

Bridging the Gap: Does Closure to Efficient Causation Entail Quantum-Like Attributes?

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Received: 16 September 2010 / Accepted: 4 January 2011 / Published online: 1 February 2011
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Abstract This paper explores the similarities between the conceptual structure of quantum theory and relational biology as developed within the Rashevsky-Rosen-Louie school of theoretical biology. With this aim, generalized quantum theory and the abstract formalism of (M,R)-systems are briefly presented. In particular, the notion of organizational invariance and relational identity are formalized mathematically and a particular example is given. Several quantum-like attributes of Rosen's complex systems such as complementarity and nonseparability are discussed. Taken together, this work emphasizes the possible role of self-referentiality and impredicativity in quantum theory.

Keywords Closure to efficient causation · Robert Rosen · Complex systems · Relational biology · Quantum · Noncommutativity · Complementarity · Entanglement

Abbreviations

CEC Closure to efficient causation
GQT Generalized quantum theory

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1 Introduction

Sit down before fact like a little child, and be prepared to give up every preconceived notion, follow humbly wherever and to whatever abyss Nature leads or you shall learn nothing

Thomas Henry Huxley

Putting aside, at least for a moment, the enormous intellectual challenge imposed by an understanding of the nature of consciousness, modern science remains with two equally marvelous and defying problems, the *quantum* and the *living*. Both quantum and living systems depart from the classical mechanistic description in fundamental ways. This fact flies in the face of reductionism as a scientific program, and undresses the weirdness of these two poles (the extremely small and the extremely complex) when seen through the prism of classical physics.

Usually quantum physics and biology are perceived as two different scientific fields, aimed to account for two different domains of reality. Quantum theory was developed to describe the behavior of matter at the atomic-molecular scale, while theoretical biology is engaged in the description of primarily physicochemical systems at and above the macromolecular scale, which present extremely large levels of structural complexity and organization. Furthermore, quantum and living systems depart from the classical mechanistic description for (apparently) different reasons. Quantum weirdness is associated, among others, with the non-continuous transfer of energy, superposition of states, non-Boolean logics, wave-particle duality and the infamous legacy of quantum nonlocality (Greenstein and Zajonc 2006). Although quantum theory has been shown to be consistent with the actual behavior of microscopic quantum systems, its epistemological and ontological implications have shocked everyone in the field, and a lot of controversy is still ongoing since the time of Einstein's critical remarks (Rae 2004; Jammer 1974). On the other hand, although specific processes occurring within the living machinery have been well characterized by the tools of classical physics and chemistry, life itself does not admit a clear-cut definition in mechanistic terms (Woese 2004). Questions like what it takes to be alive and what kind of process brings matter from a non-living into a living state remain an insoluble conundrum so far (Brooks 2001; Peretó 2005). Not surprisingly, mathematical modeling of the living process in its totality has proved to be a *hard problem* (Rosen 2000). That is because the analytic process of fragmenting the system in its elementary fractions is not suitable for the task at hand, mainly due to the structural complexity of the system, the intertwined pattern of bottom-up as well as top-down interactions across different spatial and temporal scales, the presence of 'circular' self-referential causal loops, the anticipatory and inherently teleological nature of life, and the awkward capacity of autonomy and self-maintenance (Boogerd et al. 2007). As a consequence, the fabrication of artificial life from non-living material constituents, despite extraordinary efforts (Szostak et al. 2001; Rasmussen et al. 2004), remains an elusive chimera (Rosen 2000; Louie 2010a).

The picture sketched above acknowledges the non-classical character of quantum and living systems, underlies some of the main differences between them, and exposes several open issues waiting for deeper investigation in both research fields.

It is my conjecture that quantum and living systems are related in non-trivial ways, and that the comprehension of this link would be of crucial benefit not only for theoretical biology, but also for quantum theory. In other words, are the formal descriptions of quantum and living systems homomorphic to a certain extent? Is there any common ground to the bizarreness present in both quantum and living systems?

Bridging the gap between the domains of the *quantum* and the *living* is the imperative motivation for this essay. In Sect. 2, general considerations about the role of quantum physics in biology are given. Next, it is briefly discussed how this relationship was perceived by founding fathers of quantum theory and by the theoretical biologist Robert Rosen. Based on these early views and more recent approaches, it is argued that a ‘generalized’ quantum theory, preserving the most salient features of the formalism, would make the connection to biology meaningful and informative. Consequently, Sect. 3 presents a specific version of ‘generalized’ quantum theory. In addition, the conjecture of generalized entanglement in operationally-closed systems is discussed, and its relation to the Rosen’s theory of metabolic-repair (M,R)-systems is presented. In Sect. 4, the notion of closure to efficient causation (CEC), central to the Rashesvky-Rosen-Louie school of relational biology, is outlined and the notion of organizational invariance is discussed. In addition, a mathematical example of the ‘cyclic entailment’ property of (M,R)-systems is given. In the spirit of bridging the gap between the *quantum* and the *living*, a preliminary assessment of possible quantum-like attributes of Rosen’s complex systems is made in Sect. 5. Section 6 provides concluding remarks with open issues which merit further investigation.

2 The Role of Quantum Theory in Biology

The scientific inquiry of the relationship between the *quantum* and the *living* has a rich history, with many ramifications and diversity of approaches. It has ranged from a strictly reductionistic thesis where living processes are described in quantum mechanical terms, to weaker versions in which quantum notions (e.g. complementarity), which can be rigorously formalized beyond physics, can then be applied to the biological domain. This spectrum of strategies essentially realizes a one-way sailing trip from the *quantum* to the *living* domain. And I would consider fair to say that this research style has covered the entire scientific field so far. Another logically possible approach is to sail from the *living* to the *quantum* domain, i.e. to depart from a theoretical formalism that describe the fundamental aspects of the *living* and then, explore if its formal structure shares similar properties with quantum theory. A brief sketch of the early history of these endeavors could help to properly frame the conceptual linkage between quantum and living systems.

2.1 A Brief Historical Note

Niels Bohr, one of the founding fathers of quantum theory, gave his opening address at the meeting of the International Congress on Light Therapy in Copenhagen in

1932. The title of his speech “Light and Life”, already announced the great intellectual audacity of his ideas on the possible role that the principle of complementarity (as understood in quantum theory) has in the description and comprehension of biological phenomena (Bohr 1933). Bohr was a strong advocate of the limitation in principle of a mechanistic conception of reality and for him, the quantum description of atomic and molecular processes in the function of living organisms was not sufficient for a complete explanation of biological phenomena. Instead, he predicted that mutually exclusive physicochemical and teleological descriptions would be jointly necessary for a comprehensive understanding of life, a notion similar to complementarity in quantum physics. He understood this complementarity in biology as arising not by any means from the underlying quantum level, but believed it to be truly of biological origin because teleological notions of final causation (impossible to accommodate in a mechanism) were inherent to the nature of life (Bohr 1933). However, Bohr’s conjecture remained of a rather philosophical character, and it was not further formalized in terms of pairs of non-commutative observables, as in the case of position and momentum in ordinary quantum mechanics (McKaughan 2005). Max Delbrück was a postdoctoral researcher working with Bohr, and he could attend his Copenhagen opening address. Bohr’s insights on complementarity in the biological domain happened to be a turning point in Delbrück’s research career, and it shaped his life-time research program, where finding experimental evidences of biological complementarity was one of his leading motivations. Delbrück predicted ‘paradoxical’ situations where the mechanistic analysis of biological macromolecules, if pushed to its limits, would lead to an exhaustion of such an approach and the necessity of a complementary description of the *living* in its own terms (Delbrück 1949). Schrödinger, also a founder of quantum physics, assumed a more precautionous stance. In his influential book ‘What is life?’ he neglected at the outset the role of complementarity in biology and argued for the direct relevance of quantum principles to the stability of biological order (Schrödinger 1944). However, he also defended the view that the investigation of biological phenomena would lead to the discovery of ‘new laws of physics’. Remarkably, he considered these new laws to be based on a generalization of quantum theory that could then be meaningfully applicable to the biological domain (McKaughan 2005). In particular, he acknowledged the necessity of vicious causal cycles underlying the capacity of self-organization and self-maintenance of living systems (Schrödinger 1944). As in the case of Bohr and Delbrück, no formalism comprising these theoretical notions was developed. The theoretical incursion on the nature of life of these three eminent physicists had a large impact on the next generations of turning-to-biology physicists (e.g. Walter Elsasser (1969)). New research programs catalyzed the birth of molecular biology, eventually leading to the discovery of the DNA (Domondon 2006, Ogryzko 2008).

In this fertile context dominated mainly by physicists, a modest but seminal figure appeared in the thought-provoking landscape of these years. In the fall of 1957, Robert Rosen had joined as a PhD student the Committee on Mathematical Biology at the University of Chicago, where a radically new approach called ‘Relational Biology’ was founded by the biophysicist Nicolas Rashevsky (Rosen 2006). Remarkably, Rosen embarked in a two-ways ‘sailing trip’ to explore the

relationship between physical and living systems, or as he said “the tangible bridge between the rocks and the life” (Rosen 2006). From one side, he pioneered the application of the quantum (algebraic) formalism to describe the transfer of genetic information (Rosen 1960, 1974). In this enterprise, Rosen joined Bohr, Delbrück and Schrödinger in his claim that the applicability of the formal structure of quantum theory was not exhausted by its typical use in the description of atomic and molecular processes. Accordingly, he indicated that for an understanding of the physical basis of life, it is indispensable to create a more general ‘quantum-theoretic’ analysis of systems. In this approach, he stressed, systems are characterized by a set of observables with a definite algebraic structure together with a set of states on which these observables are evaluated. A more detailed account of his formulation can be found in Rosen (1960) and his previous publications cited there. The genius of Rosen included complementing a ‘quantum-theoretic’ analysis of living systems with a ‘living-theoretic’ approach to physical systems in general. Rosen’s life-time imperative was to develop a theory of abstract (M,R)-systems aimed to tackle the Schrödinger question ‘What is Life?’ (see Sect. 4 below). His theoretical work unveiled a quite unexpected and iconoclastic picture of the *living* (Louie 2007a), and from this ‘shore’, explored the general structure of causal entailment in physical systems (Rosen 1991).

2.2 Modern Quest for Quantum-Like Behavior in Biology

After more than 50 years since the pioneering work exposed above, the connection between quantum theory and biology has increased in scope and depth. Given that the interactive and multiscale complexity of life is of an epigenetic nature, the notion of complementarity in biology has regained new and empowered footing (Mazzocchi 2010). Nowadays, it has been proved that entanglement, one of the characteristic traits of quantum theory, is ubiquitous and robust in macroscopic systems (Vedral 2008). This has led to audacious speculations supporting the potential role of entanglement in the functioning of biological systems. A first step in this direction has been taken by researchers assessing the role played by quantum coherence in photosynthetic systems (Engel et al. 2007; Lee et al. 2007). This has paved the way to more substantial conjectures on the role of entanglement in epigenetic stability (Ogryzko 2008) and magnetoreception in the avian compass (Rieper et al. 2009). Beyond the strictly biomolecular level, other quantum traits (e.g. context dependency) have been incorporated in modeling approaches of higher-level neurocognitive processes such as: concept formation, information retrieval, decision making, non-Boolean logical reasoning and interpersonal empathic relationships (Abbott et al. 2008; Bruzza et al. 2009; Bruzza and Gabora 2009).

3 Generalized Quantum Theory: Quantumness Beyond Physics

The necessity of the quantum in the construction of existence: out of what deeper requirement does it arise?

John Archibald Wheeler (2006)

As seen in the preceding section, there is an explosion of experimental and theoretical approaches in biology and cognitive psychology that runs into the shore of the *quantum* while studying (apparently) classical systems above the atomic-molecular level. This surprising encounter calls for the identification of general principles of quantumness that could answer the question “why quantum theory?” as posed by Kitto (2008).

A generalized quantum theory (GQT) has been recently proposed by Römer and collaborators to describe systems to which a set of observables and a set of states can be meaningfully associated (Atmanspacher et al. 2002). In this scenario, the axioms which seem to be special to the microphysical world are relaxed, but the active operational character of observations is maintained. Thus, observables are identified with mappings acting on states giving rise to new states. In GQT, composition of two observables is an observable and two observables do not necessarily commute. Thus, the propositional structure of GQT is in general non-Boolean. GQT embodies the most general framework on which, by adding stepwise more structure in the form of new axioms, the full-fledged formal scheme of ordinary quantum theory with its zoo of ‘weird attributes’ can be reconstructed. For a detailed exposition, refer to the original formulation (Atmanspacher et al. 2002) and its applications in describing bistable perception of ambiguous stimuli (Atmanspacher et al. 2006; 2008).

A crucial quantum trait in this general framework is the noncommutativity of observables that lead to the notion of generalized complementarity and entanglement. In particular, holistic correlations may arise if for a composite system observables pertaining to the whole system are incompatible with observables of its parts. If the system is in an entangled state, in which a global observable has a well defined value, there are typical interactionless entanglement correlations between the results of measurements of local observables. One trouble with this framework is that it is not possible to distinguish between entanglement of epistemic and ontic origins. Associated with this caveat, the theory does not contain so far in its axiomatic structure an additional set of minimal conditions that should be met to get complementarity between local and global observables, in order for a system to reside in an entangled state. Therefore, it remains open what procedural steps should be followed to fabricate an entangled state of ontic origin, if at all possible.

However, in a later publication by von Lucadou et al. (2007), it was advanced an intriguing idea borrowed from the theory of autopoietic (self-reproducing) systems (Varela 1981), which was intended to describe the ubiquitous presence of hierarchical causal loops in the metabolic processes of the cell. von Lucadou et al. (2007) suggested that sufficiently complex composite systems, which in addition were organizationally closed, had the capacity to reside in an entangled state. For a detailed discussion of this hypothesis see von Stillfried (2010). If they were true, then entanglement is ubiquitous in biological systems, and not just because of their atomic-molecular composition, but by virtue of their relational structure. However, the rigorous examination of this hypothesis is hindered by the qualitative character of the definition of organizational closure (Varela 1981). Accordingly, Lucadou and coworkers did not incorporate the notion of organizational closure in the axiomatic structure of GQT, leaving obscure in which precise

way organizational closure was related to or even led to the capacity of a system to reside in an entangled state. Thus, a rigorous implementation of this powerful concept in a formal model of living systems is missing so far.

4 From GQT to Relational Biology

One can best feel in dealing with living things how primitive physics still is
 Albert Einstein

More clarification and insight on the relationship between entanglement and organizational closure could be obtained if the notion of closure could be rigorously formalized in mathematical terms. Rosen's (algebraic) theory of (M,R)-systems, a class of relational model that captures the central aspects of living systems, boldly relies on the central notion of closure to efficient causation (Rosen 1991; Louie 2006). Letelier et al. (2003) demonstrated that autopoietic systems are indeed a subset of (M,R)-systems, so that the notion of organizational closure is incorporated naturally in the mathematical formalism of (M,R)-systems. This may open new possibilities for investigating if indeed closure to efficient causation is a necessary condition for a complex system to reside in an entangled state as defined by QGT. Moreover, an examination of the properties of (M,R)-systems could identify, in addition to complementarity and entanglement, the presence of other quantum-like attributes in biological systems.

4.1 Algebraic Formulation of (M,R)-Systems: Closure to Efficient Causation

Rashevsky, the founding father of the school of relational biology, grasped the heart of his scientific view of life with the dictum "*Throw away the matter and keep the underlying organization*", meaning that it is the entailment of relations, and not the underlying physicochemical structures, that matters for an understanding of life. In this approach, organization is treated itself as a real and crucial aspect of the *living*, while the material components are considered as part of a specific realization of this organization. The reader is referred to the publications (Rosen 1991; Louie 2009) which explain in great detail the algebraic representation of (M,R)-systems.

Metabolic-repair (M,R)-systems are thermodynamically opened systems (e.g. a cell) that take raw materials and energy from the environment for supporting its internal functionality. A metabolic process is formally represented by the mapping f which produces from an input a (an element of the set A pertaining to the environment) an output b (an element of the set B , internal to the system).

Accordingly, for $a \in A$ and $b \in B$, metabolism is represented as:

$$f(a) = b \quad A \xrightarrow{f} B \quad f \in H(A, B), \quad (1)$$

where $H(A, B)$ is a set of mappings from A to B .

In Aristotelian parlance, a is the material cause of b and f is its efficient cause.

Note that in real metabolic networks f is a process degrading in time due to the finite lifespan of the metabolic components. In this sense, f needs to be repaired. Therefore, a new mapping ϕ is defined to represent the ‘repair’ process which produces new copies of f from the input b .

The repair process is then represented as:

$$\phi(b) = f \quad B \xrightarrow{\phi} H(A, B) \quad \phi \in H(B, H(A, B)) \quad (2)$$

where $H(B, H(A, B))$ is a set of mappings from B to $H(A, B)$.

The synergy of metabolic and repair processes creates a new situation where the mapping f is entailed from *within* the system, with b its material cause and ϕ its efficient cause. Note that in the causal path from ϕ to f , the mapping ϕ is placed at a ‘higher’ level in the hierarchy of causal entailment.

For the same arguments pointing to the necessity of repairing the mapping f , also ϕ needs to be repaired by another mapping that will eventually need to be repaired and so on. This clearly entails an unrealizable infinite chain of mappings. Rosen (1991) discovered that under certain conditions, the infinite regress is avoided because the mapping which creates new copies of ϕ may be already entailed within the metabolic-repair system. The new process that repairs the mapping ϕ , coined by Rosen as replication, is represented as a mapping β which produces from its input f new copies of ϕ .

Accordingly, replication is represented as:

$$\beta(f) = \phi \quad H(A, B) \xrightarrow{\beta} H(B, H(A, B)) \quad \beta \in H(H(A, B), H(B, H(A, B))), \quad (3)$$

where $H(H(A, B), H(B, H(A, B)))$ is a set of mappings from $H(A, B)$ to $H(B, H(A, B))$.

Note that the mapping β is placed at a ‘higher’ level than ϕ in the causal hierarchy. As said above, Rosen constructed the mapping β in such a way that it is already entailed in the network of metabolic and repairing processes. For this, Rosen defined the evaluation mapping \hat{b} so that:

$$\hat{b}(\phi) = \phi(b) = f \quad \hat{b} \in H(H(B, H(A, B)), H(A, B)) \quad (4)$$

If the mapping \hat{b} is invertible,

$$\hat{b}^{-1}(f) = \phi \quad \hat{b}^{-1} \in H(H(A, B), H(B, H(A, B))) \quad (5)$$

For this construction $\beta = \hat{b}^{-1}$, the replication mapping β is defined as the inverse of the evaluation mapping \hat{b} . In this case the set $H(H(A, B), H(B, H(A, B)))$ is isomorphic to the set B , and therefore β can be identified with an element b of the set B .

Constructing the replication mapping β as above reflects the enchanting character of (M,R)-systems, where each mapping is entailed by another mapping in a hierarchical cycle *within* the system. In other words, all efficient causes are contained in a closed path within the system; hence the system is closed with respect to efficient causation.

In this particularly case of CEC championed by Rosen (see other ways of CEC in Louie (2006)) f is the efficient cause of b , ϕ is the efficient cause of f , and b is the efficient cause of ϕ . Thus:

$$f(a) = b \quad \phi(b) = f \quad b(f) = \phi \tag{6}$$

4.2 Organizational Invariance in (M,R)-Systems

In his exposition of (M,R)-systems, Letelier et al. (2006) introduced the term *organizational invariance*, a term used to emphasize the essential notion of invariance of the pattern of connections or relations underlying the functional and structural dynamics of an (M,R)-system. This notion relies on the existence of the replication mapping β within the system. This invariance can be made mathematically explicit for a particular case of (M,R)-systems, called here *invariant (M,R)-system*, as follows.

An *invariant (M,R)-system* is constructed by introducing an additional constraint on the mapping ϕ . Let define the evaluation mapping \hat{a} :

$$\hat{a}(f) = f(a) = b \quad \hat{a} \in H(H(A, B), B) \tag{7}$$

If the mapping \hat{a} is invertible,

$$\hat{a}^{-1}(b) = f \quad \hat{a}^{-1} \in H(B, H(A, B)) \tag{8}$$

The constraint $\phi = \hat{a}^{-1}$ restricts the existence of the mapping ϕ as the inverse of the evaluation mapping \hat{a} . As a consequence the set $H(B, H(A, B))$ is isomorphic to the set A and ϕ can be identified with an element a of the set A . Note that this identification does not necessarily imply that an invariant (M,R)-system is closed to material cause, i.e. thermodynamically closed.

For an invariant (M,R)-system the Eq. 6 can be rewritten as:

$$f(\phi) = b \quad \phi(b) = f \quad b(f) = \phi \tag{9}$$

Combining all three Eq. 9 we obtain:

$$f(b(\phi(b))) = b \quad \phi(f(b(f))) = f \quad b(\phi(f(\phi))) = \phi \quad \text{or} \tag{10}$$

$$f \circ b \circ \phi(b) = b \quad \phi \circ f \circ b(f) = f \quad b \circ \phi \circ f(\phi) = \phi \tag{11}$$

where the three mappings $f \circ b \circ \phi$, $\phi \circ f \circ b$ and $b \circ \phi \circ f$ can be identified with the identity mapping in its respective set (see Louie (2007c) for more details). Thus:

$$\mathfrak{S}_0 = f \circ b \circ \phi = 1_{H_0} \quad \mathfrak{S}_1 = \phi \circ f \circ b = 1_{H_1} \quad \mathfrak{S}_2 = b \circ \phi \circ f = 1_{H_2} \tag{12}$$

where

$$H_0 = B, \quad H_1 = H(A, B) \quad \text{and} \quad H_2 = H(B, H(A, B)) \tag{13}$$

As seen in Eq. 12, an invariant (M,R)-system explicitly show a kind of organizational invariance operating on the system as a whole. In other words, whatever the structure of the three mappings f , b and ϕ , their cyclical composition is equivalent to the identity mapping, independently of any particular realization. In this sense, this invariance could be metaphorically matched up to a kind of

conservation law, i.e. the conservation of a global property of the invariant (M,R)-system embodied in the three mappings \mathfrak{S}_0 , \mathfrak{S}_1 and \mathfrak{S}_2 , which satisfy the Eq. 12. This global property could be tentatively interpreted as the *relational identity* of an invariant (M,R)-system. Note that the relational identity, being defined for the three sets H_0 , H_1 and H_2 , has an inherent hierarchical character.

In the context of this interpretation three remarks are appropriate. First, in an (M,R)-system the entailment of all efficient causes occurs within a hierarchical cycle, where both the hierarchy and the cycle are essential aspects of CEC (Louie 2007c). Second, although the model of (M,R)-systems above captures the essential relational character of the *living*, (M,R)-systems in general are not constituted by three components corresponding to the metabolic, repair and replication mappings, but are actually realized in a network of many processes which are intertwined in a very complicated fashion (Louie 2006). Third, although time does not enter into the Rosen's formalization of (M,R)-systems, the mappings f , b and ϕ , have an inherent dynamic character and in general change in time, due to e.g. internal processes of structural and functional decay, adaptation to external environmental contingencies, etc. The condition of CEC implies that the concerted action of all three mappings takes place simultaneously. In other words, introducing time as a parameter t , the mappings f_t , b_t and ϕ_t should be simultaneously evaluated.

Based on the formulation of CEC sketched above, Rosen (2000) and Louie (2007b, 2009) proposed a new taxonomy of natural systems, which presents a sharp dichotomy between simple systems (or mechanisms) and complex systems. In this taxonomy, simple systems have no closed path of efficient causation. Remarkably, physics has been usually constrained to the study of simple systems. On the other hand, complex systems contain at least one closed path of efficient causation, meaning that not all efficient causes are necessarily contained in a closed path, i.e. some efficient causes may be entailed from *outside* the system, or not entailed at all. Organisms or living systems are particular cases of complex systems. A natural system is an organism if and only if it is closed to efficient causation (Louie 2007b).

4.3 A Mathematical Example of Cyclic Entailment

Given the very abstract formalism of (M,R)-systems, mathematical examples of CEC would provide a clearer picture of how the three mappings f , b and ϕ could be constructed. As far as we know, only one arithmetical example has been provided in the literature by Letelier et al. (2006). In the following an algebraic example of an invariant (M,R)-system is provided.

Let define the mappings m_A , m_B and m_C as:

$$m_A(X) = -iAX \quad m_B(X) = -iBX \quad m_C(X) = -iCX \quad (14)$$

where $X \in M_2(\mathbb{C})$, i.e. the set of all 2×2 complex matrices, i is the imaginary unit, and A , B and C are also 2×2 complex matrices. If the three mappings entail each other in a cycle then:

$$m_A(B) = C \quad m_B(C) = A \quad m_C(A) = B \quad (15)$$

$$-iAB = C \quad -iBC = A \quad -iCA = B \tag{16}$$

Note that for this particular example, the metabolic, repair and replication mappings are $f = m_C$, $\phi = m_A$ and $\beta = m_B$, where ϕ is equivalent to an element A of the set $M_2(\mathbb{C})$ and β is equivalent to an element B of the set $M_2(\mathbb{C})$. Applying Eq. 12:

$$\mathfrak{S}_0 = \mathfrak{S}_1 = \mathfrak{S}_2 = 1_{M_2(\mathbb{C})} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \text{or} \quad CBA = ACB = BAC = \begin{pmatrix} -i & 0 \\ 0 & -i \end{pmatrix} \tag{17}$$

where:

$$A^2 = B^2 = C^2 \quad \text{and} \quad A^4 = B^4 = C^4 = 1_{M_2(\mathbb{C})} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{18}$$

A particular non-trivial solution to the Eq. 16 is (Louie 2010b):

$$A = \begin{pmatrix} -t & 1-t^2 \\ 1 & t \end{pmatrix} \quad B = \begin{pmatrix} -it & -i(t^2+1) \\ i & it \end{pmatrix} \quad C = \begin{pmatrix} 1 & 2t \\ 0 & -1 \end{pmatrix} \tag{19}$$

where t is a parameter, in general a complex number, and may be used to represent time.

The condition of ‘cyclic entailment’ is reasonably a very restrictive constraint imposed on the matrices A , B and C , so one may expect that there is a finite set of complex matrices satisfying Eq. 16. As the mappings m_A , m_B and m_C are defined as a multiplication-by-a-fixed-matrix, cyclic entailment requires that A , B and C are the fourth root of the identity matrix $1_{M_2(\mathbb{C})}$. Therefore, the set $S = \{m_X : X \in M_2(\mathbb{C})\}$ is actually a very small subset of $H(M_2(\mathbb{C}), M_2(\mathbb{C}))$, the set of all possible mappings from $M_2(\mathbb{C})$ to $M_2(\mathbb{C})$. The set S is nevertheless infinite, i.e. there are *infinitely* many mappings m_A , m_B and m_C satisfying the ‘cyclic entailment’ property (15). This example reaffirms that even for mappings with the simple structure of a 2×2 complex matrix, the ‘cyclic entailment’ property inherent to CEC is not only mathematically possible, but also that the number of non-trivial solutions is infinite.

Let us consider that the mappings m_A , m_B and m_C change with time. The three matrices A , B and C satisfy Eqs. 16–18 at each moment of the time parameter t . As a consequence, the global property we have coined as relational identity remains invariant and strictly equal to the identity matrix $1_{M_2(\mathbb{C})}$. When the parameter $t=0$, we obtain the Pauli spin matrices

$$A = \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad B = \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad C = \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{20}$$

which correspond to the observables of spin of a spin $\frac{1}{2}$ particle in the three spatial directions (Liboff 1980). This intriguing connection to quantum theory will be discussed in Sect. 5.

Note that given the one-to-one correspondence $m_X \leftrightarrow X$ the set S is isomorphic to $M_2(\mathbb{C})$. Thus when one is restricted to multiplication-by-a-fixed-matrix mappings, one does not have true hierarchy in the cycle, since $S \cong M_2(\mathbb{C}) \prec H(M_2(\mathbb{C}), M_2(\mathbb{C}))$. The hierarchical cycle formed by the mappings m_A , m_B and m_C collapses into a sequential cycle, i.e. a ‘degenerate’ case of CEC. However, this example is illustrative of some features of the abstract formalism of (M,R)-systems.

5 Does (M,R)-Systems have Quantum-Like Attributes?

Deduce the quantum from an understanding of existence

John Archibald Wheeler

After briefly presenting in Sect. 3 and 4 two specific theoretical formalisms of generalized quantum systems and living organisms, my aim is to bring back into focus an assessment of the possible relationship between the *quantum* and the *living*. As stated in the introduction, bridging the gap between these two domains may be of crucial benefit for both theoretical biology and for quantum theory. A preliminary step in this direction could be taken by exploring if certain properties of (M,R)-systems resemble quantum-like attributes. Note that these properties are also inherent to the more general class of Rosen's complex systems (Rosen 2000; Louie 2009).

5.1 Context-Dependence

For Rosen's complex systems, the property encoded by each mapping depends on the larger context of processes in which each functional component is embedded (Rosen 2000). For instance, in an invariant (M,R)-system, the mapping f does not depend only on the intrinsic features of a functional component of the system. Actually, the mapping f is causally entailed by the other two mappings ϕ and b . In such *contextual* situation, if the system interacts with its environment *without destroying* the hierarchical causal closure, then the three mappings f , ϕ and b may change accordingly, but in such a way that the relational identity of the system remains invariant. This feature of Rosen's complex systems resembles a similar situation expressed by the Kochen-Specker theorem in quantum theory, where the same operator may correspond to different observable outcomes, depending on the context brought by the measurement procedure (Kitto 2008).

5.2 Complementarity

Many disjoint descriptions are necessary to characterize a complex system in its totality (Louie 2009). Furthermore, it is impossible to incorporate every single description into a largest model that is suitable for describing the complex system as a whole. Therefore, the presence of a hierarchical causal loop in complex systems implies the necessity of complementary modes of descriptions. As already stated in Sect. 2, this is also a crucial feature of quantum systems (e.g. wave-particle duality; Greenstein and Zajonc 2006).

5.3 Nonfractionability

If a complex system is partitioned in two subsystems, then a functional property encoded in one mapping (e.g. f) of the original system can not be separated into two parts modeled by disjoint direct summands (see Louie 2009) for a detailed mathematical exposition), so that the property in question is manifest in only one of

these parts. This nonfractionability is associated with the absence of a one to one relationship between the relational organization of a complex system and the underlying physicochemical structure. As put by Louie (2009): “A functional organization cuts across physical structures, and a physical structure is involved in a variety of functional activities”. Nonfractionability entails a kind of property/relational holism, and it remains to be clarified if this form of holism leads to state nonseparability (entanglement) as in the case of physical quantum theory (Healey 2008). In any case, nonfractionability in complex systems is of ontic origin.

5.4 Self-Referentiality/Impredicativity

A hierarchical causal loop in a complex-system entails the presence of a hierarchical cycle of inferential entailment in its formal description (Rosen 1991). This is identical to the structure of impredicatives (Louie 2007c). Impredicativity implies that the definition or specification of an object invokes the object itself being defined as expressed by the fundamental hyperset equation $\Omega = \{\Omega\}$. This irreducible instance of self-referentiality and impredicativity is inherent to the algebraic structure of (M,R)-systems and complex systems in general. In the case of an invariant (M,R)-system, its self-referential and impredicative character is expressed in the Eqs. 9 and 12. For instance, the mapping f is causally entailed by the other two mappings ϕ and b , which themselves are specified by each other and the mapping f . In this sense, the specification of the mapping f invokes the mapping f itself. This self-referential character is at the heart of the invariance of the relational identity expressed in Eq. 12. Self-referentiality has been invoked in the context of physical quantum theory, specifically for topics such as the measurement problem (Chiara 1977; Breuer 1995), entanglement and the observer/observed duality (Filk and von Mueller 2010), organizational closure in quantum systems (Groessing 2005) and has even been qualified as a central feature of the quantum world (Small 2006; von Stillfried 2010). Specifically Small (2006) argued that quantumness can be accommodated by a self-referential logical structure. In an argument partially similar to that of Filk and von Mueller (2010), Small proposed that if the dichotomy between the observer and the quantum system is lifted, so that the observing and observed systems are embedded in a self-referential loop, then critical quantum features, specially entanglement and the measurement process, can be emulated by a causal loop of inferential entailment, i.e. an impredicative model. Therefore, if Small’s argument is valid, then self-referentiality is at the root of quantum-like behavior.

5.5 Cyclic Entailment/Pauli Matrices

As shown in Sect. 4.3, in an attempt to construct a particular algebraic example of an invariant (M,R)-system, the Pauli spin matrices were obtained as a particular non-trivial solution to the Eqs. 14–16, which mathematically represent the ‘cyclic entailment’ property of an invariant (M,R)-system. The Pauli spin matrices correspond to the observables of spin of a spin $\frac{1}{2}$ particle in the three spatial directions. Spin is an internal property of the quantum particle with no counterpart

in classical physics. Thus, spin is considered of intrinsically quantum character (Liboff 1980). This derivation of the observables of spin of a spin $\frac{1}{2}$ particle from the condition of ‘cyclic entailment’ suggests that spin is a quantum property with an intrinsic self-referential character, i.e. observables of spin in the three spatial coordinates cyclically entail each other according to the Eq. 16. The meaning of this alleged self-referential character of spin for physical quantum theory is an open question that merits further investigation.

6 Concluding Remarks

Rosen (2000), in his masterful collection of essays on life itself, called the attention of the scientific community at large with his proverbial declaration “Perhaps the first lesson to be learned from biology is that there are lessons to be learned from biology”. Has physical quantum theory (and GQT) something to learn from relational biology? My tentative answer is yes. As seen above, Rosen’s complex systems and in particular living systems seem to have properties that resemble quantum-like attributes. At the heart of this unexpected bridge between the *quantum* and the *living* is the existence of a hierarchical causal loop which entails self-referentiality and impredicativity. Therefore, within the Rosen-Louie’s taxonomy of natural systems, quantum systems may be viewed as a particular case of complex systems. This hypothesis brings quantumness under a new light and merits deeper scrutiny.

Acknowledgments I thank Prof. Harald Walach and Prof. Thomas Filk, for the time they have devoted to explain and clarify to me many of the philosophical and technical issues related to Generalized Quantum Theory. I thank Dr. Nikolaus von Stillfried, for his continuous encouragement and support. I also thank my wife, for her lovely support while I was working for and writing this paper. Special thanks to Dr. Aloisius Louie, current “torch bearer” of the school of relational biology, for being together with Prof. Robert Rosen’s scientific legacy, a great source of inspiration.

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