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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 Métaphysique, VI, 1686

1 Introduction

The main thesis of this presentation is that Complex Systems afford many and distinct levels of descriptions, dynamical, structural, geometrical or topological, metric or probabilistic, or even a hybrid interplay of the above. Moreover, especially for 'real-life' complex systems, any observation will necessarily be partial, incomplete and always depending on the observer's choices due to incompressible initial conditions and/or approximate parameter estimation. This points to the fact that no single set of mathematical or other formalism — as we know them — is or could be capable of both a complete and consistent description of a complex whole.

Therefore a new double-edged approach is called for. A concertated approach which, on the one hand, would synthesize and unify, at different levels, using different tools and descriptions. And, on the other hand, being able to discriminate among several given aspects of the facts under scrutiny, and how these facts were acquired based upon the specifics of sets of objects and relations which provided these facts.

In short, we are fast reaching the point where we need to concern ourselves not only with the study of nature, but with the nature of that study. Being aware of the limits of our descriptions we can describe the limits of our awareness. That, as a consequence, will set the search of a 'Science towards the Limits' as William James called the scientific endeavour which is capable of reflecting not only upon its abstractions — a discourse that epistemology provides — but also reflecting upon its fundamental objectifications — that is one step beyond considering a pre-epistemology able to provide such a discourse.

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' and in the entry 'complex' we see that it means:

> 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 might seem places the emphasis on 'whole' and 'interrelated parts'. As we came to understand, something complicated is not necessarily complex although a complex system could be complicated. The terms 'whole' and 'interrelated parts' are emerging as fundamental notions upon which the nonlinear relations among constituent parts rely and as such are identified. This has been the case mainly in physical sciences but it is not necessarily restricted to only there.

Indeed, this connection between complexity studies and nonlinear science brings forth a deeper understanding across the divide of subjective and objective narration in fields as diverse as physics, chemistry, biology, cognitive and consciousness studies, and even sociology and economics.

In complex system studies one is confronted with nonlinear relations which give rise, usually, to a great number of states. This multitude of states most of the times signifies many levels of ongoing processes of different time, and space, scales. The signature of complexity is the presence of multistationarity and/or chaotic regimes of motion.

All these aspects unavoidably lead to the breaking of symmetries both in the spatial (pattern formation) and the time (irreversibility) domain.

It is, now, well understood that these emergent patterns and rhythms are due to 'nonlocal' — in the sense that the correlation lengths of the patterns and rhythms emerging are orders of magnitude larger than the correlation lengths of their constituent parts — as well as an associated limited horizon of predictability due to strong 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 alien 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 physicochemical 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, aside from the structural aspects of complexity the dynamical basis of it has been a path-breaking area of research during the sixties and onwards. 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 ellucidated. 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 behavior of the collective of the parts) 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 (function) and stochastic processes (fluctuations) were discovered in complex systems.

3 The Complex and the Quantum: Classical Objects Misbehaving

A curious thing about Complexity as the hailed 'third revolution in physics' is that it did not happen 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 most wide array of disciplines possible 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 characterized by a noted interdisciplinary nature and an intrinsic multitude of approaches.

Probably it was a 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 jumps'. 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 Poincaré. Having participated in a very late autopsy, I would like to describe some of the findings.

What Poincaré 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, that 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 triggered another famous mathematician of these days, Hadamard, to study a more general setting. Hadamard was — probably — the first to articulate what we now call 'sensitive dependence on initial conditions' or 'the butterfly effect', the hallmark of chaos. Indeed, it was in the year 1898, almost twenty years before the dawn of quantum mechanics, when Jacques Hadamard published his work on the motion of particles in surfaces with negative curvature. In the course of this work he showed that this motion is everywhere unstable [8]. 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 the motion onto partitions upon the surfaces in the regions that takes place 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 showed subsequently that the possible sequences are *exactly* the ones which do not contain these forbidden pairs. Actually he was the first to intoduce a new and powerfull tool that now we call *'symbolic dynamics'* with fundamental notions central to (discrete) probability and what later will be identified as *information theory.*

This work, although quite mathematical for the physicists of his time, proved to be rather fertile and was later taken up by Birkoff and von Neumann in their work on ergodic hypothesis, published in the early 1910's. Further decisive progress came, again, from the work of Poincaré. He was concerned with problems of instability and integrability of dynamical systems. As a famous mathematician and philosopher of his time, he increased his fame even more by winning the prize of 2500 kroner put forth by King Oscar II of Sweden and Norway. The contest consisted of several questions, one of them formulated by Weierstrass and concerning 'our understanding of the solar system': Three bodies, Sun, Moon, Earth, attract each other by Newton's law for gravitation. Could one find a solution in a closed form or in form of a converging series? Poincaré won, although his celebrated result is a negative one: he managed to show that this 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 as the competition, set by the king, demanded. It also enabled us to deal with a wide class of systems with unstable motions. Poincaré based

[a]Actually what Poincaré showed is that the Bernoulli technique of finding a conserved quantity cannot yield any conserved quantity analytic in 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 asked. But Sundman's technique is useless for any calculation, even though it is constructive, so it remains undeservingly forgotten.

his methods on geometry and he provided us with a wealth of techniques and concepts widely used 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 equaled by Lyapunov and his celebrated 'Russian School' in dynamical systems. Later on, Adronov in his work on nonlinear oscillators formalized and 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 drawing almost all the attention.

Yet, although the period 1910–1950 was stagnant for nonlinear dynamics some results were paving the way for the future renaissance of the field, which happened in the mid sixties. In a series of papers starting in 1921, Marston Morse had given a scheme of enumeration of the orbits of the class of systems considered by Hadamard. This body of work motivated the studies of Artin, Heldund and Hopf cumulating in proving that the motion of a ball on a surface of constant negative curvature was ergodic. One of the first physicists who realized the importance of these results was Krylov, arguing that a physical billiard *is* a system with negative curvature along the lines of collision. Later, Sinai showed that a physical billiard 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 prototype system for chaos [9]. Fig. 1 is an illustration of the complexity of such a *seemingly* simple system. Complexity, in describing the sequence of the trajectory of a test-particle visiting each disk here, enters through the nonlinear relationship (the curved surfaces of the disks) between its parts (the disks). It is this aspect that makes the dynamics of such systems chaotic. If it were that the reflecting surfaces were flat, i.e. rectangular boxes instead of disks, the system would be *complicated* but not *complex*, the parts would have uniquely define the whole as their linear superposition; whereas in complex systems the whole is more that its parts due to the intricate, nonlinear, interrelations between parts and whole that. Thus one attributes emerging properties to such systems.

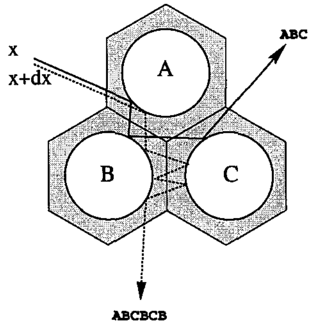

Figure 1. Motion of a test particle in 'pinball' serves as a simple, representative and very descriptive model for chaotic/complex systems. Chaos arises due to complexity because of the strong nonlinear relations among its parts.

4 The Fallen Doctrine of Classical Determinism

The link between deterministic causality and stability of classical systems did not escape these early days the penetrating genius of James Clark Maxwell. Reflecting upon the roots of causality, he has written (quoted in [10]):

> It is a metaphysical doctrine that from the same antecedents follow the same consequents. No one can gainsay this. But 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'.

What chaos and complexity studies have revealed is that our classical notion which expects determinism to imply predictability is a long held fantasy stemming from the Newtonian/Laplacian paradigm. As a matter of fact, it is more than a false fantasy, it is a persistent fallacy in scientific and philosophical thought for over three hundred years. Laplace's all-knowing daemon, the god of reductionism, is symbolized in one of Laplace's most famous proclamations:

> ...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 only to start coming to its natural end by Werner Heisenberg's proclamation of his uncertainty principle. What is of interest here regarding this principle is that it talks, at a different level, for complex systems as well. Let us follow Heisenberg's line of thinking; he states that [11]:

> In the strict formulation of the 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 the, ontologically probabilistic, quantum mechanics. But is it not true when we encounter complex, or chaotic, dynamics? Even if we think of them as ontologically deterministic, could we ever hope to know in perfect detail and exactly 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 irrationals and impose the need for infinite amount of information? Definitely in the mind of the Laplacian god of reductionistic mechanism that could be true but in any act of projection, such as measuring or specifying initial conditions, that we pure humans have to go through, we necessarily loose certainty and end up with probabilities. We must stress, once more, that the above is unavoidable even if the laws are deterministic and our theories at hand — providing these laws — impeccably correct.

Definitely the vivid discussions over causality, determinism and Quantum Mechanics — and Relativity, to certain extent — covered 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 nonlinear, 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 sciences.

We have chosen to follow a certain line of historical developments of this field which have not been narrated as often as the one we learn from the recent rediscovery of chaos and complexity. Of course it is not an exhaustive account. The aim of this presentation is not to give historical details but to help, hopefully, in revealing aspects of complexity studies that are instructive of what kind of issues and ideas inform about the new way of thinking.

The lessons we are learning from this new era are numerous and still being born. One of these that we shall focus on is that we must be fully conscious with what objects we are preoccupied. 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, our own partial objectifications, 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 a very general setting, what kind of 'simple', deterministic, nonlinear dynamical systems can tell us about the distinction between determinism and predictability. What this brings to the concept of causality and how it gives rise to a probabilistic way of approaching complex systems which resembles at certain aspects the Schrödinger picture of quantum mechanics.

A common, yet historically important, example of such systems is what is known as the logistic map. A time-discrete dynamical system which can be found in any other standard textbook of 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. It is a one-dimensional system characterized by a state variable, say x, which takes continuous values within an interval, say $[0,1]$, which is updated in a discrete fashion each discrete time step, t. The 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 behaviors: from stable periodic via quasi-periodic 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, then would look *as if* it were random. The left-hand side of Fig. 2 shows exactly this evolution. This '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 due to the fundamental inability to explicitly express any typical initial condition (i.e. an irrational number) in full accuracy.

Turning now from this point-like 'topological' description of trajectories to a probabilistic treatment, we see a different picture emerging. If we now set as observables not each point but the statistics of each typical trajectory, we observe that they all have the same histogram. Each one of the erratic trajectories 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 Fig. 2. To complete this probabilistic description one starts over

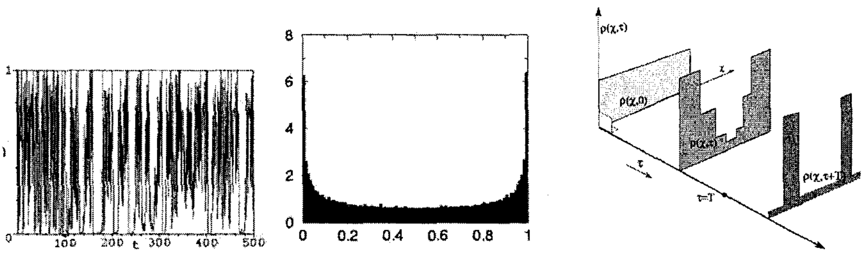

Figure 2. A typical trajectory, i.e. a point-like description, of a chaotic system (on the left) is unstable and erratic. A statistical treatment (i.e. its probability density in the center) reveals that ensembles of trajectories, i.e. a probabilistic description, follow a stable evolution (on the right).

again considering now from the beginning not one point, but a collective, or ensemble, of them (technically, of course, this is a merit of our system being ergodic). This ensemble now takes whole new meaning and interpretation. It signifies the probability to start from any point, or the initial density of state. This, or any other, (smooth) probability density will eventually take a *predictable*, stable route towards the invariant probability density after a sufficiently long time. This is sketched on the right-hand side of Fig. 2, for an initial ensemble with equiprobable starting points.

These two different, yet connected, pictures are based on different assumptions of what is an observable fact in each setting. Their evolution operators are different. The point-wise evolution operator and its erratic, unstable, unpredictable, outcome versus the operator which evolves the ensembles with its resulting smooth, stable and predictable evolution. We gained predictability for the collective but we lost the individual fate. We lost certainty of each sharp outcome and we gained accurate prediction of the probabilities of repeated outcomes.

6 A Glance at Irreversibility

In the above picture where 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 the evolution is characterized as irreversible. Coming from the future backwards we do not really know where we started, all initial settings seem equally plausible.

This is a kind of chaotic system which reflects basic aspects of the 'problem of irreversibility'. That is, the demand for a consistent description of macroscopic irreversibility in terms of reversible microscopic dynamics. All theories of physics at work, classical dynamics, Electro-Magnetism, Relativity, Quantum Mechanics, start from reversible laws. Time in these theories can go back and forth and we cannot distinguish past from future. The measurement problem (either by the collapse of the wave function in Quantum Mechanics or by the projection onto any coarse grained set of observables, in classical complex/chaotic) and the field theories of Thermodynamics and Diffusion though paint a totally different picture. Heat flows always from the hot to the cold, salt dissolves in water, for any irreversible process like these to extract an opposite behavior we have to pay the price in energy. The only law that goes against all other laws is the celebrated 'Second Law of Thermodynamics' which defines an arrow of time. Irreversibility is one of the long standing problems in statistical mechanics, actually it turns out to be its own 'Holy Grail', so far. Refraining from this long and cumbersome subject, we shall mention only that an up-to-date discusion about 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 a treatment which bears important similarities to the operator algebras of quantum mechanics, especially to the Dirac picture of quantum mechanics based on the duality between states and observables; along with all the interesting prob-

[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.

lems of convergence and non-commutativity. 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, and the 'trajectory based' picture of quantum mechanics, i.e. the original approach by 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 in the future. Finally, we shall mention an even more controvertial and daring line of approach undertaken by Edwin Thompson Jaynes [23] and recently re-emerging. Jaynes became a quite notorious figure among 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 of time point to the same direction, what we call '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 Neutral-Kaon disintegration recent experiments on CP-violation where the observed rates rule out reversed time, in probability theory where once a possibility is realized cannot be undone (what is known as 'Heads and tails don't merge'), in gravity where we observe one way collapse (so far we know about black holes but of no white holes). 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, see the contribution of Metod Saniga in this issue [22]). In all and all we observe that total entropy does not decrease. Most probably all these arrows of time are somehow connected, yet how and why still remains elusive. It is one of the biggest questions on the foundation of physics, which unavoidably touches upon epistemological issues; it would be resolved though at a deeper level if we could probe our pre-epistemological assumptions and our basic doctrines of what time really *is*.

7 Then, Who Will Observe the Observers?

We have seen that as a general outline of the evolution of a complex system, we usually say that it is drawn to its attractor(s) which can be 'strange attractors' and/or 'fractal' or 'multifractal' ones as the common knowledge assimilated over the last decades points out.

Nowhere else this fundamental role of fractal geometry in the dynamics of complex systems is 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 between the basins of these attractors. The basin of an attractor signifies the fact that if one sets initial conditions within the basin of each attractor the evolution of the system will bring the system, eventually, to 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 very counter-intuitive situations. No matter how accurately we pin-down any initial condition on the fractal basin boundary, we can never tell on which attractor we are going to end up. The unavoidable, slightest uncertainty in our approximation of the initial conditions will set us off in a totally different course of evolution landing in an indeterminable final place (within any attractor) after a given time.

To make things even more interesting, there is a quite generic class of systems, possessing more than one attractor, for which class of systems their whole phase space is a boundary! To be distinguished from the systems with merely fractal basin boundaries they are called systems with *riddled* basin boundaries (for a detailed discussion with specific examples and illustrations, 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', a novel kind of bifurcation discovered in the early nineties due to these studies on nonlinear science. Such a complexity explosion renders any slight disturbance, fluctuation, fuzziness or approximation amenable to absolute unpredictability.

Again, a deep analogy persists with quantum mechanics related to the celebrated complementarity principle. Observation 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 the system's final states. These are the eigenstates for quantum mechanical systems or the attractors for classical systems. Certain fundamental connections between, on the one side, the two-slit delayed experiment and, on the other side, the nonlinear dynamics of classical systems possessing coexisting attractors separated by smooth or fractal boundaries have been proposed quite recently in [14]. In particular, the quantum two-slit delayed experiment was studied in the above reference. It has been well known that in the delayed double slit experiment, the possibility to alter the initial disposition of the state vector and induce it to switch from one final state to another by altering the geometry of the setting has been realized experimentally and has been described theoretically. Such a switching was recognized to exist, also, in an analogous nonlinear classical system with two coexisting point attractors separated by a fractal basin boundary [14]. The classical analogue of the two-slit delayed experiment demonstrates indeed similar features through the switching of its unique, control parameter. Along with the authors of [14] we cannot but stress the fact that the above 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. A deep and far reaching, in concequences, analogy, yet still an analogy.

Nevertheless, let us allow ourselves to speculate along these lines. For systems where the 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 way that the original collection, or ensemble, of each sample make 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 end up with a situation where the act of probing to perform an observation alters the state of the system, even if this is a classical — but nonlinear, complex — dynamical system. Here because of the underlying logic and non-commutativity structure of quantum mechanical systems — although ontologically different from the classical setting — permits a fundamental similarity with classical — but complex/chaotic — systems to reveal itself.

8 The Complex and the Living

It is well known that many of the early workers on the foundation of quantum mechanics, like Pauli and Schrödinger, where 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 for living systems. Indeed living systems are *the* most profound of complex dynamical systems. Everchanging in time yet keeping a distinct sense of wholeness and identity, dynamically adjusting, equipped with vast yet undermined information processes, they stand out in the far highest levels of the hierarchies of both structural *and* dynamic complexity. Complex systems, which are not living, could provide a stepping stone towards a renewed and deeper understanding and more rich meaning of the phenomenon of life as a scientific area of study. Provided, of course, that we could raise beyond the straightjackets of any pre-ordained paradigmatic thinking.

Revisiting Aristotle, although daring, may be helpful in this respect. Aristotle maintained that plants are animals compared with rocks, but rocks compared to animals. Something similar applies to complex systems and their emerging properties. Complex systems could be seen as 'alive' compared to machines, but machines compared to living systems. Moving from the logic attached to naive mechanistic thinking, which applies to *objects* towards the logic of living systems, which applies to *organisms*, one should not be surprised if one has to go through a logic embracing complementarity, self-reference and paradox, as the logic revealed by the quantum.[c]

The idea that complementarity could be useful not only in physics but in other areas as well, in particular in biology (see [18], p. 87), was not foreign not only to Bohr, but also to other early thinkers. 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 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 has had already investigated the implications of the generalized complemen-

[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].

tarity principle in the field of statistical mechanics as well as in Biology [16].

When the modern thinking in biology is concerned, nowhere else, more urgently and more cleverly, such a radical change of view has been advocated than in the 'prophetic' work of Richard Strohman [19]. He anticipated, already in the mid-90's, the 'surprising results' of the genome project which came around circa 2001. Strohman, starting from the ideas of Goodwin [6] and others about the role of self-organization, nonlinearity and dynamic complexity in systems biology draws his argument on the profound implications of complex systems studies to epigenetic networks. His main point is to challenge the underlying naive reductionistic view of modern biology that 'everything is in the genes' by making clear that any further understanding of molecular biological systems has to rely 'not in the genes alone'.

He stresses the importance of the fact that the nonlinear interelations involved in gene expression necessitates a change of perspective influencing the whole area of investigations from an object-mediated view to that of a system wide unfolding dynamical process. After the 'surprises' coming with the conclusion of the genome initiative, where 'mainstream' biology was stunned to learn that humans have far less genes than expected in comparison to other simpler forms of life, we now realize that a gene is more of a functional unit acting as — and in relation to — a whole rather than an isolated object 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 phenotype are controlled not only by genes but by lawful self-organizing networks that display system-wide dynamics. These networks range from metabolic pathways to signaling 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 put emphasis on the concepts of self-organization, system-wide dynamics, and network structure. All of which rely upon the presence of non-linear interrelations within a complex whole. Here, the relevance to the studies of complexity and statistical mechanics has been made evidently clear from a plethora of recent advances after the seminal work on complex networks by Barabási and co-workers [21]. Although a deeper dynamical system's perspective is lacking from the investigations of 'life's complexity pyramid', the authors themselves and many others testify that such a necessary step has to be taken sooner or later. How this next step will be accomplished and where it will lead our concepts of complexity, entropy, information and life remains to be seen. Nevertheless, we can expect not only interesting breakthroughs but also some fundamental questioning of the logic underlying such investigations, like Elsasser was advocating, as well as the mode of thinking that underlies any logic implicated.

To return to Niels Bohr and his reflections upon epistemological levels, "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". In other words, those of Emilios Bouratinos [25], hinting at a pre-epistemological level: "...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 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 realization has been that structurally simple systems could give rise to a very complex dynamical behavior and classify as complex systems even if they are composed of few constituent parts. The challenge here is to find appropriate levels of description to express any underlying, hidden, universalities. Once we pass from one description to another the objects that define our systems inevitably change, i.e. from trajectories to probability densities. This redefinition of the objectification scheme required to construct a model of any complex system at hand is not a matter of choosing which is best. The situation here calls for a radically different thinking. We need to find a way of articulating the fact how *both* descriptions hold aspects of reality, i.e. both a point-like picture *and* a probabilistic view of evolution are real; moreover, such a nonlinear thinking extracts an answer for the limit up to which these partial objectifications can safely been taken as reflecting the system's realities.

The sciences of complexity and the whole field of complex systems' studies deny the domination of one single approach. They call for a creative interplay beyond and above paradigms, whatever any paradigmatic thinking brings as benefits it also brings limitations. Complexity forces us to reflect upon our objectifications. From whatever kind of thinking these objectifications might arise — reductionistic, holistic, mechanistic, probabilistic, dualistic or metaphysical mode of thought — any level of description reflects only a partial projection of the unified *reality* of a complex system.

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]. Intuition and subjectivity can now be rehabilitated theoretically, provided that they are practiced openly, knowingly and honestly (see [25]). John Searle, commenting on the 'inadequacy of objective understanding', calls for more of empiricism, but 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.

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 existence?

10 Outlook

The sciences dealing with complexity find themselves at a crossroads. According to some skeptics, the very notion of complexity is ambiguous. Furthermore, the skeptics 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 skepticism had been leveled in the past against the study of Time and Space, Entropy and Information, Cognition and Consciousness. Skeptics 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 presently at the frontier of fundamental research in the physical sciences. Despite that, they cannot be defined in exclusively objective quantitative terms. The reason is simple. These four areas constitute also the ultimate prerequisites for the observations carried out in their name.

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 don't only need to be cognizant of their limitations. They need to be cognizant of their objectifications. In addition, they need to be aware of the relative merits of different, complementary or even seemingly contradictory approaches.

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

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