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Biologically inspired information theory: Adaptation through construction of external reality models by living systems

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ABSTRACT

Higher animals act in the world using their external reality models to cope with the uncertain environment. Organisms that have not developed such information-processing organs may also have external reality models built in the form of their biochemical, physiological, and behavioral structures, acquired by natural selection through successful models constructed internally. Organisms subject to illusions would fail to survive in the material universe. How can organisms, or living systems in general, determine the external reality from within? This paper starts with a phenomenological model, in which the self constitutes a reality model developed through the mental processing of phenomena. Then, the *it-from-bit* concept is formalized using a simple mathematical model. For this formalization, my previous work on an algorithmic process is employed to constitute symbols referring to the external reality, called the inverse causality, with additional improvements to the previous work. Finally, as an extension of this model, the cognizers system model is employed to describe the self as one of many material entities in a world, each of which acts as a subject by responding to the surrounding entities. This model is used to propose a conceptual framework of information theory that can deal with both the qualitative (semantic) and quantitative aspects of the information involved in biological processes.

1. Introduction

Living systems have cognitive functions that help them cope with their uncertain environment and thereby survive. Through acting in the world and processing event data, the organisms of higher animals construct reality models for the environments with which they interact. Organisms that have not developed information-processing organs may also have external reality models built in the form of their biochemical, physiological, and behavioral structures, acquired by natural selection through successful models constructed internally. Organisms subject to illusions would fail to survive in the material universe. How can a subject, or a living system in general, understand the external reality through interaction from within?

In general, there are at least two different types of models in this context: (i) a world model for an external observer, which does not interact with the observer (called the external model) and is similar to an ordinary road map for a driver; and (ii) a model of the environment or external reality with which an observer interacts (called the internal model in the sense that it is constructed internally). This is a perception-behavior system embodied in the organism, by which it can act in specific ways to maintain a particular relationship with the environment within the world (Conant and Ashby, 1970; Friston, 2010). This is similar to a car navigation system guiding a driver toward a desirable destination by voice and visual instructions.

A classic work by Jakob von Uexküll is useful (1926) for understanding an internal model for an organism. Uexküll developed the concept of the function circle, which forms a subject-based environment, called Umwelt: “every animal is a subject, which, in virtue of the structure peculiar to it, *selects stimuli* from the general influences of the outer world, and to these it *responds in a certain way*. These responses, in their turn, consist of *certain effects on the outer world*, and these *again influence the stimuli*. In this way there arises a self-contained periodic cycle, which we may call the function-circle of the animal” (Uexküll, 1926; italicized for emphasis by Nakajima). In this function-circle process, the focal subject and external entities interact with one another in specific ways, depending on their own properties in relation to how to move or change state. Through this process, the subject experiences a particular set of events at particular probabilities. Umwelt and an

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ecological niche can both be defined as a set of environmental conditions required for survival and reproduction, containing the implication that these conditions are shaped by direct and indirect interactions between the environment and a subject organism—both concepts involves what is required from and the impact on the environment (for niche concept, see e.g., Hutchinson, 1957; Chase and Leibold, 2003). However, these are different concepts in that Umwelt is viewed from (experienced by) a subject organism, while niche is viewed from an external perspective or by an external observer (i.e., ecologist).

Although Uexküll did not develop a mathematical model for this process, and it does not extend to molecular systems and those of lower entities, this process illuminates a general aspect of the information process between a subject and environmental entities within the world, which is also applicable to various levels of nested hierarchical organization, such as cells and molecules (e.g., Koshland, 1973; Loewenstein, 1999). Biologists usually use the term "information" to describe processes in which patterns (or configurations, forms) are processed within a cell, intercellular processes in development, organism–environment interactions, and so on. However, the information concept in biology is yet to be theoretically unified with a mathematical formalism.

Shannon's mathematical theory of communication, usually called information theory, is widely recognized as a major mathematical theory that sheds light on a certain aspect of what we call information (Shannon and Weaver, 1949/1998). According to this theory, information is something that reduces the uncertainty (quantified as entropy) of an object (i.e., information source). As the authors themselves admit, the theory does not deal with the meaning of individual pieces of information, but instead, considers the amount of information as the degree of reduced uncertainty before and after receiving the information (a message). Despite its great importance in communication technology, there are several reasons why this theory has limitations in its application to biological processes. First, as previously stated, the theory cannot deal with semantic aspects of information. The reduction of uncertainty is important but is not the only necessity for living systems. They utilize goal-directed teleonomic properties to maintain *specific* relationships with others as a consequence of natural selection (Pittendrigh, 1958). Therefore, the semantics of information, which specifically relates the subject to the environment, is very important in biology. Second, this theory is not built upon an explicit causal model of entities interacting with one another. The theory may indeed have a material model such as an information source from which messages are sent from a transmitter, through a receiver, to a destination (noise may enter the path between the transmitter and receiver), but this is an abstract one-way symbol processing flow, with no explicit representations of causal interactions between component entities. In contrast, in biological systems, every material entity may serve as an information source, which interacts with others. Furthermore, the theory is based on the probability concepts of Bayesian probability and/or relative frequency, which both lack an explicit causal model of a material system. For example, $p(a|b)$ implies the probability of a under the condition that b occurs, but no causal mechanism is explicit in this formulation.

From a study of quantum physics, Wheeler (1989) proposed another type of information concept, called *it from bit*. In contrast to Shannon's model, which assumes that information sources exist out there, this concept does not assume the existence of real entities outside the subject. *It-from-bit* information is not a process from external reality to a subject, but a process (bit) used to construct external reality (*it*). This concept is important in focusing on the subject-dependent aspect of reality. However, like Shannon's theory, the *it-from-bit* concept appears to be descriptive and not explanatory for biological processes, and also lacks a semantic aspect of information. Therefore, we need to develop an information theory that can deal with both the qualitative (involving semantics and value) and quantitative aspects of the information involved in biological processes using a materialistic causal model.

This paper explores the information involved in living systems with the goal of developing a general framework of information theory to understand biological adaptation theoretically, beyond the limitation of verbal arguments in biology. We begin with information from the internal viewpoint, inspired by the philosophical concept of phenomenological reduction as a useful methodology, in which the external reality for the self is not supposed (but not denied) to exist out there (section 2). In this attempt, a simple mathematical model with an algorithmic process called inverse causality is introduced, focusing on the process used by the self to constitute symbols referring to the external reality or external objects from given phenomena. Using this model, it is shown that *it-from-bit* information can be formalized as a process based on the inverse causality (section 3). Then, information from the external viewpoint is considered, in which a focal subject receives information about external objects (section 4). In this analysis, a realistic world model is introduced, with additional assumptions to the first model, called the cognizers system model (Nakajima, 1999, 2013), in which material entities are described as the subjects of motion/action, interacting with one another within the world. Although this model has the external viewpoint of a meta-observer outside the world, it can also describe how a focal subject entity cognizes the environment and acts from an internal viewpoint. Here, the probability of events that a focal entity experiences (called the internal probability) is theorized in terms of the material properties of entities and their interactions (section 5). In this framework, information and its meaning are defined, and the uncertainty and order of the environment that a focal subject entity experiences in the environment during interaction are formalized, measured as internal entropy, which is based on the internal probability concept, rather than Bayesian probability. Finally, biological adaptations are analyzed in terms of the internal probability/entropy and the meaning of information (section 6).

2. Background: phenomenological view of reality as departure point

A realistic view presupposes the instinctive belief that objects that exist independently of the self cause percepts, which cause an inner, mental perception. In science, the subject gains information about the external reality by observation (i.e., a process from reality to phenomena). However, Descartes' skepticism uncovered distinctions between the existence of percepts (Cogito) and the existence of the objects to which the percepts refer. A percept such as "There is an apple on the table," is absolutely certain to the self because it is an immediate, indubitable experience. However, this fact does not guarantee that those things exist outside, independent of the self, despite its immediateness. That is, "this apple" would belong to the self, not to the outside realm. As revealed by skepticism, the semantic content cannot provide a secure base for proving the existence of such reality. Percepts in dreams do not reflect information about the external reality, raising a question: where is an "escape button" from solipsism (Rössler, 1993)?

This question concerns realization, which is a mental activity to constitute reality external to the self, based on phenomena or sense data occurring to the self (i.e., a process from phenomena to reality). Phenomena are generated from the reality by *observation* in the self, and the reality is constituted by *realization* in the self—"realization" is defined as the constitution of the reality external