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Comment

Embodying Markov blankets

Comment on “Answering Schrödinger’s question: A free-energy formulation” by Maxwell James Désormeau Ramstead et al.

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The free-energy principle (FEP) has been initially proposed as a theory of brain structure and function [1], but its scope is rapidly extending to explain biological phenomena at multiple levels of complexity, from simple life forms and their morphology [2] to complex societal and cultural dynamics [3].

Appealing to the same principles to explain “the mind” and “the biological world at large” may appear bizarre from a biological perspective, which recognizes a risk in applying some concepts that are typical of the mental world – such as teleology and intentionality – to the realm of biology. However, it is becoming increasingly recognized that neural tissues (the accepted seat of intentionality) did not invent their powers *de novo* but rather optimized fundamental capabilities already present in their evolutionary ancestors [4,5]. Unicellular creatures and non-neural metazoan tissues were already solving problems, maintaining physiological and anatomical homeostasis, and constantly trying to improve their lot in life – long before nervous systems evolved [6–8]. Even more fundamentally, the formal ground of this idea emerges clearly if one considers that all living systems must self-preserve their integrity and avoid dissipation; or in other words, counteract the third law of thermodynamics [9–11]. As this self-preservation imperative applies at all levels of complexity and organization that life assumes, one can attempt to use similar principles to explain, for example, how cells, schools of fish, countries or cultures maintain their (internal) identity and identity while shielding themselves by (external) disturbances, thus counteracting at their best dissipative dynamics. All the examples above – cells, schools of fish, countries, cultures – entail some form of separation between what is “inside” (e.g., organelles of a cell, citizens of a country) and what is “outside”. What is inside tends to be rather stable over time – or changes more slowly than the external perturbations. Furthermore, there is some form of separation or barrier between the inner and the outer, which is sometimes physically realized (e.g., cell membrane, country boundaries) and sometimes more fuzzy (e.g., separations between cultures). The boundary of the “self” has very practical implications, for example in the biomedicine of cancer, where individual cells revert back to unicellular programs that treat the rest of the body as the external environment [12].

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The appeal of the FEP is that it suggests a way to cast this sort of metaphorical thinking into a formal specification of “what is needed to be (and to remain) alive” [9–11]. To address this challenge, an appealing starting point is the statistical construct of a Markov blanket, which essentially formalizes the separation between an “inner” and an “outer” environment, in terms of conditional independence between inner states of a generative model and outer states, whose reciprocal influences are mediated by intermediate (sensory and active) states of the generative model [10]. Metaphorically speaking, the intermediate states of a Markov blanket “shield” inner states from the direct influence of outer states. Protected within this barrier, inner states can then preserve their integrity over long time periods, thus avoiding the usual fate (dissipation) of non-living entities. Crucially, to do this, internal variables need to develop (or become) models of the outer environment, thus being able to select adaptive actions (via the intermediate states) that both probe external dynamics (to learn them) and reciprocate their dissipative influences. This formulation is both fascinating – it seems to allude to stories of medieval fortifications and sieges – and useful, as it clarifies that the teleology intrinsic in the reciprocal inner–outer exchanges does not imply and dangerous biological finalism (e.g., the belief that there is a final cause in evolution). Rather, it appeals to more reassuring and mechanistic principles of cybernetic control [13–16], autopoiesis and self-organization [17–19].

Crucially, to explain the living at different levels of complexity and organization, one can apply the concept of a Markov blanket recursively – hence realizing a nesting of Markov blankets within Markov blankets. This nesting propagates the statistical (in)dependencies between inner, intermediate and outer variables across levels, thus providing a suitable formal model to address biological phenomena at increasing complexity e.g., from cells to individuals to societies and beyond – thus motivating a variational neuroethology that spans all these levels [10]. In sum, the formal framework of FEP and the concept of (nested) Markov blankets offers formal tools to understand “the realm of the living” at multiple levels of complexity, while also addressing the reciprocal influences between all these levels – an interesting avenue for future research.

Here we discuss the application of FEP and the concept of (nested) Markov blankets to a key construct of living beings: the body. If one considers where the FEP originates from – explaining brain and mind [1,20–26] – it may seem utterly bizarre to appeal to the same constructs to also explain bodies, at least for those who believe that the immaterial mind and the material body are two irreconcilable kinds of substances [27]. However, there are very strong – and in some cases even surprising – similarities between the ways brains and body are organized. The conservation of mechanisms is perhaps inevitable given their inescapable evolutionary histories; the conservation of algorithms by which they operate is, on the other hand, a remarkable finding with many deep implications for understanding causation [28,29] and goal-directedness [30] in a range of living and synthetic systems. These similarities can be understood at both functional and mechanistic levels.

At the functional level, one can identify analogies in the ways individual neurons located in different brain structures form functional networks (e.g., a fronto-parietal attention network [31]) and individual cells form complex organs and body parts during morphogenesis [32,33]. The formal analogies between these processes can be understood by appealing to the concept of nested Markov blankets. In the brain, individual neurons, small neural networks and big functional networks (e.g., the whole fronto-parietal circuit) represent three nested levels of organization, in which the functional interactions (and conditional independences) can be understood by appealing to (nested) Markov blankets, e.g., by considering that some “nodes” of the network play the role of intermediate states, mediating “input–output” dynamics. In the body, one can identify nested levels of organization in cells, organs and the whole body, and appeal to the same principles of (nested) Markov blankets to explain them. Clearly, brain processes are highly plastic, with rapid shifts between functional networks; whereas bodily processes are apparently less plastic at a macrolevel (e.g., organs do not change so rapidly). However, there are some cases in which plasticity is very high, such as for example during morphogenesis and regeneration, as well in relation to some diseases such as cancer [33]. An important avenue for future research is identifying formal methods permitting to treat these bodily phenomena in the same way neuronal dynamics or functional networks are understood in computational and systems neuroscience [32–34].

Intriguingly, in the case of bodies, some functional aspects of the Markov blankets become – so to say – embodied into the structure of the organism. This is the case, for example, of our sensory epithelia, whose cells play the functional role of intermediate (sensory) states of a Markov blanket, but they also actually, physically separate the body from the outside world and protect its integrity. In this case, the morphogenetic process of separation between cells that become parts of internal organs and cells that become parts of sensory epithelia actually embodies the functional separation between inner and intermediate states of Markov blankets. If one extends this idea to increasingly higher levels of complexity, one can trace similar phenomena (for example) in schools of fish or storms, where some ani-

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