



Slime mould: The fundamental mechanisms of biological cognition

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ABSTRACT

The slime mould *Physarum polycephalum* has been used in developing unconventional computing devices for in which the slime mould played a role of a sensing, actuating, and computing device. These devices treated the slime mould as an active living substrate, yet it is a self-consistent living creature which evolved over millions of years and occupied most parts of the world, but in any case, that living entity did not own true cognition, just automated biochemical mechanisms. To “rehabilitate” slime mould from the rank of a purely living electronics element to a “creature of thoughts” we are analyzing the cognitive potential of *P. polycephalum*. We base our theory of minimal cognition of the slime mould on a bottom-up approach, from the biological and biophysical nature of the slime mould and its regulatory systems using frameworks such as Lyon’s biogenic cognition, Muller, di Primio-Lengeler’s modifiable pathways, Bateson’s “patterns that connect” framework, Maturana’s autopoietic network, or proto-consciousness and Morgan’s Canon.

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1. Introduction

Classic approaches to cognition were based on human beings, or sometimes, included some great apes or close mammals, leaving unattended a long list of living entities (de Waal, 1999). This biased anthropomorphic perspective had a second problem: it blocked pathways to an evolutionary and naturalistic study of cognition (Atran, 2004). It is easy to find several studies on minimal examples of cognition among prokaryotes (Müller et al., 2001) but the amoeboid organisms of class *Myxogastria* (Myxomycetes) are the best example of the power of such cognitive studies, because they show us the connection bridge between unicellular (*Physarum*) to pluricellular (*Dictyostelium*) living systems. Thus, *Physarum polycephalum* shows to be an extremely intelligent system which offers unique ways for the understanding of the emergence of complex behaviours and cognitive strategies (Dussutour et al., 2010; Shirakawa et al., 2011; Mori and Koaze, 2013). The mapping of such

minimal cognitive elements in slime mould also makes the analysis of two different but fundamental ideas possible: first, to identify the computational nature of basic cognitive processes, which in our case offer a good example of a reliable Kolmogorov–Uspensky biomachine; this biocomputational approach offers a naturalistic way to explain the intricacies of informational processing from scratch to the supervenience of proto-consciousness. This process can be explained without relying on any anthropomorphic bias thanks to implementation of the Morgan’s Canon. As a consequence, slime mould offers a unique and special biological framework for the identification of the basic biocomputations that make cognition possible and pave the way for the emergence of consciousness (understood as meta-level of informational processing). In the next section we describe in more detail the value of such selection for the study of cognition.

2. Minimal cognition: the bottom-up approach to cognition

After the long and intense analysis of human, primate and mammalian cognition, the necessity of explaining their evolutionary and

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basic functional properties led to the interest for minimal forms of cognition. This minimal cognition interest was then focused into plants (van Duijn et al., 2006; Garzón, 2007) and the fundamental chemical mechanisms that rule their behaviour (Hanczyc and Ikegami, 2010). Fundamental aspects of biological systems were detected: they store and process information, which constitutes a form of computation (Wolpert, 2016; Koseska and Bastiaens, 2017). Other studies have also analyzed the cognitive skills of bacteria Jacob et al. (2004), Shapiro (2007), or Jacob et al. (2006). Despite some attempts at defining a minimal structure for the existence of cognition (Barandiaran and Moreno, 2006), we strongly disagree with the idea that emotional and conscious spheres are necessarily and uniquely dependent to neurodynamic processes (Moreno, 2015). The principles that allow, justify and sustain consciousness must rely at a lower fundamental level, like quantum mechanics (Matsuno, 2003) and other mathematical approaches have provided simple informational mechanisms able to be performed by slime moulds as the basis of data integration and conscious experience. It is very important to take into account that this analysis must include conceptual distinctions between 1st, 2nd and 3rd person descriptions of cognitive processes. Following Matsuno (2002), we agree with the idea that robust macroscopic data which involve physical measurements imply a 3rd person approach to the explanation of the mechanism (in present perfect tense), while this process is completely underpinned by microscopic contexts accessible only by 1st and 2nd person perspectives (in present progressive tense). Here, the supervenience and direct correlation between microdynamic mechanisms justify the functional properties of macrodynamic mechanisms, which are not bilateral. Thus, measurements allow to explain the naturalization of the study of both consciousness and self-awareness processes, which we have described at their initial level. These boundaries make possible the mechanistic transition from irreplaceable experiences to general behaviour descriptions, situated within specific spatial and temporal horizons. We have attempted to exemplify these analytic levels using a bottom up approach to the emergence of complex social behaviours (and intelligent or creative activity) based on raw and fundamental biomechanical processes.

Despite some very interesting attempts at looking for the phylogenetic emergence of consciousness (Cabanac et al., 2009), most of the studies elude the analysis of fundamental aspects which could explain a naturalistic and scalable explanation of consciousness increase in complexity. Some general analysis about this new approach has been done by (Vallverdú and Talanov, 2017b) and will be explained with more detail into next sections. In no way are we embracing panpsychist or panexperientalist approaches, as could be misleadingly inferred. At the same time we wish not to dilute our research into unending philosophical debates. Slime moulds know and gather knowledge via their specific proto-consciousness.

Taking into account these elements we wish to descend even more into the tree of life and select slime mould as a very minimal cognitive system (Adamatzky and Schubert, 2014). In spite of their very simple cognitive architecture, slime moulds are able to perform an incredible list of cognitive tasks as well as to be creative (Adamatzky et al., 2013), considering this skill as an emergent property of their genomic structure, as it works for other living systems (Ben-Jacob, 1998). As noted by Adamatzky et al. (2016), slime mould shows outstanding abilities to adapt its protoplasmic network to varying environmental conditions in which it can solve tasks of computational geometry, image processing, logic and arithmetic if and only if data are represented by binary configurations of attractants and repellents. We speculate that in slime mould cognition is embedded with computation in morphological patterns of protoplasmic networks updated locally similarly to a computational process travelling in disordered dynamically changing graphs, or storage structures, of Kolmogorov–Uspensky

machines (Kolmogorov, 1953; Uspensky, 1992; Gurevich, 1988; Blass and Gurevich, 2003).

3. Defining the nature of slime mould

The slime moulds are a polyphyletic group of protistic organisms existing in three major categories: ‘true’, acellular or plasmodial slime moulds of class *Myxogastria*, cellular or pseudoplasmodial slime moulds of class *Dictyosteliida* and the unicellular microscopic slime moulds of class *Protosteliales* (Stephenson and Stempen, 1994). Of the former two varieties, the first is a multinucleate single cell and the second is a multicellular complex. Therefore, all slime moulds could be tested to minimal cognition for proto-consciousness.

Basic regulatory functions (as metabolic ones) can explain the emergence of cognitive mechanisms (Bich and Moreno, 2016) and therefore both homeostatic and homeodynamic perspectives can allow the existence of a minimal cognition. But in no case can proto-consciousness be considered as only the sum of different minimal cognitions, instead of the result of the emergence of entangled multi-taxis or multi-tropisms functioning in coherence or decoherence playing.

Acellular slime mould *P. polycephalum* has a sophisticated life cycle (Stephenson et al., 1994), which includes fruit bodies, spores, single-cell myxamoebae and the plasmodium, a multinucleated syncytium (Mayne, 2016). The plasmodium is a coenocyte: nuclear divisions occur without cytokinesis. The plasmodium is a large single cell. It grows up to tens of centimetres when culture conditions are appropriate. The plasmodium consumes microscopic particles, bacteria and oat flakes. During its foraging behaviour the plasmodium spans scattered sources of nutrients with a network of protoplasmic tubes. The plasmodium optimises its protoplasmic network to cover all sources of nutrients, whilst avoiding repellents and minimising transportation of metabolites inside its body. The plasmodium’s ability to optimise its shape (Nakagaki et al., 2001) attracted attention of biologists, then computer scientists (Adamatzky, 2010a) and engineers. Thus the field of slime mould computing was born.

So far, the plasmodium is the only stage of *P. polycephalum*’s life cycle useful for computation. Therefore further we will use word ‘Physarum’ when referring to the plasmodium. Most computing and sensing devices made of the Physarum explore one or more key features of its physiology and behaviour:

- Slime mould senses gradients of chemo attractants and repellents (Durham and Ridgway, 1976; Ueda et al., 1976; Rakoczy, 1963); it responds to chemical or physical stimulation by changing patterns of electrical potential oscillations (Ridgway and Durham, 1976; Kishimoto, 1958) and protoplasmic tubes contractions (Wohlfarth-Bottermann, 1979; Teplov et al., 1991);
- It optimises its body to maximise its protoplasm streaming (Dietrich, 2015); and,
- It is made of hundreds, if not thousands, of biochemical oscillators (Kauffman and Wille, 1975; Mayne et al., 2016) with varied modes of coupling (Grebecki and Cieślawska, 1978).

Slime mould can be seen, if we think at a very simplified level, as a reaction-diffusion excitable system encapsulated in an elastic growing membrane (Adamatzky, 2007). The behaviour of the Physarum is governed by an ensemble of thousands of biochemical oscillators, who set local clocks and control peristaltic activity and growth via propagation of actin polymerisation waves and calcium waves. A coupling between distant parts of Physarum via waves of electrical potential is manifested in oscillations of the electrical potential.

4. What does a slime mould know?

Living systems process information in order to react to the environment and to be able to survive or to transmit their own informational structure (Terzis and Arp, 2011). We can define this process as “knowledge”, because the living system does not produce automated responses, like a thermostat can do, but it implies certain evaluation.

Physarum lives in a world of gradients; concentrations of attractants and repellents, and consequently its behavioural responses are a direct consequence of their interaction with these gradients. For example: while propagating on a substrate, slime moulds avoid domains with concentrations of repellents exceed a threshold, see Adamatzky (2010b).

5. Modifiable stimulus-response pathways from an autopoietic perspective [base of all behaviours]

We must admit that one of the key roles for the development of a living system is its operational autonomy according to the organism's own internal program (Rosen, 1991, 2013).

This determines the basic actions with which the system reacts to stimuli from the environment—stimulus acting on the system through certain internal environment structurally coupled receptors. In fact, Maturana and Varela (Maturana and Varela, 1991) determined their autopoietic theory considering that the problem of autonomy had to be reduced to its minimal form, in the characterization of the basic living unit.

An autonomous system that is self-maintained (as it is autopoietic) generates both development paths and coherent organization, allowing that we describe it as an agent. But the relationship between agency and cognition, within the framework of autonomy, is still precarious. An autonomous system is self-maintained; offering a homeodynamic balance is not sufficient reason for the emergence of a discriminatory semiosis and therefore it is a minimum cognitive principle.

In short, the basic self-maintenance networks of metabolism, capable of certain forms of adaptive responses do not show those skills necessary for the emergence of minimal cognition (Castro, 2016). A more complex organization, which gathers mechanisms that go beyond this basic metabolism, is necessary. That is, that the mechanisms of internal compensation of interactions with the immediate environment are responsible for the emergence of a biosemiotics discrimination of second level—macromolecular—allowing for detecting the distinction between what is noise which is significant for the system agential autonomous.

We also take into account the generation of autopoietic subsystems when to explain the minimum domains of perceptual activity in a structurally stable autopoietic organization. These establish a new criterion of interdependent autonomy within a hierarchy in the organization of living things. Cellular components are established as autopoietic interdependent subsystems in a hierarchical level lower than the cell. Subsystems comprising a minimum convenient inactivity, both morphologically and physiologically, exert a specific regulatory function. We can say, in the words of Leonardo Bich and Alvaro Moreno (Bich and Moreno, 2016; Moreno, 2015), that they are specific regulatory subsystems.

‘Regulation’ is understood as the capacity of living beings to internally compensate for disturbances (Moreno, 2015). Exogenous environmental phenomena to an organism or internal disturbances are managed by the agential systems that confers significant and therefore an intrinsic biosemantics to dynamic patterns of transduced self-regulation. In the words of Piaget, it is assimilation and an accommodation (Piaget, 1967) to the operational closure of the

agent to overcome the binomial “stimulus–response”. That is, the interaction between an organism and the environment through oncogenetic adaptation is considered an assimilation of external influences; it involves internal self-regulation, or accommodation, and thus a restructuring of the system. This provides a dynamic and cyclical view of self-regulation: endogenous action → interaction with Umwelt → self-regulatory disturbance compensation → internal re-balances, etc. (Castro, 2009).

To achieve effective regulation, an interdependent autopoietic control subsystem is necessary. But that is sufficiently independent of the dynamics of the processes controlled, and can be changed without interrupting these processes; but, it is also able to be linked to parts of the control mechanism of the system—a regulated subsystem—in order to be able to modulate its operations (Bich and Moreno, 2016). More specifically, the appearance of a control subsystem implies that the organism itself generates a set of decoupled processes from the dynamics of their constitutive system. The dynamic decoupling between the regulator and the regulated constituent subsystems means that both—although they are correlated through the system—are integrated, working at different intrinsic rhythms. That is, the regulation components are produced and maintained by the activity of the constituent subsystems regulated, and said activity, in turn, is modulated by the regulator.

As occurs in the two-component signal transduction (TCST) system of *Escherichia coli* bacteria (Stock et al., 2000), the function of the regulation subsystem is neither specified nor directly determined by the metabolic activity of constituent subsystems being regulated: that is, is “stoichiometrically free” latter (Griesemer and Szathmáry, 2009), so no biochemical balance between them. More specifically, the fundamental idea of this form of decoupling is that activation and operation of subsystem control is not directly dependent on its concentration (or concentration variation), i.e. of its production by the constituent subsystems regulated, even although these subsystems ensure their presence in the system. In contrast, activation of a control subsystem is caused by environmental disturbances, and operations depend on their internal organization and the structure of its functional components. So, the regulator subsystem can work operationally differently from the constituent subsystems regulated, and can, in principle, act as a regulator controller of regulated constituent subsystems (Bich and Moreno, 2016).

5.1. Recognition in regulators subsystems

In this organizational architecture, the functional role of a regulator subsystem is a basic modular constituent network, switching between different metabolic systems available in the system in relation to changes in environmental conditions. It does so in such a way that new metabolic/constituent regimes engendered by regulatory switches must be able to cope with the new environmental conditions, expanding the range of disturbances or stimuli to which the system can respond quickly and efficiently, and enrich the field of dynamic functional behaviours available.

The crucial thing is that the organism endowed with regulatory systems reacts in a new way, does things according to what it recognizes and distinguishes in its interactions with “Umwelt” of the autopoietic regulator subsystem. In fact, “recognition” is a complex process, since the specific characteristics of the interactions with the Umwelt are responsible for triggering the subsystem; regulations cannot directly drive the system response, as in the case of basic network responses. In fact, a certain disruption active regulation subsystem, may modulate the basic constituent network so as to meet the specific environmental characteristic that triggered the regulatory response.

A couple of examples applicable to Physarum would be:

- The organism is attracted to a new source of food richer in nutrients that can provide more energy, even if it must choose a path with worse environmental conditions in order to attain it (Takagi et al., 2007).
- Transformation of Physarum's morphology—plasmodium to sclerotium—to preserve it in a hostile environment lacking food, minimizing its respiration (Seifriz et al., 1936) to maximise its longevity (Seifriz, 1939; Gehenio, 1944; Jump, 1954).

In other words, the fact of recognition is a consequence of the specific nature of the disturbance and internal regulatory organization system.

5.2. Recognition and equivalence classes

In such scenarios, an environmental disturbance becomes a specific and recognizable interaction due to the nature of the relationship with the subsystem controller. Regulator subsystems are responsive to the disturbance, in the sense that they endogenously establish the equivalence classes in their environment with respect to these specific changes, according to how variations activate the controller subsystem to trigger regulatory action. These equivalence classes do not consist of external associations between the disturbances and the results of the changes brought about in the system as a whole, as in the previous case. Rather, they are the results of the evaluation (activation of control subsystems causing further regulatory action on the constituent subsystems regulated) operated by their regulation subsystem that achieve endogenous and functional significance for the system.

Therefore, beyond the debate about whether cognition is coextensive with life, it is clear that regulation becomes a necessary condition for the appearance of cognition, considering as an essential aspect of cognition that the knower should be capable of transforming an external influence on an adaptive integration or, in cognitive terms, in a meaningful interpretation (Moreno, 2015). This requirement is essential for cognition to be carried out only by regulation rather than by self-produced basic biological and self-maintenance (i.e. minimal autopoietic systems), as some of the defenders of the tautology of life and cognition have argued.

6. Significant regulation

A system with normativity capacity, in fact, is able to do things according to what it is able to distinguish between. Consequently, interactions with the environment become more than a source of confusing noise, but become a world generated of endogenously (naturalized) meanings—an Umwelt (Von Uexküll and Mackinnon, xxxx; Castro, 2011): interactions functionally become “significant” for the system itself, without being to an outside observer.

Here the term “meaning” is used as a synonym for “functional for the system” (see Barandiaran and Moreno, 2006). More specifically, a source of disturbance makes sense when the system can distinguish via the regulatory subsystem and this distinction has an operational effect on the system. Through the action of the regulatory system, the subsystem modulates its own activity (in the constituent subsystems regulated) on the basis of this distinction as contributing to their own self-maintenance.

6.1. Electrical activity

An example of normative regulatory system in Physarum can be set in the regulation of Ca^{2+} for activation or inhibition of myosin, allowing oscillations of current flow for plasmodium displacement. Here Ca^{2+} acts as an inhibitor of the oscillations of the acto-myosin, but in the opposite direction of the existing inhibitory activity in the process of contraction in animal muscle cells. The absence of

Ca^{2+} in mammalian neuromuscular processes inhibits contracture activity while in plasmodia, inhibition increased by Ca^{2+} (Nakamura and Kohama, 1999) arises. Ca^{2+} but is a powerful oscillator in the presence of cAMP in the environment of plasmodium (Smith and Saldana, 1992).

More broadly, the extensive utilization of bioelectric phenomena by Physarum (Adamatzky and Jones, 2011; Halvorsrud et al., 1995; Achenbach and Weisenseel, 1981; Kishimoto, 1958) dovetails with the broader use of ionic signalling in morphological computation throughout metazoan organisms. Indeed, ion channel and neurotransmitter hardware, which underlie the software of cognition in animal brains, are evolutionarily ancient and pre-date multicellularity (Levin et al., 2006; Keijzer et al., 2013; Moran et al., 2015; Liebeskind et al., 2011). For a review of cognitive approaches to the decision-making and memory in non-neural metazoan cells and tissues in the context of embryogenesis, regeneration, and cancer suppression see (Baluška and Levin, 2016; Pezzulo and Levin, 2015; Mathews and Levin, 2017). The reading of bioelectric states of Physarum during learning and problem-solving, to achieve a kind of “neural” decoding, is an on-going effort at the frontier this field.

6.2. Regulatory subsystems independent of metabolic processes

In the same way that the phenomenon of chemotaxis for the bacteria *E. coli* seen, myxomycetes also offer specific chemotaxis, both the multicellular pseudoplasmodial slime mould *Dictyostelium discoideum* (Bonner and Savage, 1947; Marí-Beffa et al., 2005; Song et al., 2006) as well as the acellular plasmodium of *P. polycephalum* (Keller and Segel, 1971; Knowles and Carlile, 1978; Ueda et al., 1976).

But in the case of taking the phenomenon of chemotaxis as a condition for cognitive processing requires, as (Moreno, 2015) explains, that part of the regulatory subsystems are independent of metabolic processes. This case is a complex form of driven stability taxis, achieved through the coupling of two subsystems and indirect feedback through the environment. The movement here is autonomous and depends on the internal differentiation of the organization and activity of inherent self-maintenance of the cell. Additionally, this behaviour is functional in the sense that it contributes to the maintenance of conditions of existence of metabolism and consequently of the entire system. However, in this example, although the system is capable of complex viable behaviours, the system responds as a network together without distinguishing the specific of their interaction with the environment, evaluating them and modulating action accordingly. In this case, the environment is only a noise source that disturbs the metabolism, and the behavioural response is filtered through the latter.

This chemotactic mechanism involves at least three molecular complexes:

- A receiver subsystem, which is activated by environmental effectors (chemoattractants and chemorepellents);
- A conductive tip, i.e. pseudopodia of plasmodia and pseudoplasmodia, and
- A group of molecules, and macromolecular filaments which act as a bridge between the two. Usually, the latter are activated molecules through non-covalent post-transducer modifications, such as phosphorylation cascades.

The distinguishing feature of this complex case of chemotactic behaviour is that the system, thanks to the action of a subsystem control, is able to modulate their behaviour based on specific interactions with the environment, which acquires a specific operational meaning for the system, so that the latter is able to change

their behaviour accordingly. This is made possible by the fact that the regulation subsystem is decoupled from the other. This means that the regulatory subsystem—in the case of *P. polycephalum* plasmodia, this would be a reaction–diffusion pattern (Keller and Segel, 1970) through the filaments and myosin microtubules. It is the stimulus that comes from attractants or repellents (external) that requires adaptation of the material to their spatial behaviour. The specific mechanism used is the diffusion of attractants or repellents in the environment. The presence of these stimuli at the periphery of the material provides the impetus for morphological adaptation (Mayne et al., 2015).

This decoupling actually introduces a new degree of freedom in the system, one or more new variables in the controller subsystem which does not depend directly on the constitutive regime and therefore may be sensitive to something different than the internal state of the system: in this case a characteristic of the environment. This characteristic takes an important role for the entire system, and subsystem of decoupling achieves a functional role when the effect of its regulatory action occurs, caused by the disturbance and contributes to system maintenance. From this relatively elementary chemotactic mechanism, then, a variety of more complex tactical behaviours can be implemented (Bich and Moreno, 2016; Moreno, 2015). What is common to them is that they cannot be treated in terms of input–output, as if the behaviour of the system was expelled by the disturbance. On the contrary, they can be characterized in terms of endogenous generation of adaptive response by focusing on the internal organisation of the system and, above all, regulatory subsystems.

So we conclude chemotaxis of myxomycetes represent a clear comparative example of how certain fundamental capabilities for the origin of cognition may arise in minimum living systems, and how this is possible only through the action of regulatory mechanisms. Only in the presence of regulation that specific disturbances acquire a meaning for the system. This is a biosemiotic foundation of the basics of cognitive minimum principles, emerging regulatory system factors acquire those minimum principles offered in cognitive biology (Maturana, 1970; Bateson, 1979; Maturana and Varela, 1991; Müller et al., 2001; Lyon, 2006a,b).

7. Minimal cognitive principles in myxomycetes. Cognitive biology as framework

From the Darwinian theory of species, each organism evolved from a common root. This is very important as it is the foundation of a common root of the minimal cognitive principles that underpin the higher emergent developments. For this reason, three additional elements are required in cognitive biology:

- The study of cognition in a species of organism is useful, through contrast and comparison, for the study of the cognitive capacities of another species (Spetch and Friedman, 2006);
- To proceed with more complex cognitive systems, it is useful to start from the simplest organisms (Balúška and Mancuso, 2009), and
- For a better understanding of the nature of cognition, the greater the number and variety of species studied in this sense (Lyon, 2015).

While cognitive science strives to explain human thought and the conscious mind, the work of cognitive biology focuses on the most fundamental process of cognition of any organism (Goodwin, 1978).

Cognitive biology is, therefore, a new approach to biological paradigms about cognition that need a significantly coherent

contextualisation, both to experimental data and to a semantic development of biology.

Ladislav Kováč of the Department of Biochemistry and Genetics of the Faculty of Natural Sciences of the Comenius University in Bratislava states in Kováč (2000) that:

“Cognitive biology is more a reinterpretation of existing data than a research program that offers new experimental approaches to old problems.”

and adds:

“Cognitive biology aims at a synthesis of data from various scientific disciplines within a single framework of conceiving life as the epistemic unfolding of the universe (the epistemic principle). According to evolutionary epistemology, it considers biological evolution as a progressive process of accumulation of knowledge. Knowledge manifests itself in the constructions of organisms, and the structural complexity of the constructions that carry the incorporated knowledge corresponds to its epistemological complexity. In contrast to evolutionary epistemology, cognitive biology is based on the assumption that the molecular level is fundamental to cognition and adheres to a principle of minimum complexity, which states that the most efficient way to study any trait of life is by studying it at the simplest level in which it occurs.”

For this reason the interest in a new reformulation of the concept of cognitive process and intelligence requires a deeper understanding of the behaviour of living systems, where cognition does not depend on the existence of a nervous system that channels it, but on functional circuits which allow the minimal perception of the surrounding environment and its biosemiotic processing in vivo (Kull et al., 2009).

8. Minimal cognition principles illustrated by tables of conceptual relationships

8.1. Pamela Lyon's table

Pamela Christine Lyon of the University of Adelaide in Australia argues that cognition is a natural biological phenomenon of maximum access, like other natural biological phenomena: by studying simple model systems (such as bacteria and myxomycetes) we can understand the bases and then expand to more complex examples (from bees and ants to hominids). Lyon develops a biocognition (as says van Duijn, 2012) from a biogenic framework, whose approach tries to anchor the concept of cognition itself in biology. In this approach, cognition is primarily a form of biological adaptation that confers certain selective advantages specific to organisms by allowing them to cope with environmental complexity.

Lyon (2006a) synthesizes in ten biogenic principles the development that Kováč (2000) made based on the principles of cognitive biology. This synthesis illustrates the depth of the bases with which they have been established in the school of cognitive biology of Adelaide and which are listed as follows:

1. Continuity: Complex cognitive abilities have evolved from the simplest forms of cognition. There is a continuous line of significant descent. (Do not rule out the appearance of new capabilities with greater complexity.)
2. Control: Cognition directly or indirectly modulates the physical–chemical processes that constitute an organism.
3. Interaction: Cognition facilitates the establishment of reciprocal relations of causality with the characteristics of the environment, giving rise to exchanges of matter and energy that

- are essential for the continuous persistence of the organism, well-being or reproduction.
4. Normativity: Cognition refers to the (more or less) continuous assessment of the needs system relative to prevailing circumstances, the potential for interaction, and whether the current interaction is working or not.
 5. Memory: Cognition requires the ability to retain information for a period of time greater than zero.
 6. Selectivity: Because an organism is able to interact profitably with some, but not all, properties of the environment, cognition involves the differentiation of some states from the affairs of other states of affairs.
 7. Valencia: In relation to the needs of the body and/or experience different environmental properties will be invested with different degrees of strength or importance, both positive and negative.
 8. Anticipation: Cognition is intrinsically future oriented (what happens next?) and therefore predictive.
 9. Reduction of randomness: Cognition is an important mechanism that biological systems reduce and modulate the influence of random perturbations on their functioning and, therefore, are resistant to disturbances.
 10. Interdependence: The biochemical pathways that innervate cognition are intimately linked to those of other biological functions, making delimitation difficult and largely a function of explanatory objectives. (The map is not the territory.)

To find the minimum processes of cognition in cognitive biology we must take into account the production and processing of communication signals for the behaviour of the group and types of interconnection between individual single units (cells).

Minimum cognitive principles	
Pamela Lyon (2006)	<i>P. polycephalum</i> behaviour
Continuity	Tubulin isotypes relationship between <i>P. polycephalum</i> and different mammals, including humans (Clayton et al., 1980) Intracellular communication: reaction-diffusion model (Yamada et al., 2007) Decision making and “scatter” or state of indecision between different attractors for foraging (Takagi et al., 2007)
Control	Unit microtubules for migrating towards the conductive cores plasmodium area (Ueda et al., 2000) Decision making and “scatter” or state of indecision between different attractors for foraging (Takagi et al., 2007) Anticipation and memory periodic pulses (Saigusa et al., 2008) Distribution of nutrients (Dussutour et al., 2010) Using his trail for spatial memory (Reid et al., 2012) A stimulus triggers the release of a signalling molecule, generating a feedback loop (Alim et al., 2013).
Interaction	Chemotaxis (Durham and Ridgway, 1976; Keller and Segel, 1970, 1971) Microtubule associated with chemotaxis (Ueda and Ogihara, 1994; Ueda, 2005) Irrationality making food choices (Latty and Beekman, 2011a) To leave chemicals in the environment, which are attractive to congeners to find food. Communication-based to cooperation and sociality (Vogel et al., 2015). Fusion microplasmodia to form macroplasmodia in a percolation transition (Fessel et al., 2012).
Normativity	Rules for biologically inspired design adaptive networks (Tero et al., 2010) Comparative evaluation standards for decision making food (Latty and Beekman, 2011a) Precise speed decision making (Latty et al., 2011)

Memory	Anticipation and memory periodic pulses (Saigusa et al., 2008) Using his trail for spatial memory (Reid et al., 2012)
Selectivity	Decision making and “scatter” or state of indecision between different attractors for foraging (Takagi et al., 2007)
Valencia	Unit microtubules for migrating towards the conductive cores plasmodium area (Ueda et al., 2000) Relationship of flow of electric current and polarization associated with filaments and myosin microtubules, in turn coordinate current flow (streaming) and plasmodium oscillations for “mobiligence” (Mayne et al., 2015)
Anticipation	Anticipation and memory periodic pulses (Saigusa et al., 2008)
Reduction randomness	Rules for biologically inspired design adaptive networks (Tero et al., 2010) Reaction-diffusion model for streaming oscillation patterns (Yamada et al., 2007) Composition of a set of networks basic topologies (Nakagaki et al., 2004) Using trails for spatial memory (Reid et al., 2012) Detection stimulus intensity differences through the Weber–Fechner Law (Mori and Koaze, 2013)
Interdependence	Plasmodium to sclerotia transformation (Seifriz, 1939; Gehenio, 1944; Jump, 1954) Relationship of flow of electric current and polarization associated with actin filaments and myosin microtubules, in turn coordinate current flow (streaming) and plasmodium oscillations for “mobiligence” (Mayne et al., 2015)

8.2. Müller, di Primio and Lengeler's table

Bernd S. Müller and Franco di Primio both of Institute for Autonomous intelligent Systems of German National Research Center for Information Technology and Joseph W. Lengeler of Department of Biology/Chemistry, University of Osnabrück in Germany (Müller et al., 2001) have assembled the minimal cognitive abilities into the following list:

- Modifiable stimulus-response pathways [base of all behaviours]
- Selective search
- Perception
- Memory
- Expectations formation reaction [on the sudden deprivation of food]
- Detecting the identity
- Scrutiny [Counting in selective search]
- Adaptation
- Habituation
- Learning
- Cooperation [both for the individual living in a population and the population as a whole]
- Reconfigurability of the body [Synthesizing a situation-dependent or self-destruct of effectors and sensors; to avoid hunger]
- Flexibility [tensegrity] This minimal cognition is amplified than Müller et al. contribution. We aggregate the mechanosensory transduction by bioarchitecture (Ingber, 1997) of filaments like vertebral column and wiring scaffold biophysics (Ingber et al., 2014) for electrochemical connections.

Minimum cognitive principles			
Müller, di Primio and Lengeler (2001)	<i>P. polycephalum</i> Behaviour		To leave chemicals in the environment, which are attractive to congeners to find food. Communication-based to cooperation and sociality (Vogel et al., 2015) Fusion microplasmodia to form macroplasmodia in a percolation transition (Fessel et al., 2012)
Modifiable stimulus–response pathways [base of all behaviours]	Minimum travel toward food (Nakagaki et al., 2000) Retroactivity negative (Nakagaki et al., 2000) ATP at the tip of plasmodium supervenes locomotive capacity (Takagi et al., 2007) Detection stimulus intensity differences through the Weber–Fechner Law (Mori and Koaze, 2013)	Flexibility [tensegrity]	Unit microtubules for migrating towards the conductive cores plasmodium area (Ueda et al., 2000) Ratio of electric current flow and polarization associated with the actin-myosin and microtubules that coordinate the flow (streaming) of the plasmodium and its oscillations to the “mobiligence” (Mayne and Adamatzky, 2015)
Selective search	Rules for Biologically Inspired Design adaptive networks (Tero et al., 2010)		
Selective search	Comparative evaluation standards for decision making food (Latty and Beekman, 2011a) Precise speed decision making (Latty and Beekman, 2011b) Decision making, taking into account the variables of the key strengths of different foods (Reid et al., 2013) Decision-making for solves the two-armed bandit (Reid et al., 2016)	Body reconfigurability [Synthesising a situation-dependent or self-destruction of effectors and sensors; to avoid hunger]	Plasmodium to sclerotia transformation (Seifriz, 1939; Gehenio, 1944; Jump, 1954) Reaction-diffusion parameters under sol-gel conditions the plasmalemma (Takagi et al., 2007)
Perception	Barriers of maze (Nakagaki et al., 2000) Foraging sources (Nakagaki et al., 2000)	8.3. Gregory Bateson's table	
Memory	Anticipation and memory periodic pulses (Saigusa et al., 2008) Using his trail for spatial memory (Reid et al., 2012)	Gregory Bateson's contribution to cognitive biology is that he sat that matter and energy are impregnated of circular processes of information of differences, creating “patterns that connect”. His project was to explain the mind in terms of complexity and cybernetic organisation in the way that he was conceived it.	
Expectations formation reaction [on the sudden deprivation of food]	Reaction-diffusion model for streaming oscillation patterns (Yamada et al., 2007) Distribution of nutrients (Dussutour et al., 2010)	The six criteria that integrate the cognitive processes, or as Bateson calls it, mental processes are:	
Detecting the identity	Detection of changes in rates between separate paths to take parts (Reid et al., 2012) Minimum distance (Nakagaki et al., 2000)	<ol style="list-style-type: none"> 1. A mind is a set of interacting parts or components. It is an autopoietic red concept that is a network of interacting components. 2. The interaction of the parts of the mind is triggered by difference, and difference is a non-substantial phenomenon that is found neither in space nor time, the difference is related to negentropy and entropy rather than to Energy. 3. The mental process requires collateral energy. In this criterion Bateson highlights the distinction between the ways in which living organisms and non-living systems interact with their environments. What Bateson exposes is that to describe the energy of life and to describe that of the forces and clashes of the non-living there should be a differentiated syntax. 4. The mental process requires circular (or more complex) processes of determination. Like Uexküll's Funktionkreises, biofeedback's Bertalanffy and Autopoiesis' Maturana and Varela. 5. In the mental process, the effects of difference must be seen as transformations (i.e. coded versions) of events that have preceded them. 6. The description and classification of these processes of transformation reveal a hierarchy of logical prototypes immanent in phenomena. 	
Scrutiny [in selective search]	Composition of a set of networks basic topologies (Nakagaki et al., 2004) Rules for biologically inspired design adaptive networks (Tero et al., 2010) Creating minimum transport networks (Latty et al., 2011) Decision making and “scatter” or state of indecision between different attractors for foraging (Takagi et al., 2007)	These criteria by Gregory Bateson on cognitive processes have been linked to the cognitive processes of Humberto Maturana.	
Adaptation	Morphodynamic changes that depend on the environment for motility (Takamatsu et al., 2009)		
Adaptation	Rules for Biologically Inspired Design Adaptive Networks (Tero et al., 2010) Stimulus comes from attractants or repellents (external) provides the impetus for morphological adaptation (Mayne et al., 2015). Maximizing internal flows by adapting patterns of contraction to size (Alim et al., 2017).		
Habituation [creating habits]	Responsiveness decline and spontaneous recovery (Boisseau et al., 2016) Habituation to be exposed to an innocuous repellent and transfer learning to another cell no exposed (Vogel and Dussutour, 2016).		
Learning	The aversive response still occurred to another stimulus (Boisseau et al., 2016) Associative learning to acquire a reversed thermotactic property, a new preference for the lower temperature (Shirakawa et al., 2011).		
Cooperation	Production of fruiting bodies (Seifriz, 1902, 1938; Seifriz et al., 1936) Interdependent collective irrationality of cooperative behaviour and violation of the principle of collective decision regularly supply (Latty and Beekman, 2011b)		
		Mental/cognitive processes	
		Gregory Bateson (1979)	<i>P. polycephalum</i> behaviour
		A mind is an aggregate of interacting parts or components	Interdependent collective irrationality of cooperative behaviour for decision making (Latty and Beekman, 2011a) Precise speeds and decision-making (Latty and Beekman, 2011b) Distribution of nutrients (Dussutour et al., 2010)

	Using his trail for spatial memory (Reid et al., 2012) Association with actin filaments and microtubules myosin coordination of current flow (streaming) of the plasmodium and its oscillations to the “mobiligence” (Mayne and Adamatzky, 2015)
The interaction of the parts of mind is triggered by difference	Using his trail for spatial memory (Reid et al., 2012) Collective cooperativeness in making food choices (Latty and Beekman, 2011a) Detection stimulus intensity differences through the Weber–Fechner Law (Mori and Koaze, 2013)
The mental process requires collateral energy	Distribution of nutrients (Dussutour et al., 2010)
Mental process requires circular (or more complex) determination processes	Reaction-diffusion model for streaming oscillation patterns (Yamada et al., 2007)
In the mental process, the effects of the difference should be seen as transformations	Internal communication: Reaction-diffusion model (Yamada et al., 2007) Decision making and “scatter” or state of indecision between different attractors for foraging (Takagi et al., 2007) Rules for biologically inspired design adaptive networks (Tero et al., 2010) Comparative assessment standards for making food choices (Latty and Beekman, 2011a) Precise speed and decision-making (Latty et al., 2011) Decision-making for solves the two-armed bandit (Reid et al., 2016)
The description and classification of these transformation	Rules for biologically inspired design adaptive networks (Tero et al., 2010)
Processes reveal a logical hierarchy of immanent phenomena prototypes	Comparative assessment standards for making food choices and violation of the “principle of Condorcet” (Latty and Beekman, 2011a) Precise speed decision making (Latty et al., 2011)

8.4. Maturana's table

While Bateson worked from the scientific intuition forged from the observational method, typical of psychoanalysis, Maturana made it from the cybernetics itself with an innovative language. To paraphrase Dell (1985), Maturana contains the ontology that Bateson did not develop. While Bateson exposes his ideas in a sort of “cosmology” of biology for a cybernetic epistemology, Maturana realizes an ontology of biology in an epistemology that conjugates with the ideas of Bateson. Maturana sums up his analogy with Bateson's ideas in these three points previously implicated with Bateson's:

1. An autopoietic network is a network of interacting components. Here he conjugates with Bateson insofar as the mind is an aggregate of parts or interacting components. In other words, mind/cognition and autopoietic network support two plausible homeomorphic stages (not identical in themselves, as observed from the incorrect tautology between life and cognition). While according to Bateson the interaction of parts of the mind is triggered by difference, for Maturana the difference is a non-substantial phenomenon that is found neither in space nor in time. The difference is rather related to negentropy and entropy, rather than to energy (Brier, 2001, 2008).
2. The response of an organism requires structural coupling and non-linear patterns. Something that fits the idea of Bateson, in which a mental process requires a collateral energy.

3. The characterization of a living system, in terms of nonlinear patterns, infers autopoiesis. Nonlinear causality generates dissipative structures. In this case it follows the point at which Bateson explains that a mental/cognitive process requires circular (or more complex) processes of determination. Autopoietic systems require nonlinear patterns such as the reaction-diffusion equations, and serve as a non-linear pattern for uncoupled oscillations in the Physarum. Likewise, the concentration factors of multiple cells of *Dictyostelium discoideum*, or of *Dictyostelium mucoroides*—already observed by Von Uexküll (1940)—by the cAMP generate patterns of dissipative structures, excitation patterns, of Belousov–Zhabotinsky medium. These, among other factors, such as the role of Ca^{2+} in actin-myosin in the streaming of Physarum protoplasm are part of what are considered as adaptive regulatory factors, fundamental for the generation of minimal cognitive processes. Let us see how this theory is deduced, from the role of biological autonomy.

Mental/cognitive processes	
Humberto Maturana (1970)	<i>P. polycephalum</i> behaviour
An autopoietic network is a network of interacting components	Interdependent behaviour irrationality of collective decision making (Latty and Beekman, 2011a) Precise speeds and decision-making (Latty et al., 2011) Distribution of nutrients (Dussutour et al., 2010) Using his trail for spatial memory (Reid et al., 2012) Relationship of flow of electric current and polarization associated with filaments and myosin microtubules, in turn coordinate current flow (streaming) and plasmodium oscillations for “mobiligence” (Mayne et al., 2015)
The response of an organism requires structural coupling and nonlinear patterns	Anticipatory mechanisms underlying behaviour from the perspective of nonlinear dynamical systems (Nakagaki et al., 2004) Decision making and “scatter” or state of indecision between different attractors for foraging (Takagi et al., 2007) Arboreal behaviour patterns similar to excitation waves in Belousov–Zhabotinsky medium (Adamatzky, 2009b,a) Rules for biologically inspired design adaptive networks (Tero et al., 2010) Detection stimulus intensity differences through the Weber–Fechner Law (Mori and Koaze, 2013) The stimulus comes from attractants or repellents (emiulxternal) provides the impetus for morphological adaptation (Mayne et al., 2015)
The characterization of a living system, in terms of nonlinear patterns Autopoiesis inferred. The non-linear causality generates dissipative structures.	Anticipatory mechanisms underlying behaviour from the perspective of nonlinear dynamical systems (Nakagaki et al., 2004) Reaction-diffusion model for streaming oscillation patterns (Yamada et al., 2007) Decision making and “scatter” or state of indecision between different attractors for foraging (Takagi et al., 2007) Arboreal behaviour patterns similar waves in Belousov–Zhabotinsky system (Adamatzky, 2009b,a)

9. Emerging sources of cellular levels of sentience and consciousness

Consciousness is emerging as a basic and inherent property of biological organisms which is relevant for their survival and evolution (Mashour and Alkire, 2013; Barron and Klein, 2016; Baluška et al., 2016; Calvo et al., 2017). Importantly in this respect, plants and several unicellular organisms generate endogenous anaesthet-

ics any time they are wounded or stressed (Baluška and Mancuso, 2009; Tsuchiya, 2017). The hypothetical basic unit of consciousness in multicellular organisms, such as humans, non-human animals and plants (Griffin and Speck, 2004; Baluška and Mancuso, 2009; Trewavas and Baluška, 2011; Gardiner, 2012, 2015; Barlow, 2015; Barron and Klein, 2016; Baluška et al., 2016; Calvo et al., 2017) might be represented by cellular and subcellular levels of consciousness (Margulis, 2000, 2001). There are at least three possible sources of sentience and consciousness (understood as a gradual self-mapping tool) at the cellular and subcellular levels.

It is important to realize that ion channel and neurotransmitter hardware, which underlie the software of cognition in brains, are evolutionarily ancient and pre-date multicellularity (Levin et al., 2006; Liebeskind et al., 2011). For a review of cognitive approaches to the decision-making and memory in non-neural metazoan cells and tissues in the context of embryogenesis, regeneration, and cancer suppression see (Baluška and Levin, 2016; Pezzulo and Levin, 2015; Mathews and Levin, 2017).

The excitable membranes with critical proteins embedded especially in highly ordered lipid rafts, vibrating and excitable microtubules and actin filaments, as well as biological quasicrystals based on the five-fold symmetry.

Possible relevances of biological excitable membranes for cellular consciousness is supported by their sensitivities to diverse anaesthetics inducing loss of consciousness in humans, as well as loss of responsiveness in animals and plants (Perouansky, 2012; Mashour and Alkire, 2013; Grémiaux et al., 2014). It is important to be aware that electrically-active membranes evolved early in the biological evolution (Wayne, 1994; Johnson et al., 2002; Eckenhoﬀ, 2008; La Monaca and Fodale, 2012; Cook et al., 2014; Brunet and Arendt, 2016) and are present even in prokaryotic organisms and eukaryotic organelles of endosymbiotic origin (Masi et al., 2015; Prindle et al., 2015; Catterall and Zheng, 2015; Baluška et al., 2016). Our recent report reveals that the sensitivity of plant movements and behaviour to local and general anaesthetics is linked to membranes, action potentials, and to endocytic vesicle recycling (Yokawa et al., 2017). Another possible source of sentience at the cellular and subcellular levels is the dynamic cytoskeleton. Especially microtubules are discussed as important in this respect (Hameroff et al., 2002; Gardiner, 2012, 2015; Barlow, 2015), representing quantum channels related to consciousness (Craddock et al., 2015; Tonello et al., 2015) and terahertz oscillations in tubulin were reported to be affected by exposures to anaesthetics (Craddock et al., 2017). Besides microtubules, also the actin filaments behave as excitable medium which transports ionic waves and mediates eukaryotic chemotaxis in response to diverse gradients (Tuszyński et al., 2004; Iglesias and Devreotes, 2012; Tang et al., 2014; van Haastert et al., 2017). Actin cytoskeleton supports lipid rafts, which are ordered domains of biological membranes particularly sensitive to anaesthetics (Morrow and Parton, 2005; Tsuchiya et al., 2010; Bandejas et al., 2013; Weinrich and Worcester, 2013).

There are also indications that special proteins or assembly of proteins, especially those having five-fold symmetry and quasicrystals properties, seem to be relevant for the cellular and subcellular levels of sentience and consciousness (Gardiner, 2012, 2015).

10. Proto-consciousness and Morgan's Canon

To date, consciousness has been studied in humans and mainly focused into finding neural correlates of such pervasive phenomena. Because of the complexity of its study, it has been called "The hard problem" (Vallverdú and Talanov, 2017a). Despite of the evident and implicit epistemical challenges, this problem is also related to the necessity of a theory about the functional meaning

of consciousness, from a cognitive-information perspective. Consciousness, or any related self-awareness checking, is essential for living systems to enjoy their agency via Sense of Self. This allows them to act in their own interest: with memories, predictions, learning, decisions etc. Thus, we must remark that Consciousness, Self-awareness and Sense of Self allow living systems to recognize and predict patterns of external (and internal!) environmental challenges, something which implies better adaptation, survival and evolution rates. This self-awareness can be understood as a genome adaptive mechanism (Ben-Jacob, 1998) necessary for molecular cooperation and, at an evolutionary perspective, basic for adaptive mutagenesis.

A Sense of Self is based on consciousness and anaesthetics switch-off both. Living systems under anaesthesia will not survive for very long as they lack Sense of Self and cognitive agency.

At least in humans, consciousness can be defined as the experiential awareness of the own existence, but it has demonstrated not to be the hard control system of the whole sum of cognitive processes, but instead of it, consciousness must be defined as a super-level mechanism of punctual data integration for specific decision-taking actions. Therefore we can trace early mechanisms of data integration for evaluation purposes in slime mould that would suggest a proto-consciousness emergence. Proto-Consciousness is essential for living systems again allows organisms to understand complex context of their environmental situation. They can act as agents successful in (a) finding food; (b) avoiding predators; (c) finding mating partners, etc. It is related to the notion expressed by neurologists as "proto-qualia" (Llinás, 2001), as the mechanism to differentiate the sensitivity of a specific perception. This is mechanistically explained by Weber–Fechner law (Castro, 2011). Using Llinás (1990), Llinás (2014), we can suggest as plausible to consider both the Physarum and CNS mammalian cells (as neurons) has as identical isotype of tubulin for build microtubules and centrioles (for cellular division or ciliary composition). But while these in Physarum are alpha-tubulins, in mammalian cells are beta-tubulins. These changes in "peanut" tubulin structure create in both different electrophysiological properties. It is very interesting to follow these changes in order to find a link between brainless cells and brain cells behaviours and biomechanical principles.

Following such a naturalistic approach to consciousness explained by Vallverdú and Talanov (2017b), we will explore the validity and usefulness in this debate of Tononi (2008), and Thagard and Stewart (2014). This is at the same time a process related to a naturalistic statistical approach to data processing, also called 'natural statistics' (Vallverdú, 2015) and that could provide a Bayesian approach to consciousness (Gunji et al., 2017) which fits perfectly with Kolmogorov algorithmic information theory (Kolmogorov, 1968), which provides a solid way to deal with the quantity of information in a system, and at the end, and in some fundamental way, living systems can be considered information processing entities for reproduction purposes. It is also interesting to note that Bayesian models fit well with slime mould information processing (Schön et al., 2014; Miyaji and Ohnishi, 2008).

At the same time, we strongly defend that the notion of proto-consciousness can provide us a naturalistic, evolutionary and bottom up mechanism of explaining consciousness. As Conwy Lloyd Morgan wrote in his "An Introduction to Comparative Psychology" in 1903 (Morgan, 1903):

"In no case is an animal activity to be interpreted in terms of higher psychological processes if it can be fairly interpreted in terms of processes which stand lower in the scale of psychological evolution and development."

For evident reasons, at this low biological level we cannot look for neural correlates, instead of biochemical correlates of (proto)consciousness.

Our starting point is simple: slime mould computes information. There are some basic mechanisms to compute it that allow us to talk about proto-consciousness in brainless living systems, easily identifiable in slime mould. We will explore this in the next section.

11. The computing slime mould as Kolmogorov–Uspensky biomachine

Late 1940s Andrei Kolmogorov published his seminal paper “On the concept of algorithm” (Kolmogorov, 1953) where he introduced a concept of an abstract machine—later called Kolmogorov–Uspensky machine—defined on a dynamically changing graph structure, a computational process on a finite indirected graph with distinctly labelled nodes. A computational process travels on the graph, activates nodes and removes and adds edges (Uspensky, 1992). Basic operations of the machine include: selecting of a node, specifying of node’s neighbourhood, adding and/or removing nodes and edges. A program for the machine specifies how to replace the neighbourhood of an active node with a new neighbourhood, depending on the labels of edges connected to the active node and the labels of the nodes in proximity to the active node (Blass and Gurevich, 2003). Gurevich (1988) suggested that the edge of the ‘Kolmogorov complex’ is not only informational but also a physical entity and reflects the physical proximity of the nodes (e.g. even in three-dimensional space the number of neighbours of each node is polynomially bounded). But the most revolutionary feature of the Kolmogorov–Uspensky machine is its ‘physical nature’; as Blass and Gurevich (2003) stated:

“Turing machines formalize computation as it is performed by a human. Kolmogorov machines formalize computation as it performed by a physical process.”

In Adamatzky (2007) we demonstrated in experimental laboratory conditions that *Physarum* can be seen as living implementation of the Kolmogorov–Uspensky machine, where nodes are represented by sources of nutrients and branching points of the network of protoplasmic tubes, programmed by spatial gradients of attractants and repellents. Each part of *Physarum* ‘reads’ and reacts to quanta of information written in its environment by acting depending on the state of its neighbourhood.

Like a Kolmogorov–Uspensky machine embodies data and program in topology of its graph the slime mould can compute several sets of data without the necessity of a high level integration, or as Andrei Kolmogorov wrote (Kolmogorov and Uspenskii, 1958):

“... the schema for computing the value of a partially recursive function may not be directly given in the form of algorithm. If one develops this computation in the form of an algorithmic process... then, through this, one automatically obtains a certain algorithm...”

The point here is to justify bio-mechanically how different data and different kinds of actions are evaluated and coordinated within a slime mould. This could provide us the key for understanding the existence of a proto-consciousness. Although we have listed a long list of cognitive patterns, these processes are not just mechanistic/automated answers to the environment, but imply a certain evaluation and decision process. This upper level is not a generally requested task involved into all cognitive processes of slime mould, but just a small part of them. From an informational perspective, the process of data binding or integration requires from a mechanism that when is found in other cognitive systems is often referred as ‘consciousness’. This can be inferred from collective behaviour

of slime mould, clearly intelligent, and that allows us to explain the hypothetical model that captures the mechanistic way of transferring informational states from one functional state to another one. That is, *the path from automation to decision*. In the next section we will explore the functional properties of this brainless consciousness mechanism of slime mould.

12. Slime mould complexity and brainless information integration system

It is beyond any doubt that slime mould do not have brain nor any nervous central system. In spite of this fact, it is also true that regardless that they are able to perform incredible cognitive tasks that go beyond automated chemical responses to the environment. For that reason, we defend the existence of a proto-consciousness mechanism in slime mould colonies. Without it we could not explain very complex responses and adaptations to the organism.

Following the formalization of the Integrated Information Theory of consciousness (henceforth, IIT) (Oizumi et al., 2014), information is a

“... set of elements can be conscious only if its mechanisms specify a set of “differences that make a difference” to the set – i.e. a conceptual structure. A conceptual structure is a constellation of points in concept space, where each axis is a possible past/future state of the set of elements, and each point is a concept specifying differences that make a difference within the set. The higher the number of different concepts and their max value, the higher the conceptual information CI that specifies a particular constellation and distinguishes it from other possible constellations.”

We have provided in previous sections several examples about how slime moulds execute integration and exclusion informational decisions. Composition is also an accomplished axiom of IIT because slime mould decide according to the environmental changes that modify substantially their behaviour.

Slime mould is an ideal minimal organism to test for consciousness in particular using ideas from IIT given its many computational and informational properties and because IIT allows a continuous spectra of degrees rather than a binary answer to the question of consciousness.

In Maguire and Moser (2016) and Gauvrit et al. (2017) it is shown how IIT is deeply and, in a formal setting, fundamentally connected to the concept of algorithmic complexity and data compression and in Zenil and Marshall (2016) how algorithmic probability—inversely related to algorithmic complexity by a formal theorem—may explain aspects of biological evolution. More recently, it has been shown that such foundations have the ability to explain a wide range of evolutionary phenomenology that would remain unexplained when making traditional assumptions related to the role of random mutation in natural selection and how organisms rather harness the highly structured nature of ecosystems (Hernandez-Orozco et al., 2017).

In Zenil et al. (2015) it is also shown how experimental behavioural observations can be explained by algorithmic complexity (as opposed to statistical tools) and help explain behavioural phenomenology in areas such as working memory (Chekaf et al., 2015; Gauvrit and Mathy, 2018), psychometrics (Gauvrit et al., 2014b, 2016), visual probabilistic reasoning (Gauvrit et al., 2014a) and cognitive structures of cultural nature (Gauvrit et al., 2014a) able to quantify a multiple range of cognitive processes that were more difficult, if not impossible (both for practical and fundamental reasons), to characterize using conventional (non-algorithmic) statistical tools. In Zenil et al. (2012) it is shown how organisms can

harness the algorithmic structure of the natural environment mirroring the non-random structure of the physical world and using the same tools it was shown how algorithmic complexity can be used to validate behavioural results of animals (Zenil et al., 2015), including foraging communication by ants, flight patterns of fruit flies, and tactical deception and competition strategies in rodents.

In fact, the only application of IIT to this date (Casali et al., 2013) completely relied on the concept of algorithmic complexity as a foundation of their proposed numerical measure using lossless compression applied on spatiotemporal patterns of electrocortical responses of humans using Lempel–Ziv where it was found to reliably discriminate levels of consciousness during wakefulness, sleep, anaesthesia and minimally conscious states even though such approach is closer to a measure of entropy and entropy has been shown to be extremely limited as a computable measure (Zenil et al., 2017; Maguire and Moser, 2016). The non-trivial behaviour of slime mould and its intricate relationship of awareness and interaction with the environment suggests that one can devise behavioural time series of slime mould behaviour and apply all these powerful tools and methods of algorithmic cognition (Zenil, 2017) to determine the complexity of its behavioural capabilities and shed light on measures of integrated information suggesting some degree of consciousness in an experimental/numerical setup as an obvious experiment.

13. Concluding remarks

So we conclude chemotaxis of myxomycetes represents a clear comparative example of how certain fundamental capabilities for the origin of cognition may arise in the minimum living systems, and how this is possible only through the action of regulatory mechanisms. It is only in the presence of regulation that specific disturbances acquire a meaning for the system. This becomes, thus, a biosemiotic foundation of the basics of cognitive minimum principles by which emerging regulatory system factors acquire those minimum principles offered in cognitive biology (Maturana, 1970; Maturana and Varela, 1991; Bateson, 1979; Lyon, 2006a,b; Müller et al., 2001).

Also we have seen that experiments with anaesthesia in plants are an outstanding framework to establish conditions of possibility to bridge sentience with a proto-consciousness (Yokawa et al., 2017). Is necessary to review this experimental task with slime moulds—as Seifriz made on for streaming behaviour studies (Seifriz, 1941)—and so to realize that ion channel and neurotransmitter hardware, which underlie the software of cognition in brains, are evolutionarily ancient and pre-date multicellularity.

According to the provided data and analysis, slime mould provides an insightful example of a biosemiotic entity able to perform cognitive tasks and to explain the first steps from mechanistic automation to decision, as well as of coordination and cooperation, and also an ideal testbed for consciousness as a minimal conscious biological organism.

Physarum exemplifies embedding cognition and computation: the slime mould perceives its world in parallel, process the information perceived concurrently, makes decisions in a decentralised manner and represents the decision, or results of the computation, in spatially distributed configuration of its protoplasmic tubes; the tubes configuration per se might act a program, similarly to Kolmogorov–Uspensky machine, which determines how the information perceived will be processed.

Finally, we have introduced Morgan's canon as a necessary epistemological condition to eradicate the anthropomorphization of the sense of cognition, as well as this bridge to consciousness.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.biosystems.2017.12.011>.

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