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Synchronicity Among Biological and Computational Levels of an Organism: Quantum Biology and Complexity

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Abstract

This paper argues that there is a synchronicity among biological and computational levels on an organism and provides arguments and proofs based on experimental research gathered in the literature. The leading thread is the interplay between quantum biology (QB) and complexity. As the paper asks whether QB does contribute to complexity science (CS), five arguments are provided: (i) Firstly a state-of-the art of QB and its relationship to CS is sketched out. Thereafter, the attention is directed to answering the question set out; (ii) Secondly, it digs into the understanding of life toward deeper levels of reality; (iii) It is shown that non-trivial quantum effects shed insightful lights on the information processing of and within living beings; (iv) Once the distinction is made between increasing levels of complexity and increasing levels of organization, the focus lies in the importance of QB for organization, and not so much for complexity as such; (v) The role of information rises at the center of all concerns, and the intertwining of complexity and information processing. At the end some conclusions are drawn.
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1. Introduction

The complexity of a living organism and, of life in general, has been studied from a number of perspectives. This paper provides one more view. It claims that the complexity of an organism corresponds to, and is grounded on, synchronicity. The general framework is the relationship between biology and computing science. Now, the study of synchronicity allows for making clear the way in which quantum biology (QB) contributes to complexity theory, a concern that has not yet been brought openly to the fore. Vis-à-vis complexity theory, the question is not any longer whether quantum physics helps understand nonlinear complex phenomena, for this issue has been settle down long ago. Thanks to the rapid and steady development in QB [1], the concern is as to the extent in which complexity science (CS) is benefited by the achievements and endeavor of (particularly, but not exclusively) physicists and biologists that work on quantum physics at large [2].

There are a number of publications that either bring together or tacitly consider the intertwining of QB and complex systems. Yet, they do not explicitly focus on the interplay between two fundamental fields. One, concerned with non-trivial effects of quantum physics, i.e. quantum mechanics in living systems. The other focused on increasingly nonlinear systems that self-organize, adapt and learn, among other characteristics.

On this basis, the second section tackles the core of the interplay mentioned. The question is raised about what can a complex understanding of life and which are the contributions and achievements made by QB. The answer to the question allows re-considering the fundamentals of the research on QB. Such is the scope of the third section. There the interest consists in a philosophical appraisal of the basic and standard evidence of non-trivial quantum effects on living beings. Now, provided that the thread of quantum science is currently information, i.e. quantum information (QI), it is said here that information can be most reasonably taken as a solid ground for answering the way in which QB contributes to complexity theory. At the end, several conclusions are drawn that support a theoretical and conceptual framework that allows a strong and direct link between QB and CS.

In sum, we claim that in the organism various time processes and scales co-exist and reinforce each other, so much so that within the organism there is no dephasing, i.e., wave collapse. In other words, both the quantum scales and behaviors exist along, together and simultaneously with classical scales and behaviors.

2. QB and complexity: sketch of a first state-of-the-art

Quantum objects consist of/are fluctuations. This has already been set out from the origins of quantum physics to-date. It is precisely the unison of those fluctuations what defines a coherent state. The trouble about quantum theory lies in the transition or rupture of coherence to decoherence which leads from the quantum realm to the classical world. Such decoherence is also known as dephasing or the collapse of the wave-function. QB is conceived as the study of the non-trivial *effects* of quantum behavior in the living systems. For, living systems live in a classical world defined by cause-effect, to some extent reductionist, deterministic to some range, linear in a sense.

To be sure, CS does not discharge the linear, deterministic and reductionist stances of life in general. Simply, it is not concerned with them, but rather focuses on non-linear, nondeterministic, emergent, self-organized, and non-algorithmic characteristics of the world and living systems because such features are by and large the most fundamental for the world to be and for living beings to exist.

Not many authors, papers and books concentrate explicitly on the relationship between QB and CS. In our view, the most relevant papers are:

Arndt et al. [3] expressly regard the way in which quantum coherences, entanglement, and other nonclassical effects have been heading toward systems of increasing complexity. The core here is information, and the authors argue that QB could be defined by its use of QI. We can safely add, hereafter, then also by QI *processing*.

Weber [4] makes a fundamental step from a theoretical standpoint, for he argues in favor of expanding the Darwinian synthesis thanks to the Lamarckian understanding of evolution. Via such an expansion, molecular biology, paleontology, developmental biology, and systems ecology are incorporated in the explanation of living beings. The complexity of biology is thus enhanced and strengthened. A more complex theory can be thus presumably attained. Focusing on a historical and conceptual study, Weber openly places at the center the importance of complexity theory taking as thread the theory of evolution.

Sergi [5] stresses the critiques against reductionism whilst openly acknowledging that biology offers the most complex systems to study in the universe. This author highlights what seems to be a general feature in the framework of quantum theory and, hence forth of QB, namely the interpretation of quantum phenomena. In general, the interpretation of experimental and theoretical findings raises passion and difficulties and can be identified as the crux of scientific research [3, 6].

Asano et al. [7] work on the theory of open quantum systems –originally developed by Breuer and Petruccione [8]– and focus on the epigenetic evolution. As a consequence, Asano et al. is a step forwards in unifying Darwin's and Lamarck's viewpoints. A model called quantum-like of a cell which processes information in accordance with the laws of QI is developed that allows understanding that complex biological systems can process information "by violating laws of classical probability theory and hence classical information theory".

Taking up a radical view, Chang [9] proposes an extensive QB, wherein the smallest live element "of different levels is namely a quantum". Such biology can also be understood as a nonlinear one, and hence chaos, fractality, and solitons appear as necessary issues. It is, the author claims, particularly in neurobiology where such nonlinear interactions appear. If so, then the problem that emerges concerns the nature of consciousness. Chang does not go so far, for he restricts himself to the study of memory.

Taking up the stated in Chang [9], in Chang [10] the focus is on what the author calls a "nonlinear whole biology". According to this author, "all of various self-organizations in biology should correspond to the nonlinear theory, which also includes the fractal biology, the chaos biology and various solitons in biology. All evolutions, from biology to genes, are the nonlinear phenomena" [10: 192-3].

Gabora et al. [11] present a quantum model of exaptation, whose most salient features are: potentiality, contextuality, nonseparability, and the emergence of new features. According to these authors, using vectors in a complex Hilbert space can represent the essential elements of both cultural and biological exaptation. Historically, the rationale for such a claim comes from the very fact that quantum mechanics is the first field to deal with potentiality and contextuality. The crux of all explanations appears to be attaining a satisfactory account of how new traits, species, and cultural artifacts come into existence. In sum, life is an unceasing innovative phenomenon.

Davies et al. [12] concentrate in the interplay of entropy and information in a living cell. Three concepts-processes are tightly related, thus: a living being, self-organization, and entropy reduction. Davies *et al*. argue that internal self-organization, information storage and transfer play a most significant role in entropy reduction. They focus at the level of a single cell. One way of the entropy reduction process is the compartmentalization of the cell – into mitochondria, nucleus, endoplasmatic reticulum, chloroplast, etc. As a consequence, the total entropy between the living cell and its surroundings should never be negative.

Melkikh [13] claims that the folding, transport and recognition of proteins are the most important steps in the transfer of information in the cell, and studies how large number of conformational degrees of freedom that proteins possess can paradoxically lead to an information channel with an exponentially small capacity. As a result, parallel processing is tenable and useful for the cell.

Bordonaro and Ogryzko [14] point out to a fundamental difference, namely whereas in physics we limit ourselves to one class of environment so that it does not (fundamentally) change, in biology it is different. It is a contribution of quantum theory the acknowledgement that in quantum theory an individual can in some sense behave like a population of objects. Thus, one can safely speak of a system of one element. Distinguishing between molecular biology and cell biology is crucial for the theoretical and practical extent of QB.

At the macroscopic scale, living systems are thermodynamically open and far-from-equilibrium systems, something that has already been well established thanks to Prigogine [15]. Ajisaka et al. [16] consider if and how nonequilibrum – both a characteristic of the living systems, and one of the sciences of complexity –, can adequately be seen also in quantum phase transitions. In fact, nonequilibrium quantum phase transitions are much less known in comparison to the same phenomena in the macroscopic scale. The point is analyzed using C^* algebra in the XY spin ½ chain, and aims at an exact solution.

Vattay et al. [17] is an important and very necessary paper about the link between QB and complexity theory. It is a simulation that helps prove that the coherence time of systems with the right level of complexity between chaos and equilibrium can increase by orders of magnitude longer than simple quantum systems. Moreover, such an increase, the authors argue, changes from exponential to power law behavior.

3. What does it mean a complex understanding of life?

A complex understanding of life means the inseparability of the different parts, levels and scales of a living system. The interaction between the different levels, scales and parts is nonlinear, in other words, non-sequential. Thus, the living organism is a system of systems. Besides, the structure of a living organism can be said to be fractal [18], which can be seen more clearly perhaps from the point of view of non-classical or alternative medicine, rather than on molecular biology and clinical medicine. This means that what happens or is expressed in one level has a fractal correspondence with what happens – may happen – or is expressed in a different level or scale. Synthetic medicine can be taken as the epidermis of synthetic biology and, both can jointly contribute to a complex understanding of life – in the framework of CS, precisely.

Such a complex understanding is perfectly different to the prevailing current explanation, which is molecular biology, characterized by reductionism and determinism, by isolation and specialization – the triumph of an analytical perspective. Now, biologists are eager enough about the recognition that CS can shed new lights to ultimately help explain the two fundamental questions, namely the origin of life and the very logics of life. QB is probably one of the most recent scientific and theoretical endeavors, whence the need to matching or explicitly thematizing the link between CS and QB – something that has not been openly done to the best of our knowledge, currently.

In any case, an important remark is made by Matsuno and Paton [19], thus: "Biology is not about applying quantum mechanics as it is already known through the experiences of traditional physics, but rather about an attempt to extend quantum mechanics in the manner that the physicists have not tried". This implies then that biology is a field wherein: a) physics is challenged, so that it is to overcome the traditional experimental and theoretical achievements; b) huge number of degrees of freedom are present and active that complexify the understanding of functions, structures, and dynamics. From the philosophy of science standpoint, S. Mitchell [20] calls for bringing together biological complexity and integrative pluralism. Synthetic biology has been identified as the locus where QB roots and is fed. We argue that it is also the locus for the encountering between QB and CS.

4. Non-trivial quantum effects, revisited

Biological systems are internally full of the act of measurement [21]. In fact, at the homeostatic level measurement is the very way in which living and non-living processes take place and interact and enhance each other. The organismic scale of homeostasis can be taken as either a global and interconnected set of reciprocal measurements, or else also as continuous information processing multilevel, in parallel and interactive. The same can be extrapolated to the homeorethic dimension. It is to be recalled that cells are grasped in the order of microns, organs in centimeters, and the organism in meters.

Biology is the dimension where quantum reality exists and at the same time serves as condition for semiclassical and classical systems and dynamics. In other words, biology allows overcome the dual distinction existing in physics between a physics for classical systems, namely the theory of relativity, and a physics for quantum phenomena and behaviors. A non-trivial effect is precisely the one that is present in a living organism that corresponds to quantum mechanics statements of principles: tunneling, superposition, entanglement, etc.

There are experimental evidences about the presence of quantum behaviors in the living beings. These non-trivial quantum effects can be summarized in table 1.

Table 1. Non-trivial quantum effects in biology

Example	References	Example	References
DNA mutations	[22]	Biomolecular systems	[30, 31]
Photosynthesis	[23, 24]	Senses: vision	[32]
Electron transfer in proteins	[25, 26]	Senses: olfaction	[33]
Magnetic sensing: Birds navigation	[23, 27, 28]	Consciousness	[34]
Enzyme-catalysed reactions	[29]		

More succinctly, quantum effects have been observed in olfaction, light harvesting, magnetic sensing (bacteria, insects, amphibians, birds, fish, sharks, rays) [35], photosynthetic energy transfer, photoenzymology, molecular motors, ion channels, and the discussion has been running about consciousness, particularly thanks to Hammeroff and Penrose [34, 36, 37].

These evidences have a clear-cut frame, the living cell which is the stance where quantum coherence exists and operates, and also where decoherence appears and dephasing takes place. Hence, without hesitation, the living cell can be said to be an interface between quantum coherence and the classical world. In other words, it can be said that the living cell is the threshold where the quantum and the classical worlds coexists and, at the same time, are differentiated. The point is a matter of level or degree, not of nature.

However, this must not be taken as if the field of quantum theory in general belongs only or mainly to the microscopic universe [38]. We would like to highlight that rather than thinking in volume and size, the quantum reality [39] refers, still better, to time, namely, microscopic times and processes. For there are macroscopic phenomena that explain and express quantum principles, too, namely superconductivity, superfluidity (the case of helium, most notably), laser light and dilute quantum gases. Moreover, the *real* time for the living beings happens to be – both biologically and culturally – the microscopic timescales, only that it is simply expressed in or as the macroscopic timescales, eventually. For the living beings, "eventually" might mean – too late, as it happens in the case of sickness or disease.

As it has been discussed thoughtfully in the literature, between the coherent and the classical states there is a semiclassical quantum state [40], and even a semiclassical quantum gravity. From the standpoint of physics, it can be argued that life is a semiclassical domain, and biology is the stance where quantum and classical principles coexist, reinforce each other and differentiate, at the same time, one from the other. QB, a research field on its own, is properly a threshold.

Being as it might be, the leading thread in the studies about QB is information [41], i.e. information processing. Now, according to Lambert et al. [23] "no *in vivo* observations of coherence have yet been performed." Hence, most of discoveries are either controlled experiments, or modeled or simulated ones. One reasonable claim about QB is that evolution enhances quantum behaviors – such as tunneling, entanglement, superposition, non-locality, and others – as a selective advantage. If so, evolution seems to have the last word, it appears [42]. It is sure that tunneling of electrons and protons are ubiquitous in biology.

According to Davies et al. [12], a biological cell also processes information and engages in signaling thereby actively performing computation. Taking up this idea in a more radical and punctual take, the computation carried out by the cell and, more generally, a living organism, has been called as biological hypercomputation [43]. Interactive (i.e. non-algorithmic and non-functional) massive parallel processing as well as multilevel simultaneous processing is carried out in and by the living beings and helps understanding and define life.

Thus, for instance, according to Davies et al. [12] "there are approximately 3×10^4 ATP production events per mitochondrion per second", which multiplied by the number of cells provide an enormous living chemical reactor whose entire harmony is simply fantastic. Non-trivial effects lie at the bottom of a healthy normal organism that moves in her environment and strives for living. According to Melkikh [13] the relationship of QI and movement can play an important role in the maintenance of coherent states, and can be taken as the real ground that supports, so to speak, the classicality of life as it can be perceived in the standard sense.

It is information and information processing that lie at the base of the autonomy of a living being. Negatively, a living system is closed to efficient causation and, positively stated, a living system is autonomous. Thus, autonomy is an upmost important characteristic of what a living system is and does, and autonomy [44] is a concept that cannot be reduced to (mere) physics. As Gabora *et al*. [11] claim we still need the equivalent in biology for the physical concept of force.

5. The role of information in QB and complexity

Information, i.e. information processing seems to be the thread that leads the homeostatic dynamic balance of a living organism. But it is also the medium that allows understanding the relationship on the living organism vis-à-vis the homeorhetic scale. A living organism does not just use information from the environment: it also processes that information, i.e. changes it, and creates new information that is hence after introduced and used in the environment. The processing of information can be taken as the very process of metabolizing.

From a theoretical point of view, against all traditional and standard interpretations Davies [45] argues that life started out as a classical complex system, and later on evolved some form of quantum behavior as a refinement. This point of view goes against the physicalist interpretation of reality in which quantum behaviors start at the outset of the universe, but later the universe became a classical system. Quantum behaviors in biology are a mark of evolution, and death can be said to be the ultimate triumph of classical physics. Thus, the very complexity of life marches along the path of quantum phenomena, to some extent [46]. The complexity of some of the most fundamental living processes encompass quantum information processing, quantum mutations, enzyme action, genetic code, and supersymmetry – and thereafter of course protein folding, DNA and RNA.

The philosophical consequence of QB allows claiming that life – which was the response of the universe to the puzzle of its own entropy – is a highly self-organizing system thanks to harnessing of quantum principles and rules. The arrow of complexification of the universe is thus the arrow of more complex organization, an argument that can be found in various contributions to Lineweaver at al. [47].

Communication travels faster than light in coherent nested time-dependent systems. Now, since living systems are aqueous systems, quantum field theory provides a solid ground for the information. i.e. communication processes carried out in and in-between the various living scales.

As mentioned, QB works at low time scales usually in the rank of femtoseconds, some in picoseconds and a few still in the range of microseconds. A living organism, we claim, is an asset of various temporal modes that make up a complex system. Thus, the complexity of a living being lies in the *synchrony* of different temporalities. Table 2 shows the relationship between the levels of the organism downwards and the corresponding time/scales along with the references found in the literature.

From the lower part of the table we can safely infer that the basic biomolecules (protein, DNA, RNA) inside a cell are in coherent states. As the complexity scales, time becomes slower, which, nonetheless is not to be taken in a hierarchical or sequential sense, for a living being is a chain of contemporary synchronic or synchronized temporalities from the bottom to the top, and vice versa acting in both positive and negative feedbacks. As Fleming et al. [35] say, coherence is present at all times and "is continuously being created, destroyed, and recreated by the interaction of the electronic system with the surrounding nuclear degrees of freedom".

Table 2. Time scales in living beings

Living organism layers	Time scale	Ref	Living organism layers	Time scale	Ref
Dephase of electronic states in photosynthesis	Femtoseconds	[48]	Motion detection	Milliseconds /seconds	[52]
Coherence between ground and excited states in photosynthesis	Femtoseconds	[48]	Motor coordination	Milliseconds /seconds	[52]
Fastest energy transfer in photosynthesis	Femtoseconds	[48]	Protein complexes processes	Hours/days	[51]
Photosynthetic fluorescence in chloroplasts	Picoseconds	[49]	Protein networks dynamics	Days	[51]
Primary events in vision	Picoseconds	[50]	Cell cycle / biological clock	Days	[51]
Molecular dynamics	Nanoseconds	[51]	Cell division	Days/weeks	[51]
Organelle subprocesses	Nanoseconds	[51]	Organ development	Days/weeks	[51]
Sound localization	Microseconds	[52]	Organism development	Weeks	[51]
Duty cycle in conscious events	Microseconds	[53]	Population dynamics	Billion years	[51]
Electron transfer	Microseconds/ Milliseconds	[35]			

Biology – and by extension the life sciences – are the ground out of which medicine and the health sciences grow and are nurtured. If so, then the highest expression of what a living being is can be grasped as her health. Health is the perfect outcome of a coexistence of coherent states along with classical ones. Such harmonious balance expresses itself as health and defines a living being in its best expression.

Indeed, as a particular case, the genetic code is a coherent system [9]. Ranging from attoseconds up to femtoseconds the living organism is coherent. This means more particularly: coherence exists and acts in the scales of femto, pico and some microseconds and in those levels the most fundamental grounds for biological processes and health are seeded. Indeed, "living cells show coherent global dynamics" [10]. Above femtoseconds classical states take the lead in the processes and understandings of a living organism.

We claim that a living system consists in a *synchrony* of the various temporalities it is made of – so much so that, from a philosophical point of view, a reasonable argument is that health consists precisely in the synchrony of the many-times in, and of, the organism. In contrast, disease or sickness consists in the breaking-down of such a synchrony. Some (indirect) hints for this argument can be driven from Bischof and Del Giudice [54]: "The main actor of the time evolution of the organism is not the ensemble of molecules but the ensemble of their correlations". The lack of synchrony can be seen as metabolic instability, and according to Melkikh [13], such instability can lead to aging and cancer.

6. Conclusions

QB has found in the study of the living cell the most solid ground upon which further research and reflection can be rooted. In general, histology serves as a most reasonable layer where either health or pathology can be safely identified in its crudest and most basic sense. Even though QB and synthetic biology have been questioned, according to Delgado et al. [53] they should be also a concern for civic society groups, sociologists and ethicists. Certainly, this is not a minor claim but one of large range and scope.

There is a general consensus as to the behaviors where non-trivial quantum effects act upon and within the organism. Such non-trivial effects concern times of very fast processes compared with the traditional standard time scales and velocities of science in history. The discussion has emerged as to the presence of quantum principles that can help understand consciousness. Here, we have left this issue aside for reasons of space and framework. However, the claim for the need for a revolution rather than an evolution concerning consciousness has been made. Along the same concern, Gabora et al. [11] called this as the need for a general theory of biocomputation.

There seems to be a consensus among complexologists and many theoretical biologists about the need and importance of synthetic approach for the understanding and explanation of complex systems and, hence after, of biological systems. In some cases, such a synthetic approach has been called a holistic and even a systemic one. We think that such names as "holism" and "systemic" approach are quite problematic, for they open up the door to confusing systems science, the sciences of complexity and holistic approaches and methodologies. We do not have here the room enough to provide arguments for such a distinction, and it is the aim of a different paper.

A merging of classical, semiclassical and quantum aspects can provide a new picture of life and the living systems. Here we have taken as ground the synchrony of such a merging. It is, we claim, an organic or alive merging that is both the basis, and the expression of, what a living being is about.

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