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ENCOUNTERING COMPLEXITY: IN NEED FOR A SELF-REFLECTING (PRE)EPISTEMOLOGY

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ABSTRACT:

We have recently started to understand that fundamental aspects of complex systems such as emergence, the measurement problem, inherent uncertainty, complex causality in connection with unpredictable determinism, time-irreversibility and non-locality all highlight the observer's participatory role in determining their workings. In addition, the principle of 'limited universality' in complex systems, which prompts us to search for the appropriate 'level of description in which unification and universality can be expected', looks like a version of Bohr's 'complementarity principle'. It is more or less certain that the different levels of description possible of a complex whole -- actually partial objectifications -- are projected on to and even redefine its constituent parts. Thus it is interesting that these fundamental complexity issues don't just bear a formal resemblance to, but reveal a profound connection with, quantum mechanics. Indeed, they point to a common origin on a deeper level of description.

Keywords: *Selforganization, Complexity, Objectification, Pre-Epistemology*

"Mais quand une règle est fort composée,
ce qui luy est conforme, passe pour irrégulier"

(But when a rule is extremely complex,
that which conforms to it passes for random)
Leibniz, Discours de M´etaphysique, VI, 1686

1 Introduction

The main thesis of this presentation is that Complex Systems lend themselves to many distinct levels of descriptions. Some are dynamical, structural, geometrical or topological, metric or probabilistic. Others represent a hybridisation of the above. Moreover, especially for living complex systems, any observation will necessarily be partial and always dependant on the observer's choices. This will be due to incompressible initial conditions and/or approximate parameter estimations. It becomes evident that no single set of known mathematical or other formalisms can yield a description of a complex whole that is both complete and consistent.

It means that a new double-edged approach is called for. On the one hand, we need a concerted approach which will synthesize and unify all relevant elements at different levels, by using different tools and descriptions. On the other hand, we need to discriminate between two things. The first is the several given aspects of the facts under scrutiny. The second is how these facts were acquired based on the specifics of sets of objects and relations which led to their conceptualisation in the first place.

We are fast approaching the point where we need to concern our selves not only with the study of nature, but with the nature of that study.

Being aware of the limitations of our descriptions we can describe the limitations of our awareness. That, as a consequence, will outline the search for a 'Science towards the Limits', as William James called it. It will consist of a scientific endeavour capable of reflecting not only on its own abstractions (a discourse that *epistemology* already provides), but on its fundamental objectifications (a discourse that goes one step deeper into what can only be described as a *'pre-epistemology'*).

2 What is Complexity that We Should Be Mindful of ?

Looking into Webster's dictionary the word 'complexity' is defined as 'the quality or state of being complex'. Furthermore under 'complex' we read:

> *Main Entry: (1)* ***complex****, Function: noun, Etymology:*
> *Late Latin complexus totality, from Latin, embrace, from complecti,*
> *Date: 1643, (1) : a whole made up of complicated or interrelated parts.*

Self-referential as this definition may seem, it places the emphasis on 'whole' and 'interrelated parts'. We have come to realise that something complicated is not necessarily complex, although a complex system can be complicated. The terms 'whole' and 'interrelated parts' emerge as fundamental notions on which the *nonlinear* relations among constituent parts rely and are identified. This has been the case mainly in the physical sciences. But it is not necessarily restricted to these alone. Indeed, the connection between complexity studies and nonlinear science allows us to bridge the divide between subjective and objective narration in fields as diverse as physics, chemistry, biology, cognitive and consciousness studies – not to neglect sociology and economics.

In complex system studies one is confronted with nonlinear relations which usually give rise to a great number of states. In most cases this signifies many levels of ongoing processes of a different temporal and spatial scale. Complexity manifests through the presence of multi-stationarity and/or chaotic regimes of motion.

All these states unavoidably lead to the breaking of symmetries both in the spatial (pattern formation) and the temporal (irreversibility) domain. It is now well understood that the above emergent patterns and rhythms are due to 'nonlocal' effects in a dual sense. The first is that the correlation lengths of the emerging patterns and rhythms are many orders of magnitude larger than the correlation lengths of their constituent parts. The second sense expresses itself through the concomitant limited horizon of predictability arising from sensitive dependence on initial conditions and parameters -- which is the sine qua non of chaotic motion.

Of course complexity of form and structure is not a new or strange concept in the field of scientific investigations. Intricate patterns and forms -- structures with great beauty and delicate design -- have captured the attention and admiration of scientific thinking since the dawn of time. A classic reference remains D'Arcy's 'On Growth and Form' [1]. Recently, the studies of structural complexity in relation to information processes, from physico-chemical and biological systems to man-made networks such as electricity's power-grid, the 'World Wide Web' and the internet, various social groups, etc., have made an impact on the scientific literature and created lively discussions (see, for example, [2, 3] for an introduction, specialized references can also be found therein).

Nevertheless, in addition to the structural aspects of complexity, its dynamical aspect has been the object of path-breaking research since the sixties. Owing to the early, seminal, contributions of Hermann Haken, Ilya Prigogine, Brian Goodwin, their co-workers and many others, the role of nonlinear relations and fluctuations to self-organization, synergetics, pattern formation, irreversibility and, in general, to what now tends to be called `emergence' has been amply elucidated. For an overview of their work, one might consult [4, 5, 6].

These pioneering contributions go well beyond qualitative descriptions, analogies and metaphors. They address fundamental issues such as the interplay of structure, function and fluctuations; they invoke a non-classical -- sometimes circular -- causality (since the parts collectively determine the macroscopic order parameters and the macroscopic order parameters determine the behaviour of the parts' collectivity) and they offer a new apprehension of the fact that determinism does not necessarily imply predictability (a corollary due to sensitive dependence on initial conditions *and* parameters).

Through the analytical tools of theoretical physics and mathematics, unexpected relations between topological and geometrical aspects (*structure)*, dynamical laws (*functions*) and stochastic processes (*fluctuations*) were discovered in the heart of complex systems.

3 The Complex and the Quantum: Classical Objects Misbehaving

A curious thing about Complexity – often hailed as 'the third revolution of physics' -- is that it did not occur as a paradigm shift over unaccommodated data and unexplained facts. Definitely it is not the brainchild of a single investigator, like Relativity, and has not been followed by explosions threatening mankind, like Quantum Mechanics. Although its technological and conceptual advances are being harvested by the widest known array of disciplines in science, it constitutes a community of ideas and workers with a quite well defined area of studies and a fertile laboratory of new concepts. Both these are characterized by an explicit interdisciplinarity and an intrinsic multitude of approaches.

Probably it was the spectacular and rapid advance of Quantum Mechanics and Relativity that attracted attention away from the developments of nonlinear science in the turn of the previous century. Indeed, it is commonly believed that classical determinism had to be revised after the advent of the uncertainty principle and the ever present, fundamental in nature, 'quantum leaps'. But this statement, although commonly accepted, is far from right. As John C. Sommerer put it in [7]:

To cast the situation as a mystery, classical determinism was widely believed to have been murdered (maybe even tortured to death) by quantum mechanics. However, determinism was actually dead already, having been diagnosed with a terminal disease 10 years earlier by Having participated in a very late autopsy, I would like to describe some of the findings.

What Poincare diagnosed was that classical systems with a given degree of complexity, due to the nonlinear interactions present among their parts, give rise to very complicated motion. Today we have arrived at calling this kind of motion -- which he first encountered -- `chaotic'. In the case of Poincaré the system at hand was the celebrated `three body problem' within the setting of classical Newtonian gravity. Poincaré's investigations inspired another famous mathematician of those days, Hadamard, to study a more general setting for this phenomenon.

Hadamard probably was the first to articulate what we now call `sensitive dependence on initial conditions' or `the butterfly effect' -- that hallmark of chaos. Indeed, it was in the year 1898, almost twenty years before the dawn of quantum mechanics, that Jacques Hadamard published his work on the motion of particles in surfaces with negative curvature. He showed that this motion is everywhere unstable [8].

Specifically, Hadamard utilized a simple description of all the possible sequences, induced by the motion on the geodesics of surfaces with negative curvature. His idea was to project this motion onto partitions upon the surfaces in the regions and examine all possible trajectories of the visiting particle. By constructing a finite set of forbidden pairs of 'symbols' associated with each region of the partitioned surface, he subsequently showed that the possible sequences are exactly the ones which do not contain the forbidden pairs. Actually he was the first to introduce the new and powerful tool we now call 'symbolic dynamics' into the fundamental notions of discrete probability and what was later identified as *information theory.*

Although quite mathematical for the physicists of his time, this work proved to be rather fertile. It was later taken up by Birkoff and von Neumann in their work on the ergodic hypothesis, published in the early 1910's. Further decisive progress came again through Poincaré. He was concerned with the instability and integrability problems of dynamical systems. As a famous mathematician and philosopher of his time, Poincaré increased his fame even more by winning the prize of 2500 kroner put forth by King Oscar II of Sweden and Norway.

This contest consisted of several questions, one of them formulated by Weierstrass and concerning 'our understanding of the solar system': Three bodies, the Sun, Moon and Earth, attract each other thanks to Newton's gravitation law. Could a solution be found in a closed form, or just a form, manifesting in a converging series? Poincaré won, although his celebrated result is a negative one: he managed to show that this particular motion does not have any conserved quantity and thus is non-integrable[(a)]. Poincaré's work opened up an area of research that enabled us to deepen our understanding of the solar system – exactly as that competition demanded. It also enabled us to deal with a wide class of systems with unstable motions. Poincaré based his approach on geometry and provided us with a wealth of techniques and concepts which are widely used today in chaotic dynamics. He is thus considered as the founding father of the theory of Nonlinear Dynamical Systems.

The work of Birkoff, Poincaré and others was almost equalled by Lyapunov and his celebrated 'Russian School' in dynamical systems. Later on, Adronov, in his work on nonlinear oscillators, formalized and

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(a) *Actually what Poincaré showed is that the Bernoulli technique of finding a conserved quantity cannot yield any conserved quantity reducible to the momenta and positions of the bodies. Curiously enough, a Finnish mathematician named Sundman was later able to find a series of the type Weierstrass had asked for. But Sundman's technique, though constructive, is useless for any calculation. So it remains undeservingly forgotten.*

deepened the understanding of the particular class of planar dynamical systems and prepared the ground for the interpretation of the experimental results of Lord Rayleight III, laid out in his famous treatise `Theory of Sound', as well as those of van der Pol and Duffing on forced oscillators with friction. These latter works were later taken up by Lady Mary Lucy Cartwright and J.E. Littlewood. While Adronov was `leading his group' in Russia, in the other parts of Europe this area of study was almost halted. The theory of Relativity and Quantum Mechanics were attracting almost all the attention.

Yet, although the1910-1950 period was generally stagnant in the area of nonlinear dynamics, even so some work paved the way to a renaissance in the field during the mid sixties. In a series of papers starting from 1921, Marston Morse presented a scheme for the enumeration of orbits in the class of systems considered by Hadamard. This body of work motivated the studies of Artin, Heldund and Hopf, which finally proved that motion of a ball on a surface of constant negative curvature was ergodic. One of the first physicists to realize the importance of these results was Krylov. He argued that a physical billiard ball is a system with negative curvature along the lines of collision. Later, Sinai showed that a physical billiard ball can be ergodic (the well studied `Sinai billiards').

After more than a century of development, today, we come to appreciate a 'billiard' -- or a pinball, in modern terms -- as a typical example of a chaotic system [9]. Figure 1 illustrates the complexity of such a seemingly simple system. In describing the sequence of the trajectory of a test-particle visiting each disk here, complexity enters through the nonlinear relationship (the curved surfaces of disks) that develops among its parts (the disks). It is this aspect that renders the dynamics of such a system chaotic. If the reflecting surfaces were flat (i.e. rectangular boxes instead of disks) the system would be complicated but not complex -- the parts would uniquely define the whole as their linear superposition. Not so in complex systems. There the whole is more than its parts because of the intricate, non-linear, interrelations between parts and whole. Thus emerging properties are attributed to such systems.

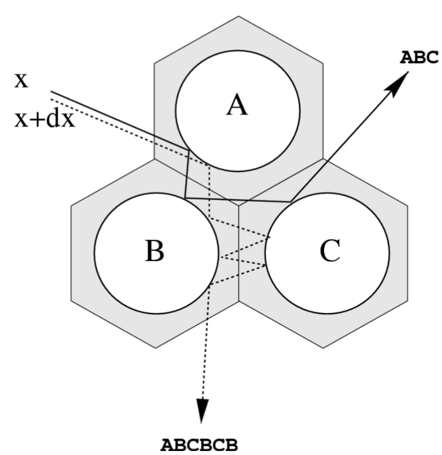

Figure 1. *Motion of a test particle in `pinball' serves as a simple, representative and very descriptive model for chaotic/complex systems. Complexity gives rise to chaos on account of the strong nonlinear relations among its parts.*

4 The Fallen Doctrine of Classical Determinism

The connection between deterministic causality and the stability so typical of classical systems did not escape, in those early days, the penetrating genius of James Clark Maxwell. Reflecting on the roots of causality, he wrote (quoted in [10]):

It is a metaphysical doctrine that from the same antecedents follow the same consequents. No one can gainsay this. …It is not of much use in a world like this, in which the same antecedents never again concur, and nothing ever happens twice. . .The physical axiom which has a somewhat similar aspect [with this doctrine] is `that from like antecedents follow like consequents.

Chaos and complexity studies have shown that the classical belief in determinism as a reliable source of prediction, represents no more than a fantasy. This fantasy stems from the Newtonian/Laplacian paradigm. As a matter of fact, it embodies something more than even a fantasy. It embodies a persistent fallacy in scientific and philosophical thought, which has lasted for over three hundred years. Laplace's all-knowing daemon, the god of reductionism, is symbolized in one of Laplace's most famous proclamations in the following manner:

. . . if we can imagine a consciousness great enough to know the exact locations and velocities of all the objects in the universe at the present instant, as well as all forces, then there could be no secrets for this consciousness. It could calculate anything about past or future from the laws of cause and effect.

A relevant discussion about the Newtonian/Laplacian doctrine and modern developments of chaos theory can be found in [11], (pp. 9-14). This prevailed as a paradigmatic bias which was overthrown only by Werner Heisenberg's uncertainty principle. What is of interest here regarding this principle is that on a different level, it speaks of complex systems as well. So let us follow Heisenberg's line of thinking. He states that [11]:

In the strict formulation of causality -- `When we know the present precisely, we can calculate the future' -- it is not the final clause, but rather the premise, that is false. We cannot know the present in all its deterministic details. Therefore, all perception is a selection from an abundance of possibilities and a limitation of future possibilities.

This is true for quantum mechanics on account of ontologically probabilistic nature. But is it not also true of complex, or chaotic, dynamics? Even if we think of them as ontologically deterministic, could we ever hope to know in perfect detail their precise initial conditions? If we ascribe to the fact that initial conditions are represented by the continuum of real numbers, can we pin down with infinite precision real numbers since almost all of them are irrational, calling for an infinite amount of information?

For the mind of the Laplacian god of reductionistic mechanics, that would be definitely true. However in any act of projection, such as measuring or specifying the initial conditions that we poor humans need to work with, we necessarily lose all absolute certainty, ending up with probabilities. We must stress, once again, that the above is unavoidable even if the laws are deterministic and our theories stipulating these laws turn out impeccable.

Definitely the vivid discussions over causality, determinism and Quantum Mechanics -- and Relativity, to some extent – dealt with what chaos and complexity studies were whispering until the sixties and seventies. With the appearance of fractals, self-organization, emergent pattern-forming systems and the realization that seemingly simple, deterministic yet non-linear, dynamical systems (which are, by the way, fully transparent to rigorous mathematical investigations) give rise to chaos, we now have entered a new frontier in science.

We have chosen the line of historical developments in this field because it is less known than the recent rediscovery of chaos and complexity. Even so, our presentation is not geared to giving historical details. It merely hopes to help reveal some aspects of the complexity field that are instructive of the kind of issues and ideas that underly the new way of thinking.

The lessons we are learning from this new era are numerous and still continuing. One that we shall focus on is that we must be fully aware of what kind of objects we are dealing with. The multitude of available states of complex systems and their inter-relations make possible different levels of description of a complex whole. These levels of descriptions – i.e. our own partial objectifications of the whole -- are projected on to and even redefine its constituent parts.

5 Probabilistic Conceptions of Chaos and Complexity

Prediction is difficult, especially for the future
Niels Bohr

Let us see now, in very general terms, what deterministic, nonlinear dynamical systems can tell us about the distinction between determinism and predictability; how it influences causality; and how this influence gives rise to a probabilistic approach to complex systems that resembles, in certain aspects, the Schr¨odinger understanding of quantum mechanics.

A common, yet historically important, example of such a system is what has come to be known as 'the logistic map.' A time-discrete dynamical system, which can be found in any standard textbook on nonlinear science (for a detailed account see [11]; for an introduction into its probabilistic approach, see [5, 9],) describes a wide array of diverse phenomena in population biology, electrical circuits, birth-and-death processes, even lasers and information processing.

This system is one-dimensional, but it is characterized by a state variable, say x, which takes continuous values within an interval, say [0, 1], and is updated in a discrete fashion at each discrete time step, t. Updating follows the simple deterministic rule $x(t + 1) = \mu x(t)(1 - x(t))$, where μ is a real-valued parameter. By changing its parameter, we observe a tremendous repertoire of qualitatively different dynamical behaviours: from stable periodic to quasi-periodic and finally to chaotic. For $\mu = 4$ we are in the region of what is called 'fully developed chaos' with its sine-qua-non sensitive dependence on initial conditions. A typical trajectory, the motion from a single starting point to its iterates, would then look as if random.

The left-hand side of Figure 2 shows exactly how this evolution takes place. The 'erratic' motion cannot be repeated, as a whole, by any other starting point no matter how close they are. It is nevertheless fully determined in 'theory', although not determinable in practice due to the fundamental inability to explicitly describe any typical initial condition (i.e. an irrational number) in full accuracy. Moving from this point-like 'topological' description of trajectories to a probabilistic treatment, we come upon a different picture. If we specify as observables not each point but the statistics of each typical trajectory, we observe that they all have the same histogram. Each erratic trajectory now produces the same statistical distribution over very large time intervals (infinite in the theoretical treatment, sufficiently large in practice). They all visit the available phase-space according to the so-called invariant measure of the iteration rule (or `mapping'), as depicted in the middle of Figure 2.

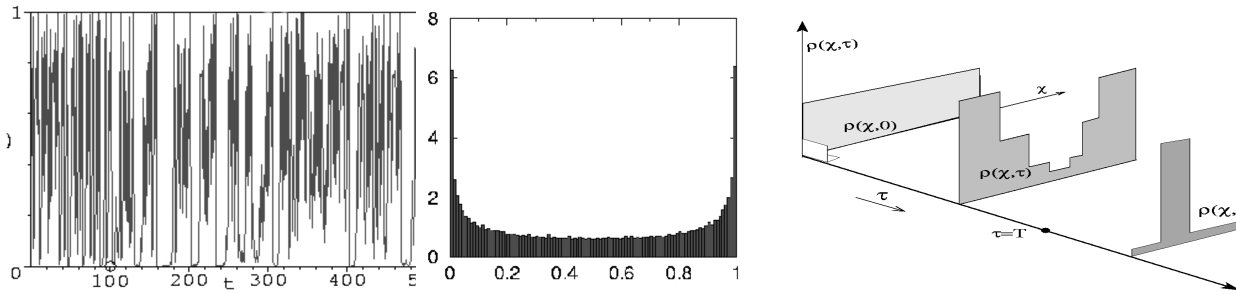

Figure 2. *A typical trajectory, i.e. a point-like description, of a chaotic system (on the left) is unstable and erratic. A statistical treatment (i.e. its probability density in the center) reveals that ensembles of trajectories, i.e. a probabilistic description, follow a stable evolution (on the right).*

To complete this probabilistic description, one starts all over again – with the difference that right from the beginning one doesn't consider single points, but an ensemble of them. (Technically this is due to our system being ergodic).

The above ensemble now acquires a totally new meaning and interpretation. It signifies the probability of being able to start from any point – i.e. or the initial density of the state. This, or any other, (smooth) probability density will eventually take a predictable, stable route towards an invariant probability density after a sufficiently long time. It is sketched on the right-hand side of Figure 2, for an initial ensemble with equiprobable starting points.

The above two different, yet connected, pictures are based on different assumptions of what constitutes an observable fact in each setting. Their evolution operators are simply different. On the one hand we have a point-like evolution operator and its erratic, unstable, unpredictable, outcome. On the other hand we have an operator which evolves entire ensembles -- with a concomitant smooth, stable and predictable evolution. We have gained predictability for the collective, but lost the ability to ascertain the fate of the individual; we have lost the certainty of each sharp outcome, but gained accurate prediction of the probabilities of repeated outcomes.

6 A Glance at Irreversibility

In the above picture, in which the probability densities evolve[(b)] deterministically and all initial probabilities tend to the invariant probability density, we can say that the system looses `memory' of its initial conditions in the course of its evolution. Thus this type of evolution is characterized as irreversible. Moving from the future to the past we do not really know where we started or why. All initial settings seem equally plausible.

This represents a kind of chaotic system which manifests basic aspects of the '*irreversibility problem*' – i.e. the demand for a consistent description of macroscopic irreversibility in terms of reversible microscopic dynamics. All physical theories -- classical dynamics, Electro-Magnetism, Relativity and Quantum Mechanics -- start from reversible laws. Time in these theories can go back and forth, so that we are unable to distinguish past from future.

However, the measurement problem (either through the collapse of the wave function in Quantum Mechanics or through the projection onto any coarse grained set of observables, in classical complex/chaotic systems) and the field theories of Thermodynamics and Diffusion, paint an altogether different picture. Heat flows always from the hot to the cold, salt always dissolves in water. So for any irreversible process like these to extract an opposite behaviour, we need to pay a price in energy.

The only law that goes against all other laws is the celebrated 'Second Law of Thermodynamics', which defines the arrow of time. Irreversibility represents one of the long standing problems in statistical mechanics. Actually it turns out to be its own 'Holy Grail' -- so far. Not expanding on this long and cumbersome subject, we shall mention here only that an up-to-date discussion of irreversibility and its relation to the underlying chaotic dynamics can be found in [12] (with one of the most detailed list of publications on the subject).

Nevertheless, we must also mention that the evolution operators appearing in this context of complex system studies admit of a treatment which bears important similarities to the operator algebras of quantum mechanics -- especially the Dirac picture of quantum mechanics based on the duality between states and observables; along with all the interesting problems of convergence and *non-commutativity* that this brings in its wake. The role of non-commutative algebras underlying the fundamental connection of unpredictability and complex causality in the framework of another picture of quantum mechanics, that of Heisenberg’s, and the 'trajectory based' picture of quantum mechanics, i.e. the original approach of Bohm and Hiley, is elaborated in [13]. There, new perspectives on 'Active Information' and its relation to Shannon's Entropy are outlined with envisioned far reaching implications for both complex and quantum system studies.

(b) *The operator evolving these probability densities for such discrete systems is called the Perron-Frobenius operator (its dual being the Koopman operator) and is related to the Liouvilian operator of statistical mechanics.*

Finally, we shall also mention an even more controversial and daring line of approach. It is that of Edwin Thompson Jaynes [23,] which has recently re-surfaced. Jaynes became a quite notorious figure for his peers in the late 1950s when he published (against the advice of referees) his ideas about the generalization of the second law for far beyond equilibrium systems. Quoting from his obituary published in Physics Today:

[Edwin Jaynes] insisted that some of the thorniest conceptual problems faced in physics, notably in statistical physics and quantum theory, arise from a mistaken identification of probabilities as physical quantities rather than as representations of the available information on a system -- a confusion between what is ontological and what is epistemological. . .

Something even more puzzling about the Second Law's time arrow is that all other ‘arrows’ point in the same direction, i.e. `the future': biological aging, the fact that in radiation we observe no converging electromagnetic waves; in the Quantum realm where a wave function once collapsed stays that way; in the recent Neutral-Kaon disintegration experiments on CP-violation where the observed rates rule out reversed time; in probability theory where once a possibility is realized it cannot be undone (what is known as 'Heads and tails don't merge'); and in gravity where we observe one way collapse (so far we know about black holes but of no white ones).

Add to these time-arrows the cosmological arrow of time and the subjective or psychological arrow of time, (where normally we can't remember the future, as Metod Saniga explains in this issue [22]) and a very clear picture emerges. We observe that total entropy does not decrease and suspect that all the aforementioned arrows of time are somehow connected. However, how this happens and why is not evident. So we are landed with one of the biggest questions about the foundations of physics – and this question unavoidably raises profound issues. We need to probe not just into general epistemological considerations. We need to probe into our very pre-epistemological assumptions and basic doctrines about what time actually is.

7 Then, Who Will Observe the Observers?

We have seen that in general the evolution of a complex system depends on the attractor(s) drawing it forward. As work in the past decades has shown, these attractors can be either `strange,’ `fractal' or ‘multifractal.'

Nowhere else is the above fundamental role of fractal geometry in the dynamics of complex systems so pronounced (with respect to the unpredictability of deterministic systems) as in the case of systems with riddled basin boundaries. Systems comprising more that one attractors naturally possess boundaries among the basins of these attractors. The basin of an attractor signifies that if one stipulates the initial conditions to exist within the basin of each attractor, the system evolves in such a way as to eventually stamp itself on each corresponding attractor.

Interesting phenomena arise whenever the boundary itself is fractal. A structural fractal geometry in phase-space adds to the dynamic fractal geometry of time-evolution a number of very counter-intuitive situations. No matter how accurately we pin down any initial condition on the fractal basin boundary, we can never tell with which attractor we are going to end up with. The unavoidable, slightest uncertainty in the approximation of initial conditions will set us off on a totally different evolutionary course. Indeed, it will land us in an indeterminable final place (within any attractor) after a given period.

To make things even more interesting, there is a quite generic class of systems, possessing more than one attractor, for which class the whole phase space constitutes a boundary! To be distinguished from the systems with merely fractal basin boundaries, this class is called ‘systems with riddled basin boundaries.’ (For a detailed discussion of this, with specific examples and illustrations attached, see [7] and references therein).

The route towards systems with riddled basin boundaries, starting from systems with simple basin boundaries via the change of their parameters, is known as 'Blown-out Bifurcation.' Discovered in the early nineties as a result of such studies in nonlinear science, this route embodies a novel kind of bifurcation. Such an abundance of complexity implies that the slightest disturbance, fluctuation, fuzziness or approximation renders predictability absolutely impossible.

Here too, then, a deep analogy with quantum mechanics comes to view, related to the celebrated complementarity principle. Observations in both classical and quantum measurements share the common feature of the projection or collapse of any mixed or `entangled' initial state onto one among a limited set of final states for that system. These are the eigenstates for quantum mechanical systems, or the attractors for classical systems.

Certain fundamental connections between the two-slit delayed experiment on the one hand and the nonlinear dynamics of classical systems (which possess coexisting attractors separated by smooth or fractal boundaries) on the other, have been proposed quite recently in [14].

In particular, the quantum two-slit delayed experiment was studied in the above reference. In the delayed double slit experiment, the possibility of altering the initial disposition of the state vector -- thereby inducing it to switch from one final state to another by altering the geometry of the setting-- has been well established experimentally and described theoretically. A similar switch was also recognized as possible in a nonlinear classical system with two coexisting point attractors, separated by a fractal basin boundary [14].

Indeed, the classical analogue of the two-slit delayed experiment demonstrates similar features through the switching of its unique control parameter. Along with the authors of [14], we cannot but stress that the said work draws an analogy between the measurement problem, as elucidated by the delayed two-slit quantum system, and that of a classical, yet nonlinear, information processing system with fractal basin boundaries. It means that we have here a deep and far reaching analogy –even though it still represents no more than a mere analogy.

Even so, some speculation along such lines is called for. For systems where measurement requires a relatively, or sufficiently, long interval of time, the parameters of the system might as well change over the period of observation. They might even change in such a manner that the original collection, or ensemble, of each sample makes it split into a number of given subsets according to the respective results of the measurements performed.

Now, given the ubiquity of fractal, or even riddled basin boundaries for nonlinear dynamical systems with high dimensionality of their phase-space (degrees of freedom), it is reasonable to assume that we will end up with a situation in which the very act of probing (in order to perform an observation) alters the system's state. This will happen even when the system probed is classical, if nonlinear.

I.e. it will happen even though the system being measured is both complex and dynamical. Because of the underlying logic and non-commutative structure of quantum mechanical systems, a complex/chaotic system comes to view. It occurs in spite of the fact that ontologically the above system is quite different from what the classical setting stipulates. This suggests that a fundamental similarity between classical and complex entities is not only possible in theory, but exists in actual fact.

8 The Complex and the Living

It is well known that many early workers exploring the foundations of quantum mechanics, like Pauli and Schrödinger, were preoccupied with the question 'what is life?'. Bohr was the first to point out that a generalized complementarity principle, which he proposed in the framework of quantum mechanics, could be at work in the case of living systems. Indeed living systems are the most profound of complex dynamical entities. Ever changing in time, yet keeping a distinct sense of wholeness and identity, dynamically adjusting themselves, equipped with vast yet undermined information processes, they stand out on the highest levels of the hierarchies for both structural and dynamic complexity. Non-living complex systems could provide a stepping stone towards a renewed, richer and deeper understanding of the phenomenon of life. The one condition for this to happen is for us to avoid at all costs the straight-jackets imposed by pre-ordained paradigmatic thinking.

Revisiting Aristotle, though daring, may prove helpful in this respect. Aristotle maintained that plants are animals compared with rocks, but rocks compared with animals. Something similar applies to complex systems and their emerging properties. Complex systems can be seen as 'alive' compared to machines, but machines compared to living systems. Moving from the naive mechanistic logic of hard objects towards the sophisticated logic of living organisms, one should not be surprised if one finds himself going through a further logic – that of complementarity, self-reference and paradox. The case of quantum mechanics suggests as much[c].

The idea that complementarity can be useful not only in physics but in other areas as well -- particularly in biology (see [18], p. 87) -- was familiar not only to Bohr, but to other early thinkers in the field as well. As Walter Elsasser remarked as early as 1968 [16]:

> *"L. Brillouin has gathered a great many illustrative examples to show how in problems of classical physics any initial uncertainty increases with time. His work is clearly related to the fact that since the advent of quantum mechanics there have been the two schools of thought: those who tried to return to classical determinism and those who found in quantum theory a challenge for investigating all*

(c) *Recently, in the context of analytical philosophy certain extensions of standard logics to non-classical ones have been investigated and remarks on their relevance to physics have been discused in [15].*

possible ramifications or generalizations of indeterminacy which may be part of physical description and prediction."

Brillouin's work belongs to the second category, so does Elsasser's, who had already investigated the implications of the generalized complementarity principle in the fields of statistical mechanics and Biology [16].

However, when it comes to modern thinking in biology, no one has expressed the urgent need for such a radical change more eloquently (and convincingly) than Richard Strohman [19]. Already from the mid-90s he had anticipated the 'surprising results' of the genome project, which became public knowledge around 2001. Building on the ideas of Goodwin [6] and others on the role of self-organization, nonlinearity and dynamic complexity in systems biology, Strohman developed a sound argument about the profound implications of complex systems studies for epigenetic networks. His main point was to challenge the underlying naive reductionist view of modern biology that 'everything is in the genes'. Indeed, he explained why no further understanding of molecular biological systems could rely 'on genes alone'.

Strohman realised that the nonlinear interrelations involved in gene expression necessitate a change in perspective that will influence the entire area of investigations. This radical change will help scientist move from an object-mediated view of biological systems to a system-wide understanding of dynamical processes. After the `surprises' generated by the conclusion of the genome project (when 'mainstream' biology was stunned to learn that humans have far fewer genes than expected in comparison to other simpler life forms) we now realize that a gene represents more a functional unit acting in relation to a whole and not an agent operating on its own in the DNA.

As Strohman put it when he introduced a collection of state-of-the-art publications dedicated to the topic [20]:

"Human disease phenotypes are controlled not only by genes, but by lawful self-organizing networks that display system-wide dynamics. These networks range from metabolic pathways to signalling pathways that regulate hormone action. When perturbed, networks alter their output of matter and energy which, depending on the environmental context, can produce either a pathological or a normal phenotype. Study of the dynamics of these networks by approaches such as metabolic control analysis may provide new insights into the pathogenesis and treatment of complex diseases."

In the above quotation we would like to underline particularly the concepts of self-organization, system-wide dynamics and network structure. These concepts rely heavily on the presence of non-linear interrelations within a complex whole. They reveal the fundamental relevance of the recent advances in complexity and statistical mechanics, which result from the seminal work of Barabási and co-workers [21]. Although a deeper dynamical system's perspective is absent from these investigations of `life's complexity pyramid', as they call it, the authors themselves (as well as many others) maintain that such a step has to be taken -- eventually.

How this will be accomplished and where it will take our understanding of complexity, entropy, information and life remains, of course, to be seen. Nevertheless, it is certain that we can expect not just interesting theoretical breakthroughs in biology. We can also expect some fundamental questions to be raised about the logic and mode of thinking that permeates such investigations – like those raised by

Walter Elsasser.

To return to Niels Bohr and his epistemological reflections: *"no experience is definable without a logical frame. Any apparent disharmony [among observed phenomena or levels of phenomena] can be removed only by appropriately widening the conceptual framework "*. It means that we must take on board the notion of Emilios Bouratinos' [25] that there is a need to investigate the pre-epistemological level of conceptualisation. As he writes, *". . . modern science is constantly broadening, deepening and differentiating the world image. But if the world image is being constantly enriched, so must our ways of knowing it. . . "*

9 Pre-Epistemology: The Complex and the Subjective

There are powers and thoughts within us, that we know not till they rise
Through the stream of conscious action from where the self in secret lies.
But where will and sense are silent, by the thoughts that come and go,
We may trace the rocks and eddies in the hidden depths below.
James Clerk Maxwell, quoted in [10]

The understanding has been that structurally simple systems can give rise to a very complex dynamical behaviour. In this way they classify as complex systems -- even when composed of few constituent parts only. The challenge is to find appropriate levels of description to express any underlying hidden universalities. Once we pass from one description to another, the objects defining our systems inevitably change from trajectories to probability densities.

This redefinition of the objectification scheme required for understanding any complex system, is not a question of just choosing the best model available. The situation calls for something radically different. We must find a way for articulating the fact that both the trajectory description and the probability description of reality reveal aspects that are true. Moreover, such nonlinear thinking reveals the extent to which these partial objectifications can be considered as reflecting the system's realities.

The sciences of complexity and the entire field of complex systems' studies reject the notion of a single description. They call instead for a creative interplay beyond and above paradigms.

Whatever the benefits of a paradigmatic conceptualisation, it also brings limitations. Complexity forces us to reflect on our objectification scheme. Regardless of the kind of thinking this scheme arise out of (reductionistic, holistic, mechanistic, probabilistic, dualistic or metaphysical) a description reflects only partial aspects of the unified picture of a complex system – and it does so only on one level of the abstracting structure required for portraying it.

One of the greatest twentieth century's mathematicians working on probability, B. O. Koopman, maintained that '*knowledge is possible, while certainty is not*'! As he wrote in 1940, *"both in its meaning and in the laws it obeys, probability derives directly from. . . intuition and is prior to objective experience"* [24]. As a result of Koopman's work, intuition and subjectivity can now be rehabilitated theoretically. But there is a condition: they must be practiced openly, knowingly and honestly (see [25]). Thus commenting on the 'inadequacy of objective understanding', John Searle is able to call for more empiricism -- though of a different order [26].

If science is the name of the collection of objective and systematic truths we can state about the world. . . then the existence of subjectivity is an objective scientific fact, like any other. . . If the fact of subjectivity runs counter to a certain definition of 'science', it is the definition and not the fact that we have to abandon.

It follows that the crucial question confronting us is: To what extent can we experience reality without being blinded by our preconceived ideas about it? How can we be free from our own projections if we deny their very existence?

Outlook

The sciences dealing with complexity find themselves at a crossroads. According to some sceptics, the very notion of complexity is ambiguous. Furthermore, the sceptics believe that it has given rise to a very ambitious project. They insist that its basic concept is far too all-embracing, holistic and blurred to ever become the subject of a proper scientific investigation. Needless to add that similar sceptical reservations had been raised in the past against the study of Time and Space, Entropy and Information, Cognition and Consciousness. Sceptics in science frequently want to fit reality into their static vision of science. But the real challenge for investigators would be to fit their vision of science into the dynamics of reality. We shouldn't allow our concepts to fashion the picture of the world. Rather we should allow the essence of the world to fashion the nature of our concepts.

Scientific thinking today has reached a stage which doesn't compare with that of any other in its history. The feeling is that Complexity and Emergence, Time and Space, Entropy and Information, Cognition and Consciousness are now at the forefront of fundamental research in the physical sciences. Despite that, these realities cannot be defined in exclusively objective and quantitative terms.

The reason is simple: they also constitute the ultimate prerequisites for the observations carried out in their name. You need to have emerged into complexity to become aware of its operation; you need to be in time and space to observe their function, or even their occasional absence; you need to be experiencing entropy to sense it; you need to be properly informed to be in a position to assess information; you need to be cognizant to cognise; and finally you need to be conscious to know the significance – and operations -- of consciousness.

In our times the very foundations of what we perceive as a properly established epistemological ethos have been cast in doubt. This calls for a radically new kind of science -- one that can reflect on its own foundations. It also calls for a new kind of scientists. They need to be aware not only of their limitations, but of their objectifications. In addition, they need to be familiar with the relative merits of different, complementary or even seemingly contradictory approaches to their subject-matter.

Never before has the need for qualitative change in science been so apparent and pressing. The importance of complexity studies lies in that it has made such a radical change not just possible, but imperative. It can only directly inform and inspire the struggle for introducing self-reflection into the practice -- and the understanding -- of science.

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