Symmetry and Signs of Self-Organized Criticality in Living Organisms

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Abstract. Symmetry methods have been of crucial importance to physics. Group theory and conservation laws have become the fundamental language of symmetries, going all the way from the realm of quantum mechanical phenomena to general relativity. However, these ideas have had less impact in the biological domain. In this paper we present a view of self-organized biological systems as characterized by and evolving towards critical points, in the language of phase transitions as seen in physical systems. Self-similar (or scale invariant) behavior seems to signal homeostatic dynamical equilibrium in living organisms. Deviations of this homeostatic balance is associated with illness and elderly.

1. Introduction

Life is the best example of a complex system. Complexity comes from the Latin *complexus*, from the verb *complector* which means to weave, braid, twine, entwine together. There is as of yet no precise definition of a complex system [1, 2, 3], nor a single mathematical framework to describe it (even when some use the renormalization group [4]).

Nevertheless, there are many properties that seem to be common to complex systems, living organisms in particular: they have a large number of components that interact non-linearly, the interconnections usually follow hierarchical structures that exhibit self-organization, and their dynamics feature adaptability (resilience to perturbations), emergent behavior (collective dynamics that cannot be predicted from its components), and scale invariance (fractal structure which can be spatial and temporal, e.g. stochastic time series that exhibit long-range correlations) [5, 6].

The main reason that the strong theoretical framework of physics, grounded on well-defined mathematical laws, has not had the same success when dealing with complex systems is that in these systems (as is clear in biology) matter not only interacts, it self-organizes, and we do not yet understand the organization laws of nature, as Lehninger points out[7].

In this work we will briefly review the central ideas relevant in describing life as a complex system: symmetry and self-organized criticality. In the last section we show applications of these concepts to human health, mainly the search for biomarkers to be used as early warnings of illness.
2. Symmetry
Symmetry is a very well-established concept in science and mathematics. It can be defined as the set of operations that leave a particular system unchanged after they are applied. For instance, in the case of spatial systems these operations might be rotations, flips or translations [8]. Symmetry seems to be a universal property of the language of nature, being mathematically formalized by group theory [9, 10, 11, 12, 13].

Conservation laws, building blocks of many physical theories, can be seen to derive from symmetry and invariance. Some examples are:

- If all locations are equivalent, the system is invariant under spatial translational symmetry yielding linear momentum conservation [14].
- If all spatial directions are equivalent, the system is invariant under spatial rotational symmetry leading to angular momentum conservation [15].
- If all times are equivalent, the system is invariant under temporal translational symmetry producing energy conservation [14].
- If all space-time points are equivalent, the system is invariant under Lorentz transformations generating invariance of the equations of motion that can be mathematically described by continuous Lie groups [10].
- If all particles are identical (bosons or fermions), the system is invariant under permutation symmetry [16].
- If particles are organized into a structure (like atoms in a molecule), the arrangement can invariant under certain geometric symmetry as described mathematically by the framework of point groups [12].
- Internal symmetries are associated with quantum numbers (spin, isospin, up, down, strange, etc.) [17].
- Dynamical symmetry is linked with the conservation of the interaction between constituent particles and/or external fields that describe the spectral properties of quantum systems [10].
- Gauge symmetry leads to the conservation of the interaction between particles and external fields [18].
- Scale invariance also known as self-similarity reflects the symmetry of structure, associated with fractals, common in living beings [19].

2.1. Symmetry on Living Organisms
Living systems have adopted fractal-like structures in many ways. For example, as a by-product of natural aggregation rules of cellular structures (see Lindenmayer’s L-system [20]) the growth patterns of many plants is fractal, yielding from simple rules leaf shapes that are efficient for photosynthesis, and the fractal branching of mammal lungs dramatically increases the available surface for gas exchange.

3. Criticality
A critical point is a state in which two phases of a system coexist, a dynamical region in which a second-order phase transition occurs [21].

The dynamics of a system as it approaches a critical point can be investigated with the Ising model. Consider a lattice of spin sites, each having two possible orientations: up (+1) or down (-1). The dynamics of the spin sites orientations are determined by two competing mechanisms: on the one hand, sites tend to align with their neighbors; on the other hand, thermal fluctuations tend to randomize the orientations. The global magnetization M, defined as the average of the
sites’ orientations, is a function of a single parameter, the temperature $T$, which determines the balance between the tendency for alignment and random fluctuations. The Ising model exhibits a phase transition at a specific critical temperature $T_c$, as has been studied extensively both analytically and through numerical simulations of the lattice [22]. At the critical point, the spin lattice structure becomes fractal (spatially scale invariant), with “islands” of same-orientation spin sites of all sizes (the size distribution being a power-law) forming and disappearing over time [23].

In the time domain, the critical point is seen as a sharp (almost discontinuous) transition. As the system approaches criticality, the statistical moments of the time series are radically altered, with the variance diverging and the higher-order moments moving away from the values for a Gaussian distribution [24]. Spectral analysis shows that the system also becomes temporally scale-invariant, as shown by its power spectrum becoming a power law [24]. If complexity is measured in terms of Shannon’s entropy, at a critical point the complexity of the system is also maximized [25, 26].

Scale invariance characterizes the critical point. And proximity to the critical point can be assessed by measuring changes in the early-warning signals of the system: the statistical moments of the time series, its autocorrelation function (specially the lag-1 autocorrelation), the establishment of a power-law in the power spectral density, and the increase of the complexity of the system.

3.1. Self-Organized Criticality in Living Organism

Life is characterized by a homeostatic balance between robustness, the capacity to maintain homeostasis, and its adaptability, the capacity to rapidly and effectively change in the face of a changing external environment [27]. To achieve this balance life has structured around organizational and dynamical structures that are neither too rigid nor too volatile: “life is the phenomenon that lies between order and chaos” as Kauffman pointed out [28].

From proteins to neurons to flocks of birds, living systems have evolved to exist in configurations that dynamically balance these two needs; poised near a critical threshold or tipping point [29], because in this regime information transmission and processing is optimized and maximum complexity achieved.

In the case of bird flocks, for instance, both theoretical models and analysis of real data have shown that the velocity fluctuations of the birds and their correlation function are scale-invariant, which is a hallmark of criticality [30]. This in turn translates into a quick and efficient response to external perturbations, letting the flock better react to predators.

Computational models show that evolution naturally drives systems to Self-Organized Critical regions. For example, in gene regulatory networks, natural selection based evolution of random Boolean networks, taking into account the interplay between these two needs, naturally drives the networks in a population towards criticality [31].

Moreover, it has been proposed that the brain resides in a state of criticality [32, 33, 34]. The size distribution of neuronal avalanches in cortical networks are scale-invariant [35], the degree distribution of networks obtained from brain FMRI data matches that obtained from the Ising model at the critical temperature [36], and the inter-spike intervals of the spontaneous neuronal firing can be used as a signature of criticality [37].

4. Human health

The homeostatic balance between robustness and adaptability has also been found in studies of human health, where scale invariance and high complexity are detected in various physiological time-series. Fig. 1 shows data from various signals taken simultaneously from a young healthy man (22 years old, with 21 kg/m² of body mass index): heart rate (as measured through the RR intervals in an electrocardiogram), breathing cycle waveform, and blood pressure
Figure 1. Physiological time series of a 22 years old, healthy man, standing up: RR intervals of the electrocardiogram (left), BB intervals of the breathing cycle (middle), and systolic blood pressure SBP (right). From top to bottom, the rows are: 5 minute time series, histograms (continuous line are Gaussian distribution), Poincaré plots, and power spectral density (PSD) in log-log plot (vertical line corresponds to 0.15 Hz, the boundary between low (LF) and high frequency (HF) regions; minimum least square line is also plotted, and the inset shows the proportion between LF and HF).
Cardiac, respiratory and vascular signals are complex, asymmetric (far from being Gaussian distributed), correlated (ellipses on Poincaré plots), and scale invariant as revealed by the power spectral density. All these are signs of the criticality of these physiological variables.

Study of heart rate variability has revealed that for young, healthy individuals, the intervals between heart beats exhibit scale-invariant random fluctuations [39, 40]. The loss of homeostatic control capacity as individuals age drives the heartbeat dynamics to shift towards rigidity [40]; for homeless subject (living on extreme conditions), the dynamics becomes more random [41]. The idea that health can be characterized by criticality has opened the possibility to obtain useful biomarkers from non-invasive physiological measurements through analysis techniques that specifically look for the properties of criticality [39]. These new biomarkers could function as cheap and easily obtainable early warnings, auxiliary to traditional clinical diagnosis of different diseases. This has been shown to be workable in particular when applied to Type 2 Diabetes Mellitus [42, 43].

5. Conclusion
Living beings are in a homeostatic state with non-symmetric parameters that are far from those of a Gaussian distribution, with many signals exhibiting scale invariance and high complexity. Criticality appears to be a natural emergent property of naturally evolving systems, one that engenders dynamical robustness while at the same time allowing the system to adapt effectively to a changing environment. Illness, age or living under extreme conditions negatively impacts the capacity for this dynamical balance, and this can be measured through the analysis of physiological time series.

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