Opinion

Facts, opinion and conjectures on *non-linearity* and *intelligence*

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The complex nonlinear world – the whole is more than the sum of its parts

Our complex world, constituted by complex systems of all categories (people included), is also plagued by a *complex terminology:* random, stochastic, turbulence, chaotic, criticality, nonlinear dynamics, self-organization, fractals, power-laws, etc. Quite frequently, two or more of these terms are employed as synonyms, even in the specialized literature. This "jungle of terms" converges to only two fundamental statistical concepts: extensivity and nonextensivity, which are two different signatures of *non-linearity*. The last two decades witnessed a *boom* in what is now called *nonlinear science* which, in the usual sense, is not a new branch of science but encompasses all the existing disciplines in science. This represents a breakthrough, since we were provided with a formidable tool to treat any complex system: from molecules of a gas to galaxies conglomerates. A system is nonlinear if the output from the system, $y(x)$, is not linearly proportional to the input x; in this case, y is related to x by a power-law, namely, $y(x)=\beta x\alpha$ (1) where α and β are constants. When $\alpha=1$, linear proportionality is attained. Moreover, a nonlinear system could be *extensive ($\alpha=2$)* or *nonextensive ($1<\alpha<2$)* and these two statistical regimes are established by the *short- and long- range* character of the interactions among the constituents of the system, respectively. *Long-range interactions* among elements of biological systems, straightforwardly thus explain the observation of power-law like behavior for many of their biological responses. Interestingly, power-law and fractal structure are at the heart of self-organization and self-similarity of living organisms. Nearly all fractal structures could emerge through a self-organized criticality, and the distinctive signature of such fractal structures are the power laws. In a system constituted of elements interacting by means of *short-range forces*, each of these elements interacts only with the elements of the system in its close vicinity. This is known as a *simple random walk*, and the most notorious example in this category is the *Brownian motion*: a continuous random movement of microscopic solid particles when suspended in a fluid *milieu* Because of the short-range character of the interaction, each particle undergoes random jumps to one of its nearest–neighbor sites, and the jumping lengths are small. The process is described by the conventional *extensive statistics* (as e.g. normal distribution statistics). The signature of a nonlinear system is the breakdown of the superposition principle, which states that the sum of two solutions of the equation describing the system is again a solution. But, if the system is nonextensively nonlinear, the physical consequence imposed by long-range correlations is that the behavior of *the whole is more than the sum of its parts*.[1–4]

It is worth making salient what the non-extensive statistics (as in the grounds of the *Tsallis statistics*), here discussed, added to our understanding of ancient concepts as pure chance, randomness, indeterminism and chaos.[5,6] Actually, pure chance and determinism were discussed by Aristotle, Lucretius, and Aquinas, but were relegated to illusion and ignorance in modern times. Yet when they

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"If the Higgs boson is God's particle, nonlinearity is God's aesthetic sense"
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reappeared in contemporary Physics, they found the way already prepared, becoming thus theoretically tractable.

Non-linearity and intelligence

A frequent and intriguing question one poses is: how intelligence emerges from the co-operative action of a large number of simple and non-intelligent agents? It is reasonably known nowadays that the human brain is a complex nonlinear feedback system, containing billions of neurons. In this case, the interaction between two nearby neurons is a short-range process, which is responsible for the level of the brain randomness. Although we know that certain regions of the brain perform certain functions, activity in one area can trigger more neuronal responses throughout a large region. This is the first fair evidence for the existence of long-range interactions, which is corroborated by experiments showing that the brain has strange attractors. Plots of electroencephalogram activity in the brain show one particular type of strange attractor when a person is at rest, but quite another attractor when the same person is solving a physical problem. Therefore, we can argue that the long-range component of the interactions among the 10 billion neurons give rise to the formation of patterns, which follow a strange attractor. It is very appealing, then, to associate the strange attractor with the phenomenon known as personality. We note that a healthy brain maintains a low level of randomness, which often self-organizes into orderly patterns when presented with a familiar stimulus - this is nonextensivity!

A statistically non-extensive brain, although unpredictable in the sense of a chaotic system, should exhibit repetitive patterns as those in other complex systems. From this, it is inferred that we can never truly predict how people will behave, but the identification of long-term behaviour patterns could be realised. It is a truism that a non-extensive statistics describes our complex world, from the intricate interplay of neurons to the explosion of a supernova. However, at the micro scale of the neurons prevails the statistics of the Quantum Physics, where the quantum concepts of *coherence* and *indeterminism* play a key role, by providing us with a deeper insight into the long-range aspects of consciousness and intelligence.[7] It has been argued

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that *quantum coherence* is the basis of conscious experience, which involves the possibilities of *nonlocal* intercommunication between distant parts of the brain, and the simultaneous recognition of whole and part in our perceptive field. *Nonlocality* refers to the transfer of information or interaction without local signals; the interactions are of the kind action-at-distance and instantaneous. Under the quantum framework, we observe that attempts to simulate human behaviour with computers are so far merely science fiction. As pointed out by the Nobel laureate in Physics Richard Feynman, any computer wouldn't succeed simulating nonlocality. Albert Einstein, in 1935, referred to this nonlocal potential as a "spooky action at a distance". Since then, however, all the counter-intuitive predictions of quantum mechanics have been experimentally verified and nonlocality is nowadays recognized as the most characteristic feature of the so-called "non-trivial" quantum mechanics. In order to shed much more light on the possible role quantum physics may play in the cognitive process of life, in particular memory encoding, storage and retrieval, reference 5 is strongly recommended. In fact, to a traditional mind, quantum theory is perplexing. Such curious and intriguing features as correlation between separate and distant events, looking almost like telepathy in nature, do not match non-specialists common sense, although quantum effects are *asymptotically* around us, like chaos itself. Results from several theoretical works seem to confirm that it is reasonable and useful to consider chaos as an amplifying mechanism, at macroscopic levels, of the indeterminism inherent to quantum mechanics.

Final remarks – n*on-linearity* and the new statistics

As discussed above, occurrence of power-law like behavior points to the existence of long-range interactions among elements of a system. Thus, self-organization and self-similarity could be exhibited by these elements.[8,9] In fact, an initially homogeneous collection of interacting particles can disperse, aggregate and form clusters, as frequently observed in many different physical, biological, and sociological contexts. When the interactions are of long-range character, the formation of swarms, schools, herds, or even the flocking of birds, provide compelling zoological illustrations. In a socioeconomic context, on the other hand, stock markets provide a rich variety of extreme dynamical phenomena, where market crashes are among the most dramatic occurrences.[10] These examples show that *nonextensivity* improves biological systems as a whole. So,

being nonlinear is good. It underlies the biological diversity and complexity; life itself. In physics research, nonlinearity is e.g. vital to the operation of a laser, the formation of turbulence in a fluid, and the superconductivity of Josephson junctions.

Biology could greatly benefit from the newly developed statistical physics concepts, in order to gradually move into a new era that focuses less on specific microorganisms and more on the processes and mechanisms that link them.

Acknowledgements

Conflict of interest

The author declares no conflict of interest.

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