (Upshot). In my target article, I quite obviously failed to include a reference to the *Handbook of Natural Computing* (Rozenberg, Bäck & Kok 2012), which presents and defines this rather young field of research. Natural computing (including morphological computing, not mentioned in this handbook) already has various practical applications in evolutionary algorithms; swarm intelligence, artificial neural networks, artificial immune systems, artificial life, DNA computing, and quantum computing (Stepney 2012). Furthermore, Ehresmann has worked on practical implementations of IC, as described in her commentary.

« 29 » Ehresmann presents a mathematical approach to the IC framework, demonstrating how it can be interpreted rigorously in mathematical terms. It underlines the importance of the *multiplicity principle* (MP) as an important property of natural computation that leads to the development of increasingly complex cognitive processes and structures. This has the consequence that even though local dynamics are classically computable, the global dynamics is not. So even though basic layers of computational behaviours can be automata-like, there are higher cognitive activities that are not Turing-machine type of computation, based on the fact that symbols have ambiguous meanings. If they follow natural computing in biological systems, they will also be able to change (evolve).

« 30 » Ehresmann's *Memory Evolutive Neural System* (MENS) models the cognitive system of an animal with the *neural, cognitive and mental systems* at (*micro, meso, macro*) levels of description and across different timescales. In MENS, a whole network exists of *co-regulators* (CRs) that function asynchronously. Each CR collects and processes information and operates through a central flexible *memory*, building the knowledge of the system and changing it to adapt it to the environment.

« 31 » Ehresmann makes the important observation that due to the degeneracy (synonymy) property, or MP, the difference that makes a difference on one level of cognitive information processing may make no difference on the higher level (two patterns may be equivalent in the same way as two symbols can be synonymous, even though there are differences that make difference on the lower level of information processing).

Ethical implications

« 32 » Last but not least, there are ethical aspects that need to be addressed. In his commentary Gash notes that ethical implications of constructivism have a low profile in accounts of constructivism (§5). I find the position of cybernetics and particularly Norbert Wiener (1948) inspiring examples of the genuine understanding of the importance of values and ethical judgment for technology. The most important new developments that I consider an integral part of IC are *computer ethics* and *information ethics*. Computer ethics was developed by James Moor, Terrell Bynum and Deborah Johnson (Bynum & Moor 2000; Johnson 2008) and that addresses a variety of issues related to computers and ICT such as privacy, personal integrity, changed value systems, roboethical issues, cognitive enhancements, etc.. Information ethics, developed by Luciano Floridi (2010), with the emphasis on the role of information in our individual ethical judgments and social behaviors.

« 33 » Furthermore, Gash hints at the possible contribution of IC to ethics in acquiring insights into mechanisms of information transfer and processing in ethical deliberation. "If this insight could be made more commonplace, perhaps negotiations between opposing groups with different views on their reality would have a sounder footing" (§6) and "Perhaps there are computer models of negotiations that can take these ideas and develop them?" (§7). This is definitely a desired and expected outcome of the study of info-computational mechanisms in knowledge construction and decision-making. The IC approach and its implementation in Ehresmann's MENS can help make this process more transparent and understandable as it shows the mechanism of information processing in a cognizing agent on its different levels of organization. Already now, agent-based models are used as info-computational tools for analysis of social situations. Economists and sociologists are constructing computer simulations in order to visualize and better understand possible outcomes of different scenarios. Computational models can be seen as a cognitive enhancement or augmented cognition as they can compensate for our lack of intuition when it comes to the behavior of large, complex systems.

Conclusion

« 34 » Let me emphasize that IC is an epistemological framework and does not elaborate on ontology. IC follows von Glasersfeld, according to whom *reality is constructed from experiences*. Interactions with the world are building blocks and sources of experiences. Unlike sensorimotor interactions with the environment through automatic responses, experience is always connected to memory, and thus in general is a more complex phenomenon than pure sensorimotor interaction. However, intrinsic cognitive activity such as experience implies interactions between different distributed parts of the cognitive system itself. Reality as experience for a human cannot be anything but the reality of interactions memorized. Interactions are also the source of reality for a virus. Of course, the richness of the two realities is different. While von Glasersfeld focused on the human context, IC is interested in the more general scenario, where even the simplest animals and future cognitive robots can be seen as learning. As von Glasersfeld pointed out, cognition does not serve the discovery of the world but rather the organization of experiences for an agent.

« 35 » Does IC defend a dualism, as Schroeder's distinction between "mental world" and "physical world" suggests? In IC there is no mental world without the physical world. The mind is a complex of processes in the physical world. Meaning and intentionality emerge with living agency, as developed by Deacon and Kauffman. The material and the mental are aspects of the same substrate and not two different substrates. IC is a monism as it considers information and computation as complementary notions. In this sense, the notion of "info-computation" acquires its explanation.

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