Constructivism

Info-computational Constructivism and Cognition

Gordana Dodig-Crnkovic • Mälardalen University, Sweden • gordana.dodig-crnkovic/at/mdh.se

1 Introduction

1.1 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.

1.2 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.

1.3 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).

1.4 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 observed server. 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 three periods have been largely assimilated into the design of control systems and machines.
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 autopoesis in relation to IC and the construction of the reality for an agent. In Chapter 5 I discuss several criticisms of info-computationalism.

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.

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).

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: xii).

We see that data becomes integrated into structure when data becomes integrated into structure. What is important from the world moves intact into an agent. This potential (proto) information is characterized 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).

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

are atoms of information. Information is obtained when data becomes integrated into structure (correlated), which happens in the interaction with a cognizing agent.

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.
### Constructivist Foundations Vol. 9, No. 2

#### Info-theoretical Concepts in Constructivism

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**Gordana Dodig-Crnkovic** is professor of Computer Science at Mälardalen University, Sweden. Her research interests include computing paradigms, natural computing, social computing and social cognition, info-computational models, foundations of information, computational knowledge generation, computational aspects of intelligence and cognition, theory of science/philosophy of science, computing and philosophy, and ethics (ethics of computing, information ethics, robot ethics, and engineering ethics). The most recent events she has organized are the symposia “Natural/Unconventional Computing and Its Philosophical Significance” (co-organized with Raffaela Giovagnoli), “Social Computing – Social Cognition – Social Networks and Multi-agent Systems” (co-organized with Judith Simon), both at the AISB/IACAP World Congress 2012 and the Symposium “Representation and Reality: Humans, Animals and Machines at AISB 2014.” She is the author of more than eighty international journal and conference publications.

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**Notes**

- [1](#) This does not imply that reality is subjective.
- [2](#) Observers form shared reality through processes of social cognition, as explained in third-order cybernetics (Johannessen & Hauan 1994).
- [3](#) 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).
- [4](#) 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 comes information, “a difference that makes a difference,” (Bateson 1972) for a cognizing agent in a process of interaction.
- [5](#) 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. [6] (Hewitt 2007: 293, my emphasis)

- [6](#) 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.

- [7](#) The world as proto information presents the potential form of existence corresponding to Immanuel Kant’s *Ding an sich* (thing in itself). That proto information be dependent. [8]

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**Column B**

- **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”) [9] 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 is thus informational and agent-dependent. [10]

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**Column C**

- [8](#) 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 ‘observer’ or, in other words, we need a theory of the observer.” [11] (Foerster 2003b: 247)

- [9](#) 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: [12]

> 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.

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**Column 1**

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**Column 2**

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1. **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)

2. **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**

4. **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).

5. **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 between the proto-informative and the environment 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.**

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1 ability to learn (adapt, change their morpho-
2 gogy) and can be argued to possess rudimen-
3 tary forms of knowledge. 22 In his book An-
4 ticipatory Systems, Robert Rosen claims:
5 6 "I cast about for possible biological instances
7 of control of behavior through the utilization of
8 predictive models. To my astonishment I found
9 them everywhere […] the tree possesses a model,
10 which anticipates low temperature on the basis of
11 shortening days." (Rosen 1985: 7)
12 12
13 = 35 = Karl Popper ascribes the ability to
14 know to all living things:
15 16 "Obviously, in the biological and evolutionary
17 sense in which I speak of knowledge, not only
18 animals and men have expectations and therefore
19 (unconscious) knowledge, but also plants; and,
20 indeed, all organisms." (Popper 1999: 61)
21 21
22 And similarly Maturana and Varela:
23 24 "Living systems are cognitive systems, and living
25 as a process is a process of cognition. This state-
26 ment is valid for all organisms, with or without a
27 nervous system." (Maturana & Varela 1980: 13)
28 28
29 = 36 = The above understanding of cog-
30 nition is adopted by info-computational
31 constructivism as it provides a notion of
32 cognition in degrees, which bridges from
33 human-level cognition to minimal cogni-
34 tion in the simplest biological forms and
35 intelligent machines. For a cognizing agent,
36 information is meaningful data, which can
37 be turned into knowledge by interactive
38 computational process. Information is al-
39 ways embedded in a physical substrate: sig-
40 nal, molecule, particle or event (Landauer
41 1991), which will induce a change in a struc-
42 ture or a behavior of an agent. For IC this is
43 important: we must know how to construct
44 cognitive artificial agents that are able to
45 function adequately in their environment,
46 so we must know how to treat information
47 acquired, stored, processed or used by an
48 agent.
49 49
50 = 37 = The information-processing view
51 should be identified neither with classical
52 cognitive science, nor with the related no-
53 tions of input–output and symbolic repre-
54 sentations. It is important to recognize that
55 connectionist models are also computational
56 as they are based on information processing
57 (Scheutz 2002; Dodig-Crnkovic 2009; Clark
58 1989). The basis for the capacity to acquire
59 knowledge is in the specific morphology of
60 organisms that enables perception, memory,
61 and adequate information processing. That
62 morphology is a result of the evolution of
63 living organisms in the interaction with the
64 environment.
65 66 William Harms (2004) proved a
67 theorem showing that under certain condi-
68 tions, by nature, the total amount of infor-
69 mation in the living system will always in-
70 crease, which will always lead a population to
71 accumulate information, and so to “learn” about its environment. Samir Okasha sum-
72 marizes Harms’ results:
73 73 "any evolving population ‘learns’ about its envi-
74 ronment, in Harms’ sense, even if the population
75 is composed of organisms that lack minds entire-
76 ly, hence lack the ability to have representations of the external world at all." (Okasha 2005: §10)
77 77
78 4 Construction of “reality” as info-computation
79 in an agent via “structural coupling”
80 80
81 In order to understand cognition and knowledge as a natural phenom-
82 enon, the process of re-construction of the
83 origins, development and present forms and
84 existence of life, processes of evolution, and
85 development based on self-organization are
86 central. The work of Maturana and Varela
87 on the constructivist understanding of life
88 is of fundamental importance. They define
89 autopoiesis as a network of processes in the
90 “autopoietic machine” (a unity in space con-
91 stituted by its components) that govern pro-
92 duction, transformation, and destruction of
93 those components and so enable incessant
94 regeneration and maintenance of the au-
95 topoietic machine as a whole (Maturana &
96 Varela 1980: 78). Or, in the words of Milan
97 Zeleny:
98 98 "A cell produces cell-forming molecules, an or-
99 ganism keeps renewing its defining organs, a social group ‘produces’ group-maintaining individuals, etc. Such autopoietic systems are organization-
100 ally closed and structurally state-determined…" (Zeleny 1977: 13)
101 101
102 40 What does it mean that an au-
103 topoietic system is organizationally closed? It
104 means that it conserves its organization. How-
105 ever, this applies only to the snapshot of an
106 organism’s inner operation. In the course of
107 evolution, organisms change their struc-
108 ture through interactions with the environ-
109 ment and successively, as they evolve, even
to change their organization. In other words, organisms tend to preserve their organiza-
110 tion, but that organization evolves on an evo-
111 lutionary time scale. That is what Maturana
112 calls “ontogenetic structural drift” (Maturana
113 2002: 17).
114 114
115 41 The information-processing pic-
116 ture of organisms incorporates basic ideals of
117 autopoiesis and life, from the sub-cellular
to the multi-cellular level. Being processes of
118 cognition, life processes are different sorts
classical, as they are based on information processing
119 and organization of living beings in the sense of
120 meta-morphogenesis. In Sloman’s work on
121 meta-morphogenesis, understood as “evolu-
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123 cessing machinery,” he presents…
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126 morphogenesis are attempts at computa-
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evolution in all living organisms within the
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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). 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).

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) 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 & Tavor 2006) to the acquisition of cognitive skills on higher levels of organization 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 understanding self-reproduction, self-regeneration, self-maintenance, and self-repair 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 Foerster’s 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:

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

No information without humans?

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.”

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-dependent of the physical model both explicit and natural.

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.

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 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).

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?

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).

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 actual facts 17 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 consists of differences that make a difference.** (Bateson 1979: 110, my emphasis)

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.

Brier continues his critical examination of IC, which in his view does not provide an account for...

The 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 data carriers it may be possible that the Cartesian gap between mind and matter:
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 2003), Irarantu (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 transculturality 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.
Open Peer Commentaries on Gordana Dodig-Crnkovic’s “Info-computational Constructivism and Cognition”

IC and the Observed/Observer Duality
Manfred Füllsack
ISIS, University of Graz, Austria
manfred.fuellsack/at/uni-graz.at

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 system 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 no- tion 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 
of non-linear dynamics runs up (Strogatz 1995; Kauffman 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 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.

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 newborn 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 asymptotic metric 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 1995a), 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 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; Cersmey 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.

Manfred Füllsack is Professor of Systems Sciences at the University of Graz. His research includes: systems, complexity, networks, games and computational theory, work – its history, its sociology, its economy, and its philosophy, and computer-based simulations.

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Manfred Füllsack

Constructivism

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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.

http://www.univie.ac.at/constructivism/journal/9/2/223.dodig-crnkovic
Phenomenological Computation?

Søren Brier
Copenhagen Business School, Denmark • sb.ikk/at/cbs.dk

The main problems with info-computationalism are: (i) Its basic concept of natural computing has neither been defined theoretically or implemented practically. (ii) It cannot encompass human concepts of subjective experience and intersubjective meaningful communication, which prevents it from being genuinely transdisciplinary. (iii) 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.

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.

I also find info-computationalism 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.

I am also 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).

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.

From a Peircean ontology of contingency 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.
A Mathematical Model for Info-computationalism

Andrée C. Ehresmann
Université de Picardie Jules Verne, France • ehres/at/u-picardie.fr

> 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 Gordonia 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.

2 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.

3 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.

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5 It is not the other way round.

6 Supporting constructivist info-computationalism.

7 Received: 14 February 2014

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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-computing 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 transdisciplinary interactiveness.

Søren Brier is Professor in the Semiotics of Information, Cognition, and Communication Sciences at Copenhagen Business School. He is the editor of Cybernetics & Human Knowing, a fellow of the American Society for Cybernetics, and a member of the board of the International Association for Biosemiotic Studies and its journal, Biosemiotics.

A Mathematical Model for Info-computationalism

Andrée C. Ehresmann
Université de Picardie Jules Verne, France • ehres/at/u-picardie.fr

> 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.

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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 (20) 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.

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 functional equivalently- equivalent information patterns; thus it acts as a multi-faceted component. Such multi-faceted components are constructed through successive complexification processes (Ehresmann & Vanbremeersch 2007). The complexification also constructs the links interconnecting two multi-faceted 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

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.

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. §33). However, the complexifications may also destroy some existing category neurons, 11 in particular records in the memory that are no longer adapted to the context.

### Dynamics of MENS

"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" (§26) 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 acts to it by selecting an adequate procedure: if the color of O is already known, the category 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 \( O \) 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).

However, there is a whole network of co-regulators that can function simultaneously (as in Hewitt's actor model, cf. §16). At \( t \), the different procedures they try to implement can be conflicting, thus...
Information, Computation and Mind: Who Is in Charge of the Construction?

Marcin J. Schroeder
Akita International University, Japan
mjs/at/aiu.ac.jp

> 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 contrasting info-computationalism with other schools of thought, that truth is an invention or construction, which the mind can participate in as a co-regulator during one step is classified as an informational structure, and the perception of the need for the question above can be justified. But even then, it is worth attempting to clarify this issue.

« 3 » The article declares in the first paragraph that “II [IC] asserts that, as living organisms, we humans are constructing agents who construct knowledge through interactions with their environment, processing information within our cognitive apparatus and through information communication with other humans.”

However, this sentence is preceded by a 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.

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.

« 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 get 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 solves 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.
The development of this direction of thought — constructivism, which included the division of historical roots of info-computational constructivism, or even its later forms, as the initial source of info-computational constructivism. Thus, the ontological foundation of the “physical world” in which some 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 makes a difference in another physical system that makes a difference in one physical system that makes a difference for an agent. […]  

Questions regarding understanding information  

The target article also refers to Mihajlo Mićić’s article on “autopoiesis, the world as proto information presents the relationship with the world is described in the target article as follows:  

<table>
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<th>Column A</th>
<th>Column B</th>
<th>Column C</th>
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<td>1 and does not contribute to it as a creator or constructor, we deviate from the main tenet of constructivism.</td>
<td>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:</td>
<td></td>
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<td>2 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: social cybernetics: cybernetics, biological cybernetics and social cybernetics:</td>
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<td>3 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.</td>
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<td>4 The reference to first-order cybernetics, 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 &amp; 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.</td>
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<td>5 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.</td>
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<td>6 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.</td>
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<td>7 The target article also refers to Milan Zeleny’s view: 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).</td>
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<td>8 » » 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:</td>
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<td>9 » » » 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?</td>
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clearly defines the term "processing." 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 not actually 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

It is similar to the 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."

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.

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:

"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 (informational 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, we have put informational structures and data structures alongside each other.

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.

Confusions regarding the concepts of computation, informational structures, and computation and their relationship to constructivism make understanding computationalism and constructivist thought very difficult. It is possible that it is a matter of difference in the understanding of informationalism. In fact, for the present author, the definition of informationalism as "understanding of the whole nature as a computational process" is not clear as long as a computational process (i.e., progressively) is just any change of an 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

Info-computationalism can be related to constructivist approaches only if 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-computational-
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. It was thought that in order 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 our 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. 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. It was thought that in order to explain this and then ask whether the IC position might offer a solution to explaining the RC position and make it less irritating.

«7» Classical introductions to constructivism are presented in human terms. 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.

Modelling Realities

Hugh Gash

St Patrick’s College, Ireland

gugh.gash@at/spd.dcu.ie

> 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?

Revised: 11 February 2014
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Info-computationalism or Materialism? Neither and Both  Carlos Gershenson

University Nacional Autónoma de México • cgg/at/unam.mx

> 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 2004; Gershenson 2011).

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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**

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).
QFT. It justifies the *evolutionary emergence* of the same mathematical laws of nature with the processes they rule and therefore contradicts such laws’ “immutability”, as summed 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.

Such an alternative is related to QFT, which is a “finistic” approach to the *physical mathematics* of information, taken as a fundamental physical magnitude to gether 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 unificantly 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.

«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.”

«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 → q (1011)). On the contrary, it satisfies the logical connective of the converse implication (p ↔ 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” has nothing to do with Tarski’s truth function.
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).

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.

** 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]).

Walter Riofrío
Cayetano Heredia University, Peru
walter.riofrio@at.upch.pe

> 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.

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 (Riofrío 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 constructivist proposal. For instance, in §3, Gordana Dodig-Crnkovic claims that computation is information processing (a reformulation of Heiniz 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.

On the Emergence of Meaningful Information and Computing in Biology

Walter Riofrío

INFO-THEORETICAL CONCEPTS IN CONSTRUCTIVISM

CONSTRUCTIVIST FOUNDATIONS VOL. 9, N°2
on the emergence of meaningful information and computing in biology

Walter Riofrío

Constructivism

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:

1. Meaningful information can 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).*

2. **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).*

3. **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:

4. **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 *(Riofrío 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 *(Riofrío 2010).*

5. **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 protocols *(Riofrío 2011).*

6. **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” *(Riofrío 2008: 365–366).*

7. **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 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 *(Riofrío 2012).*

8. **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 third structure in which biological computation is defined as its dynamics, inside the biological realm. Firstly, it seems important to study the nature 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 to 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 *(Riofrío 2013).*

Walter Riofrío is Associate Research Professor in the Neuroscience and Behavior Laboratory-LID Faculty of Science and Philosophy at Cayetano Heredia University. He is working on the framework of complex systems science in topics such as the origins and properties of prebiotic systems, the structure of cell signaling networks and the nature of neural information processing, among others.

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Why We Need Information-Computational Constructivism

Gordana Dodig-Crnkovic
Mälardalen University, Sweden
gordana.dodig-crnkovic/at/mdh.se

> 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 information-computationalism, and to answer specific questions in that context.

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 information-computationalism. (Upshot)

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 André C. Ehresmann presented in this issue as well as in Ehresmann (2012) shows the direction for how this can be done mathematically.

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.

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.)

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.

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).

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.

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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.

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

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.

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).

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 a structure that no humans have (directly) observed – such as the life dinosaurs may have lived. All of history has the character 4 of reconstructed knowledge, not only observed but also memorized, forgotten, glued together from pieces of pottery and bones. 7 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 11 theoretical models. Can inferences be seen as inevitable results of observed reality? In a 13 sense, yes; they reflect observed regularities 14 in one’s experiential reality.

According to Füllsack, IC

Do we have to assume more than we actually can observe today? As we have multitude 26 of different "observers," we do not need 27 to postulate them. Reconstruction of the origin of observer assumes a lot of reasoning 29 that goes beyond observation, and will need some elaboration that I leave for the future development of IC.

Füllsack wonders "whether the IC position might offer a solution to explaining the IC position on [different realities] and make it less irritating" (§1). 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 projects...
**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, H2O, 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.

"19" Reflecting on the physical basis of IC, Gershenson claims that "materialism, IC, and cognitive science are not separable but complementary: objects are described by materialism, subjects by IC, and action by cognitive science" (§5). 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 information-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 "matter 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" (Defner & 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...
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 §19 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.”

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.

Ethical implications

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 John (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, robotethical issues, cognitive enhance-ments, etc. Information ethics, developed by Luciano Floridi (2010), with the emphasis on the role of information in our individual ethical judgments and social behaviors.

Furthermore, Gash hints at the possible contribution of IC to ethics in academia quiring insights into mechanisms of information transfer and processing in ethical deliberation. “If this insight could be made

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Conclusion

Let me emphasize that IC is an epistemological framework and does not elaborate on ontology. IC follows von Glaserfeld, 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 Glaserfeld 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 Glaserfeld pointed out, cognition does not serve the discovery of the world but rather the organization of experiences for an agent.

Does IC defend a dualism, as Schroeder’s distinction between “mental 4 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 “information” acquires its explanation.

Acknowledgements

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Combined References


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# OF RELATED INTEREST COMPUTING NATURE

If we see the universe as a network of networks of computational processes at many different levels of organization, what can we learn about physics, biology, cognition, social systems, and ecology expressed through interacting networks of elementary particles, atoms, molecules, cells, (and especially neurons when it comes to understanding of cognition and intelligence), organs, organisms and their ecologies? In this book, edited by Gordana Dodig-Crnkovic and Raffaela Giovagnoli, researchers explore various facets of computation: relationships between different levels of computation, cognition with learning and intelligence, mathematical background, relationships to classical Turing computation and Turing’s ideas about computing nature – unorganized machines and morphogenesis. It addresses questions of information, representation and computation, interaction as communication, concurrency and agent models.


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### Combined References Gordana Dodig-Crnkovic

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