World Academy of Science, Engineering and Technology
International Journal of Bioengineering and Life Sciences
Vol:17, No:1, 2023

Methodology for Quantifying the Meaning of Information in Biological Systems

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***Abstract*—**The advanced computational analysis of biological systems is becoming increasingly dependent upon an understanding of the information-theoretic structure of the materials, energy and interactive processes that comprise those systems. The stability and survival of these living systems is fundamentally contingent upon their ability to acquire and process the meaning of information concerning the physical state of its biological continuum (biocontinuum). The drive for adaptive system reconciliation of a divergence from steady state within this biocontinuum can be described by an information metric-based formulation of the process for actionable knowledge acquisition that incorporates the axiomatic inference of Kullback-Leibler information minimization driven by survival replicator dynamics. If the mathematical expression of this process is the Lagrangian integrand for any change within the biocontinuum then it can also be considered as an action functional for the living system. In the direct method of Lyapunov, such a summarizing mathematical formulation of global system behavior based on the driving forces of energy currents and constraints within the system can serve as a platform for the analysis of stability. As the system evolves in time in response to biocontinuum perturbations, the summarizing function then conveys information about its overall stability. This stability information portends survival and therefore has absolute existential meaning for the living system. The first derivative of the Lyapunov energy information function will have a negative trajectory toward a system steady state if the driving force is dissipating. By contrast, system instability leading to system dissolution will have a positive trajectory. The direction and magnitude of the vector for the trajectory then serves as a quantifiable signature of the meaning associated with the living system's stability information, homeostasis and survival potential.

***Keywords*—**Semiotic meaning, Shannon information, Lyapunov, living systems.

I. Introduction

A continuum is a continuous nonspatial whole or succession in which no portion of the whole is absolutely distinct from adjacent parts and denotes the seamless union of entities into an aggregate ensemble such as the framework that joins space and time into a single geometric structure. A continuum of information or "information space" is defined as a set of concepts and the relations between them that are contained in a unified system [1]. Because, this space contains a set of systematically interconnected pieces of the space as a whole it is considered coherent. Such a space also describes the range of possible values or meanings an entity can have under a given set of rules and conditions. The biological continuum (biocontinuum) of the living system is considered a coherent information space that includes everything that could have a potential sensory-experiential interaction and information exchanges with the biological system processes [1]. This biocontinuum space includes all possible energy, material and informational exchanges as well as communiques originating internally or external to the usual considered boundaries of the organism. As a continuum, there is a no absolute distinction between the living system and its adjacent environment since that realm includes everything internal and external to the organism. The stability and survival of living systems is fundamentally contingent upon its ability to acquire and process the meaning of information concerning the physical state of its biocontinuum.

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Shannon information is an excellent standard measure of information as classically characterized by having a source, a channel, and a receiver. However, it tells us nothing about what that information means [2], [3]. In his landmark work entitled "A Mathematical Theory of Communication", Shannon acknowledged that messages frequently have meaning if they are correlated with the attributes of the receiving system [4]. Shannon considered that the semantic aspects of communication were irrelevant to the engineering problem [3], [5]. Nevertheless, understanding living systems is more than just an engineering problem. Volkenstein was probably the first to note that the real value of information is determined by its significance to the recipient [6]. Bateson likewise defined information as "a difference which makes a difference" [7]. Therefore, meaningful information should be "about" something (the source) and have some significance to something (the recipient). Therefore, we can say that meaningful information for the living system is derived from a perceived pattern differential of matter and energy and their interactions in the biocontinuum that has a specific tangible value to affect the recipient beyond the simple perception. Technically translated this means:

1. That a causal event occurring within the biocontinuum has moved the state of the living system away from its prior steady state condition to make it differentiable.
2. That this newly ensuing state as a result of the causal event has meaningful significance to the living system.

Peirce suggests that an "interpretation" of the information by the recipient system is required to derive the meaningful significance [8]. Peirce further asserts that any meaningful interpretation of information should relate to some function of the living system [8]. McKay moreover ties the meaningfulness of the information to the interpretive capabilities of the recipient and its relative conditions of being [2]. MacKay also suggests that the meaning of any message should be defined in context to the recipient's states of conditional readiness for goal directed activity [2]. Stonier further contends that any determination of meaning necessitates that the system has a capacity to intentionally discriminate the circumstantial state information with the innate objective to functionally act upon the message [9]. In this sense, meaning is so much more than just simple associations in that it also implies an intentionality for directed action toward some specific objective [10]. The phrases 'mean to' and 'intend to' have the same inference in language and are a reflection of an understanding that something that has meaning also carries some directive for action. Meaningful information is then considered as an intentional relationship between its source and the recipient's interpretation concerning its significance rather than a unique property of the message alone. Juarrero proposes that meaning may be considered to be kinetic information that is translated into significance for an action that is of causal importance to the living system [10]. It is through the process of interpretation to meaning that information is translated into a significant action or adaptive response that reflects the causal importance of the information.

II. Methodology and Derivation

All information perceived by the living system is interpreted with regards to the degree of surprise and the significance for stability [1]. Just as the measurable degree of surprise (the difference) is dependent upon the inherent uncertainty of the observer, the significance of information (that makes a difference) is gauged by its impact on the recipient. The ability of the organism to differentiate and interpret sensory information is ultimately predicated upon a continued maintenance of the living system. Hence, the causal effect of that perceived information on stability and survival is the absolute standard by which meaning should be measured. A linkage between surprisal information and a system's steady state has been eloquently delineated in Friston's work in neurodynamics based on fundamental physical principles [11]. In the method proposed herein, a further connection of the Shannon formulation of information with its significance to the functional stability state of the recipient system allows for a determination of the quantitative physical meaning of this Shannon information as perceived by the living system.

Such a connection can be made for the individual organism using an extension of the approach of Harper and Baez in their analyses of evolutionary dynamics [12]-[14]. These investigators have considered the integration of the Kullback-Leibler information divergence metric (KLD) into a Fisher replicator dynamic to function as an inference engine for informing the evolution of population distributions [12]-[16]. The information metric differentiating capability of the KLD in combination with the mechanics of the replicator dynamics as guided by the fitness function for system stability has also been shown to establish the natural direction for the living system action dynamics [17]-[19].

$$I(q,p) = \sum_i^n ln\left(\frac{q_i}{p_i}\right) q_i = \sum_i^n [ln\,(q_i) - ln\,(q_i)]\, q_i \qquad \text{Potential Information}$$

and

$$\frac{d}{dt} I(q,p) = -\sum_i^n [f_i(P) - f(P)] q_i = \sum_i^n f_i(P)(p_i - q_i) \qquad \text{Kinetic Information}$$

Where:

I(p,q) is the information state

q is the target state with a fixed probability distribution

p is the time dependent probabilities of current state

$f_i(P)$ is the fitness of each type i in the population with fitness being a survival likelihood or probability characteristic in the context of the environment

Fig. 1 Equations describing the action functional for living systems with the properties of a Lyapunov stability function [1]

Through the integral summation of the Lagrangian integrand (defined as the difference between the kinetic and potential information – see Fig. 1) an action functional is formed that is naturally minimized by Kullback's Principle of Minimum Discrimination Information as an action principle within the trajectory of the living system's dynamics [1], [15], [20]-[22]. This formulation also provides for a Lyapunov function whose energy flow is tracked in the processing of information and powered by the constrained tensions in the nonequilibirum condition of the living system [1], [12], [13], [23], [24].

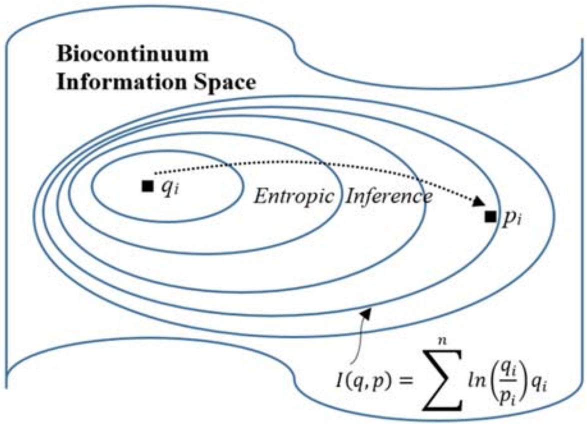

Fig. 2 The natural physical process for reconciliation of information divergences within the biocontinuum is grounded in the gradient flow formed by the entropic drive [1]

In 1892, Aleksandr Lyapunov published *The General Problem of Stability of Motion* describing techniques for the analysis of stability in dynamic nonlinear systems [23]. According to Lyapunov, a system is considered stable when outputs and internal signal variables are bounded or tend to a trajectory leading to a steady state. The basic concept behind Lyapunov's methodology is based on the fundamental physical intuition that the total driving energy within a system is continuously dissipated until the system settles to a steady state. Any such system can more generally analyzed from the perspective of global energy behavior as an action functional with energy currents (denoted as V) serving as the platform for the analysis of stability. As the system evolves in time, the summarizing functional values convey stability information about the system. This stability information portends survival and therefore has absolute existential meaning for the living system. The first derivative of the Lyapunov function (denoted as $\ddot{V}$) will have a negative trajectory if the driving force is dissipating and tends toward a system steady state $\ddot{V}(x(t)) < 0$ [1], [12], [13].

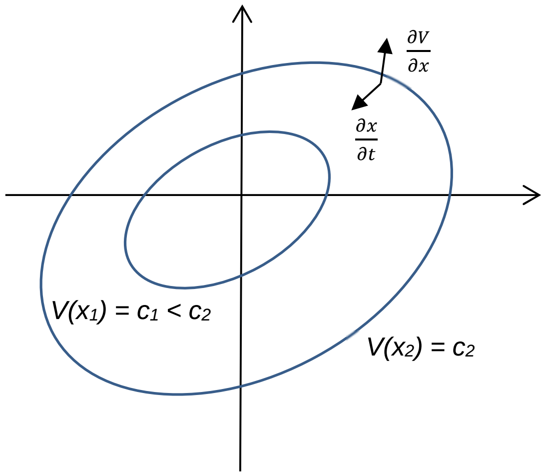

Fig. 3 Basin of attraction for Lyapunov system stability where an obtuse angle between $\frac{\partial V}{\partial x}$ and $\frac{\partial x}{\partial t}$ is dissipative

For any system, the potential energy within the system that drives change is described by some relationship V(x), where x is some state vector with some volume of phase space V. The vector of change $\frac{\partial x}{\partial t}$ is everywhere orthogonal to the normal $\frac{\partial V}{\partial x}$ at the level surface V(x) = c. The system is dissipative if the angle between $\frac{\partial x}{\partial t}$ and $\frac{\partial V}{\partial t}$ is obtuse. The state of the stable system then falls within the basin of attraction.

A quantifiable measurement of the meaning of information for living systems can then be achieved by analyzing the success to initiate an adaptive action for the objective of stability as triggered by perceived information in the biocontinuum [1], [17]. When this process is modeled by the action functional as described above, then the Lyapunov direct method can be used to identify the trajectory of the system with respect to its overall stability. The trajectory function as the first derivative of the action energy functional of the living system has both *direction* and *magnitude* of velocity that serves as a quantifiable signature of the meaning associated with the perceived information [1]. Moreover, it is meaningful because it quantitates the relative system stability in the Lyapunov sense. Systems with sustained stability are those that survive and function with a continued capacity to receive incoming information. Without the presence of such receiving system then the indeterminate information has no meaning. Therefore, the sustained survival of the living system becomes the absolute benchmark for the meaning of any perceived information. If meaning is quantitatively grounded in a definition for stability as the objective of the living system, then all perceived information is naturally imbued with meaning as it becomes actionable knowledge for guiding the living system's adaptive functions. Information that results in very little change in the dynamic trajectory of the system will be considered to carry minimal meaning regardless of its surprisal content. By contrast, signals that require significant adaptive action or result in a destabilizing trajectory will also have more meaning to the living system.

III. Conclusion

It is intuitive that the property of meaning is directly related to the goal objective for biologic systems to maintain stability and for their continued survival. In the study of living systems, it is common to consider the teleonomic purposeful activity for biologic functions such as the heart-beat [25]. The purpose of the heart-beat is to initiate a cardiac contraction that results in the pumping of blood, oxygen and nutrients to the body's cells [26]. However, this purpose should not be conflated with the global existential objective of the organism as evolved from the rote algorithmic logic of Natural Selection. Even algorithms have definitive end outcomes with meaning even if that result is not purposely prescribed. The goal-objective for this hemodynamic chain of activities is the survival of the organism. So, the meaning of the information signal of a heart-beat can readily be inferred to be connected with a significant inherent system objective related to the organism's stability and survival. Information in biologic systems that is translated to adaptive action is naturally instilled with a measure of the meaning of that action as it relates to homeostasis. By integrating surprisal information arising from the biocontinuum with the living system's natural energy driven actions for maintaining homeostasis, a Lyapunov functional can be derived for the quantitative analysis of stability. The trajectory vector of the first derivative of this Lyapunov function has both *direction* and *magnitude* that serves as a quantifiable physical signature of substantive meaning as derived from the actionable information perceived by the living system concerning the state of its biocontinuum environment [1].

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