What can biology bestow to quantum mechanics?

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Abstract

The biological hierarchy and the differences between living and non-living matter are considered from the standpoint of quantum mechanics.

Keywords: quantum mechanics, hierarchical structures

1 Quantum Mechanics and Evolution

The most important discovering in natural sciences are in some or other way connected to quantum mechanics. There is also a bias that biological phenomena will be explained by quantum theory in future, since quantum theory already contains all basic principles of particle interactions and these principle had success in molecular dynamics, the basis of life. Nevertheless, it seems there is one concept in biology that could be hardly found in quantum physics. This is the concept of Evolution.

Evolution is often identified with self-organization. At least they have much in common. The self-organization is observed in both living systems, and non-living ones, e.g. in Belousov-Zhabotinsky reaction. It is noteworthy, that the approximation of the dissipative system simply means that the system is open, having income and outcome energy flux, and some of its degrees of freedom (d.o.f.) are not considered explicitly, instead only the energy flux going out of the system (say, in the form of radiation) via that d.o.f. is taken into account.

Very often the biological studies are regarded as opposite to the physical ones in the sense that they are qualitative rather than quantitative. At the same time the biology yields a number of concepts and basic facts those are not displayed explicitly in inanimate phenomena. We suggest the following three facts to be of principle importance:

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1. The properties of a living system are more than just a collection of its component properties. In other words, it is impossible to predict the whole set of properties of a complex biological system even having known all properties of its components and interactions.

2. The properties and functions of the components of a system depend on the state of the whole system. In other words, the same components being included in different systems may have different properties.

3. There is an Evolution — a process of creating new entities, forms and functions on the base of the existing components.

Thus, at least one thing is common for biology and quantum physics: in both the relation “the part - the whole” is extremely important. And in both this relation is not trivial.

\[ \Psi(x) = \prod_i \psi_i(x_i) \]

only for the systems of noninteracting particles.

The other thing is not so important. The properties (2,3) are implicitly based on the concept of scale: an entity to become a part of another entity should be in some metric (not necessary Euclidean) smaller than it. If the metric is Euclidean, or at least Archimedian, the evolution of the Universe can be said to go from small scales to large scales, in accordance to the Big Bang scenario. In this sense, the elementary particles and atoms do have (or had had) their evolution: at early times of the Universe the nucleons had been built of quarks, the nuclei from nucleons and so long. The same is true for not so far geological history: the minerals and crystals evolved from atoms and molecules.

We do not have an ultimate answer for the question, why the evolution had taken the way it has been going through. However, if the whole is more than the sum of parts and the properties of the parts depend on the state of the whole, there are some implications for quantum mechanics.

To describe a state (in common sense of quantum mechanics) of an object \( A_1 \) (interacting with objects \( A_2, \ldots, A_N \)) which is a part of an object \( B_1 \) we have to write the wave function in the form

\[ \{ \Psi_{B_1}, \Psi_{B_1A_1} \} \]  \hspace{.5cm} (1)\]

where \( \Psi_{B_1} \) is the wave function of the whole (labeled by \( B_1 \)), and \( \Psi_{B_1A_1} \) is the wave function of a component \( A_1 \) belonging to the entity \( B_1 \). For instance, \( A_1, A_2, A_3 \) may be quarks, and \( B_1 \) may be proton. The objects \( A_1, \ldots, A_N \) are inside \( B_1 \) and hence it is impossible to commute \( [\Psi_{B_1}, \Psi_{b_1A_1}] \) or to multiply them \( \Psi_{B_1}, \Psi_{B_1A_1} \). The functions
\[ \Psi_{B_1}(x) \text{ and } \Psi_{B_1A_1}(x), \text{ taken in coordinate representation, live in different functional spaces.} \]

To label the hierarchical object \( (i.e. \text{to set a coordinates on it}) \) one needs a hierarchical tree, like those used in biology to trace the evolution.

What we generally observe, is that each hierarchical level has its own symmetry group. This is \( SU_3 \) for quark level or isospin group for nuclei. So, each hierarchy level should be described by triplet \( I, G_I, X^{G_I} \),

where \( I \) is merely a label for the scale, \( G_I \) is the symmetry group at this scale, \( X^{G_I} \) is a topology on \( G_I \), or coordinates on the \( I \)-th level. The wave function of an object \( B^{I_1} \) of the level \( I_1 \) consisting of \( N \) objects \( \{A_{i}^{I_2}\}_{i=1,N} \) can be written as

\[
\Psi_B = \left\{ \psi_B^{I_1}(x^{G_{I_1}}), \{\psi_{BA_1}^{I_2}(x_1^{G_{I_2}}), \ldots, \psi_{BA_N}^{I_2}(x_N^{G_{I_2}})\}, \ldots \right\}. \tag{2}
\]

The Euclidean space is a particular case of the translation group

\( G_I : x \rightarrow x + b. \)

In both, physics and biology, the symmetry breaking plays an important role. It is known, that the amount of information written in DNA, if calculated as one nucleotide – one bit, is far from being sufficient to describe the formation of adult organism. Therefore, the information is likely to be written more effectively than just a technical plan of the organism. What is encoded, is probably a chain of bifurcation points to be undergone in growth process. What is observed is a hierarchy of symmetry breaking, which can be described as a change of topology. If the quantum mechanics is valid on the macroscopic, \( i.e. \text{on the organism level, we can say that the higher level of the hierarchy emerge as a result of} \)

a) self-organization \([1]\);

b) auto-evolution \([2]\);

c) \( \{\emptyset; \psi_{A_1} \otimes \psi_{A_2}\} \rightarrow \{\psi_B; \{\psi_{BA_1}, \psi_{BA_2}\}\}. \)

By empty-set \( \emptyset \) at the left hand side of the latter equation we denote the non-existing common “container” for two components \( \psi_{A_1} \) and \( \psi_{A_2} \); \( \psi_B \) is a new entity formed by \( \psi_{A_1} \) and \( \psi_{A_2} \). By no means we are saying that the object \( \psi_B \) exists before
its components, we just say that the wave function $\psi_B$ should exist as a possibility for its potential components to join each other. In this sense the possibility emerge first.

The hierarchy of biological system joints the hierarchy of non-living matter by means of genom – the sequence of macromolecules which prescribes the evolution of all living systems, from cell to organism.

The hierarchy levels of living and non-living matter

| Living matter       | Non-living matter |
|---------------------|-------------------|
| ...                 |                   |
| ecosystem           | molecule          |
| population          | atom              |
| organism            | nucleus           |
| organ               | nuclon            |
| cell                | ...               |
| organell            |                   |
| genome              |                   |

The place on an entity on the hierarchy tree and its distance from the position of the organism it belongs to determines the dynamical repertoire of the entity. The evolitional distance between maximal and minimal parts of the organism determines its ability of self-recovering.

If one end of *Hydra oligactis* (a simplest animal living in water) is cut off, the remaining cells react to the absence of this part by rearranging themselves, giving growth to new cells and form a complete animal. This process involves at least three levels:

Organism $\rightarrow$ Cell $\rightarrow$ Cell component.

The above described process of self-repairing can be described by following diagram

$$
\{\psi_A; \{\psi_{AC_1}, \ldots, \psi_{AC_N}\}\} + \Gamma \rightarrow \{\psi_A; \{\psi_{AC_1}, \ldots, \psi_{AC_K}\}\} + \{\psi_{C_{K+1}}, \ldots, \psi_{C_N}\} \quad (3)

\rightarrow \{\psi_A; \{\psi_{AC_1c_1}, \psi_{AC_1c_2}, \ldots, \psi_{AC_Kc_L}\}\} \quad (4)

\rightarrow \{\psi_A; \{\psi_{AC_1}, \ldots, \psi_{AC_N}\}\} \quad (5)
$$

On the first stage (3) affected by destructive action $\Gamma$, the part of the system, a block of $(N - K)$ cells is cutted of. The remainder

$$
\{\psi_A; \{\psi_{AC_1}, \ldots, \psi_{AC_K}\}\}
$$

(6)
does not form a complete organism any longer; the product of representations \( \bigotimes_{i=1}^{K} T(G_{C_i}) \) does not contain \( T(G_A) \). So, the wave function of the remainder \( \mathbb{R} \) breaks down to the third level hierarchy wave function

\[
\{ \psi_A; \{ \psi_{AC_1 c_1}, \psi_{AC_1 c_2}, \ldots, \psi_{AC_K c_L} \} \},
\]

which provides a possibility of building a representation tensor product, which contains \( T(G_A) \). On this third level the wave functions are being rearranged according to this tensor product and the missed second level blocks rebuild.

The process \( (2–3) \) clearly has its physical counterpart in the recombination taking place after photoionization in gaseous media.

\[
\begin{align*}
A + \gamma & \rightarrow A^+ + e_{(1)} \quad \text{(7)} \\
A^+ + e_{(2)} & \rightarrow A \quad \text{(8)}
\end{align*}
\]

The stage (7) is the ionization of the atom \( A \), the stage (8) is the recombination by capturing an electron \( e_{(2)} \) from the environment. On the first stage the symmetry group \( G \) of the atom \( A \) breaks down to that of the ion \( A^+ \) and electron \( e_{(1)} \)

\[
G_A \rightarrow G_{A^+} \otimes (SU_2 \otimes U_1) e,
\]

at the second stage the symmetry is restored.

The observations at all levels of the evolutional hierarchy, from simple organnels to complex ecosystems show that only neighboring levels can interact. The quantum nature of the interactions in this hierarchy could be used to understand, why a cutted skin recovers, but the arm cutted of is not being recovered. If the lost part of the organism has \( M \gg 1 \) hierarchical levels a \( M \)-level cascade process should run in the remainder to rebuild the lost part. A process of this type will require \( (a) \) a significant flux of energy, and at the same time a tremendous flux of negative entropy, required to restore the symmetry of the wave function of the whole organism by arrange the wave functions of its components. This combination is hardly possible.

Another fact, that can be considered as an argument for quantum nature of the evolution is the memory of the cell \( \mathbb{R} \). A clone of eucaryotic cells growing, some of the cells becomes differentiated from each other and acquire different functions. Physically, the differentiation goes on in response to the action of neighboring cells and external factors. However, it is remarkable that most eucaryotic cells usually persist in their specialized states after the influences the differentiation was caused by are eliminated. This can be thought of as the cells being in \( \psi_{AC} \) state rather than in \( \psi_C \).
2 Pauli principle

Let us recall the Pauli principle. *Two electrons of the same atom can not be in the same quantum state.* Or more generally: *Two fermions of the same system can not be in the same quantum state.* The latter is a direct consequence of the fact that the wave function of a fermion system should be antisymmetric with respect to particle transposition; if two of the particles are identical, *i.e.* are in the same quantum state, the wave function should be both symmetric and antisymmetric, and hence is exactly zero.

If we suggest the interactions of neighboring levels is important only, we can say that, *two fermions belonging to the same system of the next hierarchical level can not be in the same state.* Therefore, it is impossible for two electrons in atom to have the same quantum numbers (*n*, *l*, *m*), but is it possible for two electrons of the same molecule to be in the same state? It seems evident that two electrons of different macroscopic objects can be in the same state. *But is it really possible for two electrons of the same molecule?*

So, the real question is: what should we really mean by “the hierarchy level next to atom”? There is no common sense answer to this question, but if the generalization of Pauli principle formulated above, is valid, and the only question is what is the next hierarchical level, the matter can be experimentally investigated, at least in principle. To some extent, the idea of possible experiment of this type have been already suggested by D. Home and R. Chattopadhyaya [4]. The setup of their experiment is aimed for living systems, so it is discussed in the next section.

3 Wave functions of living and non-living systems

The presence of hierarchical structure of interactions considered above in this paper *necessary, but not sufficient condition* for a system to be alive. For instance, we can imagine a two level hierarchical system (see Fig. 2 below) with coupling constants of the lower level dependent on the state of higher level and *vice versa.*

The toy-model Hamiltonians (9) accounts for the interaction of two blocks with co-
ordinates \( x_i, i = 1, 2 \), comprised of two spins \((s_1^i, s_2^i)\). The blocks are interacting with the potential that has position-dependent and spin-dependent parts \( W = U + \Lambda \). The effective mass of each block depends on the spin-spin interaction of its components, with their interaction constant depending on the velocity of block as a whole.

\[
H = \frac{m_1 x_1^2}{2} + \frac{m_2 x_2^2}{2} + U(|x_1 - x_2|) + \Lambda(S_1 S_2)
\]

\[
m_1 = m_0 + \lambda(x_1^2) s_1^1 s_1^3
\]

\[
m_2 = m_0 + \lambda(x_2^2) s_2^1 s_2^3
\]

\[
S_1 = s_1^1 + s_1^3
\]

\[
S_2 = s_2^1 + s_2^3
\]

The living and non-living systems are different in the complexity, in the Kolmogorov sense, of their evolution operators. The Hamiltonian for a non-living system can be constructed using the representations of the symmetry groups of its components and their interactions. This description is shorter than a time seria of the matrix elements \( E_{mn}(t) \) taken at each moment of time. For a living system the shortest description of the evolution operator may be the time seria \( E_{mn}(t) \) itself, or its subseria.

Let us formulate the difference in the language of group theory:

1. We can assert, that for nonliving systems the knowledge of irreducible representations of the component wave function and a symmetry group which accounts for their interaction completely determines the wave function of the whole. For example, the wave function of nucleon can be obtained since we know it consists of quarks \((SU(2) \text{ representation with respect to rotations, } SU_F(3) \text{ internal symmetry - flavor interaction})\).

2. In contrast, we assert that the wave function of a living system is constrained, but not completely determined by the representations of symmetry group of its components. This means, that even if we know the wave functions of all components of a living system we can not predict the behavior of the system without a separate knowledge of the next level wave function, i.e. the wave function of the whole. If it is so, a living system should be described by a wave function of the type (2), with \( \Psi_B \) being the wave function of the whole, \( \Psi_{BA} \) being the wave functions of the components.

Now, let us turn to the possibility of experimental testimony of these two alternatives. If long biological macromolecules, the DNA, can be used as a device for quantum measurement [4], it indirectly means that if a photon absorbed by a DNA molecule, the wave function of the whole molecule flops from one quantum state into another. But
the DNA molecule itself consists of smaller molecules. So, there are two alternatives: either the absorption of a photon changes the wave function of the DNA only by changing the wave function of one of its components, or it changes the wave function of the whole DNA. If the latter is the case, then due to the interaction between the whole and its parts, the absorption of the photon at one edge of DNA can can be immediately detected at the opposite edge, at least in principle.

To conclude with, we should mention that possible distinction between living and non-living systems, itemized above in this paper, makes a new point in the Schrödinger cat problem

$$\frac{1}{\sqrt{2}}|\text{cat dead}\rangle + \frac{1}{\sqrt{2}}|\text{cat alive}\rangle =?$$

In hierarchical formalism, the wave function of a dead cat is constructed from the direct products of the irreducible representations of its parts. The wave function of the alive cat comprise the wave function of the whole cat as well. So these two wave function live in different functional spaces.

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Appendix

The structure of the Hilbert space of hierarchical states

The Hilbert space $\mathcal{H}$ of hierarchical states (4) may be endowed with a natural structure of vector space:

$$\psi_1, \psi_2 \in \mathcal{H}, \quad a, b \in \mathbb{C} \Rightarrow \psi = a\psi_1 + b\psi_2 \in \mathcal{H},$$

where $\psi_1, \psi_2$ are hierarchical wave functions defined by (4). By definition

$$a\Psi_B = \left\{ a\psi^I_B(x^{G_1}), \{ a\psi^I_{B A_1}(x^{G_{12}}), \ldots, a\psi^I_{B A_N}(x^{G_{1N}}) \} \right\}, \ldots \right\}.$$  \hspace{1cm} (10)

The addition operation (“+”) is defined componentwise:

$$\left\{ \Phi^1, \{ \Phi^2_1, \ldots, \Phi^2_N \}, \ldots \right\} + \left\{ \Psi^1, \{ \Psi^2_1, \ldots, \Psi^2_N \}, \ldots \right\} \quad = \quad \{ \Phi^1 + \Psi^1, \{ \Phi^2_1 + \Psi^2_1, \ldots, \Phi^2_N + \Psi^2_N \}, \ldots \},$$  \hspace{1cm} (11)

where the group indices of Eq.(4) are substituted by numbers for simplicity.
Nevertheless, it may seem attractive to extend the structure $\mathcal{H} \to \tilde{\mathcal{H}}$ by incorporating some unphysical states. Let $\{e_{i1}\}$ be the basis for the first level of hierarchy ($I_1$), let $\{e_{j1}^2 \otimes \ldots \otimes e_{jN}^2\}$ be the basis for the second level ($I_2$) etc. Then we can define $\tilde{\mathcal{H}}$ as linear span

\[ \left\{ \sum_{i_1} a_{i1}^1 e_{i1}^1, \left\{ \sum_{j_1} a_{j1}^2 e_{j1}^2, \ldots, \sum_{j_N} a_{jN}^2 e_{jN}^2 \right\}, \ldots \right\}, \] (12)

where $a_k^j \in \mathbb{C}$ are arbitrary complex numbers.

Evidently, not all linear combinations of the form (12) are physical states. To illustrate this, let us consider a system $B$ (first hierarchic level) constituted of two subsystems $B_1$ and $B_2$ (second hierarchic level). Let us ascribe the spin $1/2$ to $B_1$ and $B_2$ and write down the possible spin states of the whole system. The states

\[(1, (1/2, 1/2)) \quad (-1, (-1/2, -1/2)) \quad (0, (1/2, -1/2)) \quad (0, (-1/2, 1/2))\]

are physically possible. In contrast, the state

\[(-1, (1/2, 1/2))\]

is physically impossible, but its structure does not contradict the definition (12).

To be more formal, we can use the language of group theory. Let $T^2$ be the irreducible representation of $G_{I_2}$ used to construct the basic set $\{e_{j1}^2 \otimes \ldots \otimes e_{jN}^2\}$. Let the product of representations used to construct the second hierarchy level basis be decomposed into direct sum of irreducible blocks

\[T^2_1 \otimes \ldots \otimes T^2_N = \oplus_k D_k.\] (13)

Then only those basic vectors $e_{i1}^1$ can be considered as physical (for the first hierarchy level, $I_1$), which transform according to one of the irreducible representations present in the r.h.s of (13) (built for the second hierarchy level, $I_2$). Exactly as it takes place in the angular momentum theory.

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