Collective Cognition and Distributed Information Processing from Bacteria to Humans

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Abstract. The aim of this paper is to propose a general info-computational model of cognition that can be applied to living organisms from the level of a single cell´s cognition to the level of groups of increasingly complex organisms with social, distributed cognition. We defend the project of new cognitivism, which unlike the old one acknowledges the central role of embodiment for cognition. Information processing going on in a cognising agent range from transduction of chemical signals and "quorum sensing" in bacteria, via simple local rules of behaviour that insects follow and that manifest themselves as "swarm intelligence", to human level cognition with full richness of human languages and other systems of communication.

1 INTRODUCTION

The smallest living organism is a single cell. It is upholding its existence through interchanges with the environment, by means of energy- and information processing. The central insight in cognitive sciences that we build our framework upon, was made by Maturana and Varela (1980) who recognised that cognition and process of life are synonymous:

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

If we want to study processes and structures of cognition, it is necessary to start by studying organisation of life. The fundamental empirically established property of living systems is that their structures and processes are hierarchically organised. Those structures and dynamics can be modelled computationally as agency-based hierarchies of levels (Dodig-Crnkovic 2013).

The capability of living cells to receive signals from the environment and act adequately upon them is fundamental to life. Information is communicated in a biological system both bottom-up (from input signals up) and top-down (from decision making down) in a circular motion. The lower/basic levels of cognition sort and propagate incoming perceptual information and forward the transduced information to higher levels for a more complex processing.

Here is the detailed description how the process of biological information transduction (transformation) goes on in a cell as fundamental living/cognising unit:

> *"Bacterial cells receive constant input from membrane proteins that act as information receptors, sampling the surrounding medium for pH, osmotic strength, the availability of food, oxygen, and light, and the presence of noxious chemicals, predators, or competitors for food. These signals elicit appropriate responses, such as motion toward food or away from toxic substances or the formation of dormant spores in a nutrient-depleted medium." (Nelson and Cox 2008:419)*

So information for an organism comes in different forms (such as hormones, pheromones, photons (sunlight), changes in some state like acidity or concentrations of glucose and ions such as K+, or Ca2+ in the environment, heat, cold, osmotic pressure, etc.), while receptors of information transduce information for further processing in the cell, transforming input signals into intracellular signals. This involves the same type of molecular processes as metabolism: production and degradation of substances, stimulation or inhibition of chemical reactions, etc.

> *"In all these cases, the signal represents information that is detected by specific receptors and converted to a cellular response, which always involves a chemical process. This conversion of information into a chemical change, signal transduction, is a universal property of living cells.*
>
> *The number of different biological signals is large, as is the variety of biological responses to these signals, but organisms use just a few evolutionarily conserved mechanisms to detect extracellular signals and transduce them into intracellular changes." (ibid)*

Even though there are many different kinds of signals, basic mechanisms for their transduction are preserved in different signalling pathways. The process of signals transduction (information processing) that provides information transfer in the cell goes on in parallel with cell metabolism that is handling mass/energy transfer. The two processes constrain each other.

2 OLD DISEMBODIED AND NEW EMBODIED COGNITIVISM

The cognitive process presupposes *attention* that enables *information input*, *sensory memory* (allowing an agent to retain impressions of sensory information after the stimulus has gone), *working memory* for actively manipulating information, and *long-term memory* for preserving information so that it can be reused. The process results in decision-making that will affect actuators. An active loop is sustained between inputs from the environment, internal information processing and actuators, which enable organism's response to the environmental inputs.

This view of cognitive processes is different from classical cognitivism in the first place because for old cognitivists,

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cognition was taken to be a purely intellectual activity of humans. (Scheutz 2002)

The first attempts in 1950s to recreate mind “in silico” as an “electronic brain” without a body, by simply filling an existing digital programmable computer with data failed, as computers at that time had very limited resources – both speed of information processing and memory, apart from the basic fact that they were isolated from the environment and without any adaptive or learning capacities.

The lesson learned from early computationalism was that the brain, in order to function intelligently, cannot be isolated as a “brain in a vat”, but must have a body to provide a connection to the environment and thus a source of novel input and learning. After the experience with IBM's Watson machine it may seem that bodily experiences from the interaction with the world could be replaced with the data input provided by the Internet with its open and learning structures. If intelligence is defined as a capacity to successfully process different kinds of information and adequately act upon it, no isolated computers can be expected to be cognitive or intelligent. Instead, robots are being developed as adaptive and learning systems with an ambition to reach in the future the level of general intelligence through a process of adaptation and learning.

In spite of the current impressive progress of computing machinery in performing cognitive and intelligent tasks such as different kinds of machine learning, automatic image and speech recognition, language processing, audio recognition and speech generation, etc., there is still a strong resistance among philosophers of mind to acknowledge that more advanced models of the info-computational nature of cognition do not suffer from the same limitations and problems as the old cognitivism as they embrace both embodiment and embeddedness of info-computation as *conditio sine qua non* of cognition (Scheutz 2002).

The resistance to natural info-computational cognitivism persists although life sciences as well as human, social and behavioural sciences could potentially gain immensely from a general comprehensive definition of cognition that would capture their pre-theoretic overlap at a basic theoretical level, distinguishing it from pure physical information processes in general. Such basic theory integration would eventually have to meet scientific needs of facilitating e.g., explanations of unexplained phenomena in the relevant domains, as well as more comprehensive interpretations. Also, it could be the basis for research and modelling of relations between domains of e.g., biology, psychology, behavioural- and social sciences. The model here proposed must in the end be tested against its capacity to contribute to such goals.

We see cognition as a natural phenomenon, an entirety of information processes in a living organism, organized in hierarchical levels, that meets given evolutionary constraints (Dodig-Crnkovic 2008, 2012, 2013, 2014). Our basic definition of cognitive information processing refers to evolutionary selected mechanisms for information-based production of an organism’s activities.

Unpacking the notion of activities being guided by information, we employ a naturalised framework of representation (cf. Almér 2007, Millikan 2004, Dodig-Crnkovic 2008); where representation is defined as something (such as a symbol, or a structure) that stands in place of something else.

3 COLLECTIVE BEHAVIOUR IN LIVING ORGANISMS

Adopting the social ontology proposed by Almér and Allwood (2013), we characterise types of organism-collective activity based on type, complexity, and awareness of represented information. We build the naturalist framework for cognition with the elements from a naturalised perspective on representation (e.g., Almér 2007; Millikan 1984, 2004, Neander 2006, Dodig-Crnkovic 2008) based on the discourse of natural computation within the info-computational approach of Dodig-Crnkovic (2014).

Before moving on, some core notions will be briefly introduced. First, we make use of the notion of living organism in our definition of cognitive information processing. By living organism we refer to:

a) Selected for, co-adapted and co-reproduced system of mechanisms globally selected for; function of which is the survival and reproduction of its genetic type

b) Instance of the above in a normal environment with sufficiently normal processes for survival and reproduction up and running.

This characterisation of living organism relies on the notion of biological function and normal conditions. There are two main approaches to functions in biology. One is the causal-role or causal disposition perspective, originating from Robert Cummins' (1998) work, ascribing functions to components in larger systems based on the components’ actual dispositions to causally contribute to some set of capacities ascribed to the whole system. The global capacity of the system is identified with a set of actually produced effects or with a set of actual dispositions of the system to produce such effects under specific conditions. We call functions as conceived of in terms of systems’ capacities ‘systemic functions’.

A second notion of function is backward-looking, identifying a systems’ function with some set of historical effects of its predecessors. Millikan (1984) stands for the most developed version of this type of functional theory. Davies (2000) gives a definition of selected function through conditions that describe the mechanisms of natural selection, the evolutionary outcome of the operation of those mechanisms, the purported normative aspect of functional properties by imposing a role of performance on items previous conditions. For a discussion of various attempts to understand function in biology, see e.g. (Almér 2003).

With a selected-effects characterisation of function we can distinguish between proximate function and distal function – the former being what a mechanism is selected for: A human heart, e.g., contributes to the blood being oxygenated, but its proximate function is to pump blood, while the lungs are directly involved in effecting oxygenation.

Thus we also define the notion of proximate effect. It is the effect of a mechanism directly realising a proximate function, described without reference to the function. An example would be the chameleon’s skin, which can change colour – the proximate effect – and thereby function as a social signal, camouflage, or thermal regulation.

4 REPRESENTATION IN HUMANS AND OTHER LIVING ORGANISMS

We indicated above that cognitive information processing is an activity-guiding process in living organisms. One way of framing such claim would be in terms of representation (as in mental and linguistic representation in humans and some animals, or in exchange of physical objects such as molecules or ions in simplest organisms like bacteria, where "language" consists of chemical exchanges governed by much simpler rules than human languages).

Briefly, by a representation we refer to signs co-developed with sign users, which might carry information but could also misrepresent facts, that is, they can be false. (Millikan 2004, Neander 2006). By framing cognitive information processing in this kind of evolutionary framework tied to a corresponding notion of representation, a subset of information processes is selected as bearing particular significance, namely those also giving rise to representation representing something to someone. Note that the notion of falsity does not apply to information *sui generis* that is by (Dodig-Crnkovic 2010) defined as proto-information or intrinsic information as the fabric of reality for an agent.

We must distinguish between what we could call complete correctness conditions for a representation and the part of those conditions which are explicitly codified by the structure of the representation in a way which the system using that representation is adapted to interpret. This pertains what information is accessible to such a user and in what manners it could be used for processing. Almér and Allwood (2013) expressed similar ideas in terms of "complexity of information" distinguishing between representational capacities in terms of degrees of awareness and explicitness of representation. Notice that a false representation carry natural information about the world in the very same manner as a true representation, whereas merely the latter is such that a normal interpreter gets access to the explicitly represented information (corresponding to the sign's correctness conditions) by way of the normal interpretation procedure. It is important to keep apart the notion of correctness condition from the notion of information, although there is a conceptual link in our view as just indicated.

Talking about human-level cognition, much discussed in the fields of pragmatics and philosophy in general is the interplay between contextual parameters and syntactically encoded semantic information in the interpretation of natural language expressions. For an overview of such issues, see (Almér 2007). Take the sentence "it's raining". An instance of an utterance of that sentence type typically "refers" to a particular rain event with a reasonably well-defined location in time and space, whereas the surface structure of the sentence does not seem to encode for location. The million-dollar question, perhaps somewhat surprisingly, is considered to be whether the deep structure of this sentence type contains a hidden variable or parameter for location. Let's assume it doesn't. Then we would have an instance of a representation where the location would be part of the complete correctness conditions while not being explicitly encoded in the sign.

What about awareness? On the human level, organisms are obviously capable of being aware where it rains and normally apply the mentioned sentence type with an intended place in mind. As such, awareness does not automatically connect to the structure of a representation. But we could imagine a cognitive system employing a signal type for rain here and now without being capable of explicitly representing time and location at all. Such an organism could not use their cognitive system to store information about where or when anything happens, like a rain event there and then. Still the time and location of rain would be part of the correctness conditions of a sign, and part of the natural information a true sign of that type carried for a typical user.

We, on the other hand, could use the signs of that organism as natural sign for time and location of rain. Millikan (2004) makes similar points about signs and their conditions of truth in terms of the signs' "articulation". She refers to simple warning signals in the animal kingdom as possible examples of signs not articulating time and location while obviously standing for reasonably well-defined time and location values.

Miłkowski and Talmont-Kaminski (2015) refer to the work of Gładziejewski, who distinguishes between *action-oriented accounts* of representations, characteristic of interactivism (Bickhard, 2008), and the *structural account of representation*, such as proposed by (Ramsey, 2007). They also present results of Clowes and Mendonça regarding the role of representation in embodied, situated, dynamicist cognition, claiming that in several contexts the notion of representation is useful, such as in re-use, fusion and elaboration of information; virtualist perception as well as operations over representations – extension, restructuring and substitution. The role of representation is found in informational economy (more compact manipulation of information) and better understanding of the coupling between the organism and the world. This would mean that the idea of representation in explanation has not become obsolete in enactive and radical embodied theories of cognition.

Traditional approaches to social cognition in humans are well researched compared to animal cognition and to even more scarce sources on the social behaviour and languaging (the cognitive process of developing meaningful output as part of language learning) of unicellular organisms or plants. In spite of the abundant literature and dominant position of the studies of human social cognition, it is important to understand the limitations of approaches to collective intentionality based exclusively on human language and rationality. They are expressed mainly in descriptive, external terms while we need to expand the notion of social cognition to include an embodied, evolutionary, generative approach in all living organisms.

Thus, returning to the question of roots of human representation, we are studying simple organisms interacting with their environment. For understanding them it is important to learn about what type of information (symbolic or sub-symbolic e.g.) as well as what kind of agent (its cognitive info-computational architecture) it is. Of special interest is as well how information is stored. For example, in the case of unicellular organisms it could be stored in the DNA or other cell structures, while in the case of more complex organisms specialised structures such as nervous systems or brains are used for information storage together with other bodily structures, as the body frames the way of agency and thus cognition.

It is important to understand how retrieval of information is enabled, as well as transduction and processing; whether the organism acts completely automatically upon getting information or it can make decisions, reason or plan activities related to that information; whether that information can be implicitly or explicitly synthesised with other information, and so on.

5 SOCIAL COGNITION, FROM BACTERIA TO HUMANS

With respect to signalling, in the simplest type of collective activity no social signalling (based on type of information processed) is taking part, nor are the organisms conscious of the purpose (evolutionary framed) of their own activities. However, the criterion in this model for an activity to be collective is defined in terms of the function of information-guided actions such that collective activities require contributions from more than one organism for the function to be performed. The collective function is performed without any social signalling, solely depending on mechanisms such as stigmergy, that is indirect, mediated coordination. An example of such coordinated behaviour is that in deep snow people would follow the common path, as it is easier, so collective behaviour will emerge without direct communication, constrained by the interaction with the environment affected by other people.

Thinking about signalling in the case of community of living agents exchanging "messages" we start with the cognitive level of bacteria that are both the simplest kind of organisms and their signalling is simple exchange of chemical molecules. Actually, a single bacterium itself is not so simple when it comes to internal signalling as it may seem. A bacterium is a complex network of functional cooperating parts that orchestrate their mutual interactions, led by chemical and physical exchanges and interactions with the environment. It has been shown (Ben-Jacob, Becker, & Shapira, 2004; Ben-Jacob, Shapira, & Tauber, 2006; Ben-Jacob, 2008) (Ng & Bassler, 2009) that bacterial collectives such as colonies, films and swarms exhibit advanced social cognitive behaviours like "quorum sensing" based on communication between individual bacteria using chemical "language". Bacteria have shown surprising ability to find good strategies to survive under different pressures and to develop defence mechanisms such as anti-biotic resistance.

As an example of the next level of distributed cognition we consider insects such as ants. While an ant colony as a whole is able to efficiently find the shortest path to a food source, individual ants, although capable of learning (Dukas, 2008), do not display the same level of optimisation. Simple behaviour on an individual level gives rise to a more efficient form of learning on a higher level of societal organisation.

Likewise, a slime mould consisting of a colony of unicellular amoebae can "learn" the shortest path to food and exhibit remarkably efficient collective behaviour, despite every single member of the colony lacking any necessary faculty for planning (Nakagaki, Yamada, & Tóth, 2000).

In more complex organisms, however, planning and learning become increasingly evident on an individual level, while in a social setting coordination similarly takes a more long-term form. The behaviour of the organism, then, must be regulated in order to optimise future payoff according to some utility function. Importantly, as the complexity of the organism increases, so does its perceived environment. While an amoeba may be aware of little more than intensity of light and the concentration of sugars around it, and indeed may not need be aware of much more than that, a hare relies on scent, hearing and vision, among other senses, coupled with previous experience to find food and detect predators, which in turn need to employ non-trivial planning based on some learning process in order to catch it. The central mechanism underlying this behaviour is generative – from simple local rules, a global collective pattern emerges (Marsh and Onof 2007).

Social interaction is arguably the largest contributing factor in adding complexity to an environment. Game theory tells us that in an adversarial multi-player game, in most cases an optimal strategy is random (or mixed), and depends on the strategy of the opponents, who may also change their strategies at any time. In such an environment, the dynamics of which are likely to change over time, but where courses of actions nevertheless are dependent on the situation that may need to be analysed in terms of their long-term effects, not only learning becomes crucial, but also a mechanism for modulating learning and behaviour.

Since not all events are equally important in the learning process – one may not get a second chance to learn to escape a lion, for example – the learning rate should be lowered or raised accordingly to reflect this. Likewise, while escaping said lion the long-term implications of one's actions, such as whether running to the left increases or decreases one's chances of finding dinner for the evening, is rather less important than minimising the short-term prospects of ending up as a dinner oneself. The trade-off between exploration and exploitation needs to be struck differently depending on the current environment in much the same way.

It has been suggested by Doya (2000, 2002), following the work of Montague et al. (1996) and Schultz et al. (1997), among others, that the neurotransmitters dopamine, serotonin, noradrenaline and acetylcholine are responsible for the modulation of learning parameters in the brain. Specifically, within the framework of reinforcement learning, the reward system, mainly dopamine, has been shown to correspond to the temporal-difference error, which tells the learning agent how the received reward differs from the expected reward. Serotonin controls the discounting factor, which sets the time horizon of optimisation; noradrenaline determines the level of exploration versus exploitation via the inverse temperature parameter; and acetylcholine regulates the learning rate, that is, how much weight to assign to observed events.

As the signal substances controlling learning have also been shown to cause the physiological and psychological effects associated with emotion in humans, it may be posited that emotion evolved precisely in order to facilitate adaptive learning and behaviour in a complex, non-stationary environment (von Haugwitz et al., 2012). Fear, for example, would serve to lower the discounting factor, making the organism focus on escaping immediate danger, while comfort on the other hand allows for long-term planning.

Humans are on the highest level of hierarchy of social signalling systems. The social ontology framework by Almér and Allwood (2013) has been developed largely as a response to certain philosophical suggestions that social ontology should be understood in terms of what has been called collective intentionality and collective agency (Cf. Gilbert 1989, 2000; Searle 1995, 2010; Tuomela 2007; and Bratman, 1992, 1993). Much of these discussions have been circling around whether there is such a thing as a genuine "we" in some thoughts and actions. Also, the theories tend to put much emphasis on deliberate conscious states of mind, such as "me" consciously thinking and acting together with someone else. Hudin (2008) adds to this a proposed explanation of selfless "we" mode of social cognition that requires a combination of collective intentionality and social commitment resulting in an emotional bond with the group and presenting a basis for moral sense:

"practical reasons [that] function differently from other types of practical reasons because they do not require rational deliberation in order to motivate, therefore dispensing with any need for satisfaction of members in the motivational set, or any appeal to desire (passion) in any form. " p. 237.

Experimental work of Tomasello and collaborators (2005) supports Hudin's thesis showing that humans naturally possess inclination to act for a common goal, with unique forms of sociality that distinguish humans from other animals such as great apes. That helps to understand position of humans among living organisms with respect to complex forms of cognition and morality. According to Tomasello humans social behaviour is based on the capacity of understanding of each other's intentions, sharing attention, and the capacity to imitate each other (Tomasello 2009, 2014).

The gap between cognition based on molecular languages of unicellular organisms to the human cognition is huge, and possible indications how it could be bridged can be found in the approach proposed by Feldman (2006), in his book *From Molecule to Metaphor: A Neural Theory of Language.* There are still many missing links in his explanations, but they pave the way towards more fundamental understanding of evolutionary mechanisms of cognition.

6 CONCLUSIONS AND FUTURE WORK

Social behavior has its cognitive aspects that are known as distributed cognition. The idea of distributed cognition has been developed in a number of influential works such as Lucy Suchman's *Plans and Situated Action* (1987), Varela, Thompson, and Rosch's *The Embodied Mind* (1993), Edwin Hutchins' *Cognition in the Wild* (1995) as well as Andy Clark's *Being There: Putting Brain, Body, and World Together Again* (1997) and *Supersizing the Mind: Embodiment, Action, and Cognitive Extension* (2008).

However, it should be noticed that mentioned research addresses human social ontology. Work of Searle, Miller, Tuomela, Hutchins, Tomasello, Hudin and others focus on human-level cognition that should be understood as a complex high-level type of cognition.

The model presented in current work starts in another end, with collective activities among cognising agents ranging from the simplest ones like bacteria, via semi-automatic information processing organisms like insects to the highest level cognising agents such as humans, trying to find as general principles as possible to cover all forms of cognition at the individual and at the collective level.

In order to understand the basic mechanisms of social cognition, it is instructive to analyse rudimentary forms of cognitive behaviours such as those in bacteria and insects. Based on the information-processing model of embodied cognition, our hope is to be able to contribute to the common view of cognition as natural, embodied distributed information processing.

Further progress will require building a broadly based, unified cognitive science, capable of multi-level computational modelling of cognitive phenomena, from molecules to (human) language, as emphasized by Feldman (2006). Damasio (2003) aptly notes, that there is a common basis for this unified approach:

"*All living organisms from the humble amoeba to the human are born with devices designed to solve automatically, no proper reasoning required, the basic problems of life. Those problems are: finding sources of energy; incorporating and transforming energy; maintaining a chemical balance of the interior compatible with the life process; maintaining the organism's structure by repairing its wear and tear; and fending off external agents of disease and physical injury." p. 30.*

The process of theory construction for bridging the gap between unicellular cognition and the distributed human cognition is just in the beginning, but we have better than ever models and computational (simulation) tools to explore this uncharted territory.

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