Neuro-Quantum Parallelism in Brain-Mind and Computers

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Specific characteristics of mind and computers (synergetic and neurocomputers, especially) are reviewed. The characteristics are presented which future computers would have to possess in order to be treated as mind-like. It is argued that for human consciousness a coherence of neural, quantum and virtual (attractor) levels are necessary. Mathematical analogies of the neural-network-theory and quantum mechanics are discussed. These analogies may be a mathematical framework for a research of multi-level cognitive isomorphisms involving complex systems of neurons/synapses, subcellular structures, quantum "elements" (spins etc.), and attractors, because the principles of their collective dynamics are level-invariant.

1 Mind—Computer: A Comparison

Mind is a sort of computer: it is an information processing system. However, it is also much more than that. It is easy to cite many specific characteristics of mind discussed in philosophy and psychology, but neglected by artificial intelligence: e.g.,

- phenomenal qualia: experiences of vision, audition, olfaction, etc. [6];
- consciousness including self-awareness [31];
- subjectivity and self-concepts (the "I");
- associative contextuality par excellence [27, 30];
- meaning; evaluation; judgments [6];
- high flexibility and fuzziness [34];
- evolution of virtual structures and corresponding biological "media" [1, 21, 7], including thermodynamical constraints [37].

Here we will also be interested in any possibility of creating computers with mind-like qualities using artificial neuronal and quantum devices.

In addition to

- high computational power already reached by computer technology,
- logic-based computer-reasoning using semantic networks and specific rules,
- parallel, but still mechanistic, architecture of neurocomputers [29],
- simple categorization and pattern-recognition abilities, etc. [15],
- of contemporary computers, the mind-like computers of future will need:

- complex-system-architecture with self-organization and adaptation abilities [15];
- very much higher degree of indirect interaction with the environment;
- very high complexity overriding some critical values of parameters controlling the phase transitions of the system's structure [16];
- well-differentiated and large hierarchical organization with strong intra-layer couplings and symmetric inter-layer structures;
- specific responses to environmental stimuli with formation of reversible isomorphic states;
- formation of attractors-gestalts of high order [17].

The first step in this direction are:

- *neurocomputers* based on neural network models [12, 22], especially attractor neural networks [1];
- Haken's *synergetic computers* based on models of complex physical systems [15];
- artificial life simulations; etc.

Neural and synergetic computers already provide a good basis for:

- perceptual categorization and feature extraction;
- pattern-recognition as specific pattern-formation or selective pattern-reconstruction (invariant under translations, rotations, scaling, deformations, etc.);
- content-addressable memorizing, including specific and selective memory-recall (or forgetting);
- complex interaction-patterns providing the strong context-dependence;
- multiple-knowledge concept: integrating various views;
- reflective and recursive processing, also constituting fractal properties (scale invariance).

Associative neural networks of the Hopfield type provide [20] are the simplest model of a symmetrical complex system. This simplest model includes the system of basic elements (formal neurons), and the system of connections (formal synapses) which represent strengths of interactions between two connected neurons, or the correlation between them. Symmetrical means that the same signal-summation-process is going on in every neuron, and that every synapse changes its strength according to the same Hebbian "learning rule" (i.e., proportionally to the correlations of neuronal activities) [14].

In such a network parallel-distributed neuronal patterns which act as attractors are formed [1]. Attractors represent categories or gestalts which are isomorphic to some environmental objects. Gestalts are some qualitative unities arising from collective system-dynamics which cannot be reduced to the sum of activities of the constituting basic elements alone. Patterns-qua-attractors thus represent some mind-like representations. They are not only some collective neuronal states, but also encode specific information. Whenever a given object occurs in the environment, reconstruction of a specific neuronal pattern-qua-attractor is triggered. Actually, a superposition of the sensory stimulus-pattern and the most similar memory-patterns (coded in the matrix of synapses) is formed in the system of neurons. The system of neurons is a carrier of that information which is currently being processed (i.e., which is the most important in that specific context or those circumstances, which is mostly correlated to the state of environment). So, the pattern of neuronal activities represents the object of consciousness. The neurons, and whole patterns, are constantly interacting, and their activities reflect each other; but in spite of feedback-based interaction-paths, this recursive dynamics is, it seems, not enough for the "real" consciousness as a unified self-referential system-process par excellence.

2 Consciousness: Need for the Quantum

It seems that also a very large and complex neural network would not be sufficient for consciousness. There are indications that consciousness is connected with quantum phenomena

[24, 28, 36, 39, 40]. The main reasons for this hypothesis are the following:

- Quantum systems are the microscopical basis of all physical processes and of biological or psychophysical processes also: all the classical world arises from the overall quantum background.

- Quantum systems transcend even the division of particles and waves, or interactions, or fields [9, 23]. Quantum systems, especially sub-quantum systems, are holistic in nature [5] - they cannot be satisfactorily analyzed into interacting fundamental elements, but act synthetically as indivisible parallel-distributed processes. As such, they are good candidates for correlates of the unity of consciousness.

- Neural networks with their rigid neurons and synapses, in spite of their very subtle virtual processes (often not enough understood) [33], seem to be too mechanistic, too discrete and too deterministic for consciousness and phenomenal qualia, i.e., qualitative perceptual experiences.

On the other hand, *all thought-processes, including consciousness, seem to arise from complex-system-dynamics.* Objects of consciousness and stream of conscious thought seem to be represented in some physical or at least informational (virtual) "medium". That "medium" has to be a complex-system which only is enough flexible, fuzzy, adaptive, and has good self-organizing and recursive abilities. Because the *mathematical formalism of the neural network theory is confined to the collective system-dynamics, it remains to a large extend valid also for complex systems of other basic elements* [32]. So, our formal neurons and formal synaptic connections are not necessary biological neurons and synapses (or, in models, artificial neurons—processors). There are various candidates in biological systems which may be modeled in a neural-network-like way and have, hypothetically, a relevant role in micro-cognition processes:

- *dendritic trees* where a dendrite (which is a part of a neuron) has a similar summation-task to that of a neuron (K. Pribram [17], B. MacLennan [25]);

- subcellular structures: *cytoskeleton*, especially *microtubules* (they are, for example, located in neuron's axons), which may have a role of an interface between the neural and the quantum level (S. R. Hameroff [18], R. Penrose [28]);

- presynaptic vesicular grid—a paracrystalline hexagonal lattice in the pyramidal cells (J. C. Eccles);

- webs of quantum particles (e.g., electrons) with their *spins* (A. Stern [41]);

- a "continuum" of *sub-quantum "beables"* (J. S. Bell, B. J. Hiley) or "hidden variables" (D. Bohm); etc. [4, 19]

There are several compact alternative theories which have been proposed as models of various cognitive levels using mathematical language:

- holographic and holonomic brain theory (K. Pribram) [17];

- quantum neuro-holography (W. Schempp [35]);

- synergetic computers by H. Haken extended to quantum domain;

- generalized-laser-theory of the brain as a "hot" (sub)cellular automaton (J. Šlechta) [37, 38];

- Bohm-Hiley ontological interpretation of quantum mechanics including the notions of implicate order and sub-quantum holomovement ("vacuum-processes" in old terminology) [9];

- Everett's "many-worlds" interpretation of quantum mechanics [11] and the quantum computer by D. Deutsch [10].

3 Coherence of Neural, Quantum and Virtual Processes

The *unintentional consciousness ("consciousness-in-itself", "pure" consciousness)*, especially transcendental (mystical) consciousness, may be associated with the quantum field, or better, with the "overall sub-quantum sea" [13] - the holomovement by Bohm/Hiley. On the other hand, *intentional consciousness (consciousness about some object of consciousness)* cannot be associated merely with a specific quantum-informational state. If a specific mental representation is processed under control of consciousness, this specific representation, which is associated with a pattern of neural activity, is coupled or correlated with a specific quantum eigenstate which was explicated by the "wave-function collapse".

The "wave-function collapse" is a transition of the quantum state from a state described by a linear combination of many quantum eigenstates to a "pure" state which is one eigenstate (one eigen-wave-function) only. Simply to say, a superposition of many "quantum patterns" is transformed into a single "quantum pattern" only.

Collapse of the wave-function means a selective projection from subconscious memory to the conscious representation which was explicated from the memory. There are two possible versions of memory and memory-recall: the quantum one (just mentioned), or the classical neural one. Using another point of view, subconsciousness-consciousness transitions may also be related to laser-like phase transitions from individualized to collective dynamics [37, 38] when a certain threshold is exceeded. Memory may be a parallel-distributed pattern of the system of synaptic connections, but it may also be more subtle ("parallel worlds" of the many-world interpretation of quantum theory by Everett [11], implicate order of Bohm/Hiley, etc.).

Mind is necessarily a multi-level phenomenon, because we cannot totally divide intentional consciousness from the object of consciousness which may be an internal virtual image or a real external object. If unintentional consciousness is of quantum nature, virtual representations are associated with neuronal patterns, and external objects are of classical nature, then *intentional consciousness is necessarily a combined* QUANTUM-NEURAL COHERENCE *which is furthermore correlated with a classical state in the (external) environment.*

There is still a question of relationship between quantum-informational states and virtual representations. Virtual representations are usually based on neuronal patterns which act as attractors. However, attractor is a contextual gestalt-structure which cannot be reduced to the neuronal pattern (which represents attractor's kernel) alone. So, virtual structures are attractors which thus over-build their constitutive material basis. They represent complex webs of relations and ratios; a neuronal pattern is an attractor only if it is more stable and more dominant in the system-dynamics than the neighboring neuronal configurations in the configuration-space [34].

Quantum mechanics governed by the Schrödinger equation does not exhibit attractors, but they are formed in the case of the "wave-function collapse". In that case, because of the interaction of a classical macroscopical system (either measurement apparatus, or environment, or our sensory apparatus) with the quantum system, the wave-function "collapses" and a specific quantum eigenstate (a "quantum pattern") occurs as an attractor. So, there are quantum virtual structures also, and they cannot be reduced to a quantum eigenstate alone, because they occur only as a result of interaction with a classical system. Thus quantum virtual structures are (re)constructed as a result of so-called quantum measurement where the "measurement apparatus" may be our sensory and associative neural system directly, or a machine which is then observed by that neural system - that's an indirect way. In both alternatives the "wave-function collapse" occurs as a result of a specific interaction with a classical system. The probability of the "collapse" is very much higher if the interaction is *knowledge*-based (as in the case of a radio: if we *know* the right frequency, we are able to receive the associated information).

So, again, virtual structures cannot be reduced to the corresponding state of a neural or quantum "medium", although they are closely related to it! Virtual states are always non-local, or parallel-distributed, respectively. They cannot be measured, or can be measured only indirectly—over states of their corresponding neural or quantum "ground". For the sake of modeling and analysis we indeed have to distinguish neural, quantum and virtual levels, and environmental influence also. In an "organic synthesis" they are, of course, involved in an united process, including environment. That united process is called (intentional) consciousness.

Our hypothesis is that intentional consciousness (we are conscious of some object of consciousness) emerges from collective system-dynamics which is triggered from environment (see also [37, 38]). It is a result of evolution that neurobiological systems are capable of such a specific self-referential response to stimuli from external and internal environment. On the other hand, having in mind mystical and meditational experiences [34] we can argue that a deeper processual background of these specific information-processes is unintentional (pre)consciousness which is as fundamental as various material processes [4]. Šlechta's work [36] is pioneering in proposing detailed "mechanisms" for quantum micro-cognitive processing in a mathematically well-formalized way. As a complement to Šlechta's original approach, this author is proposing a more system-theoretical view of these "mechanisms".

4 Mathematical Formalism of the Quantum Theory is Analogical to That Describing Associative Neural Networks

We have presented some reasons to investigate parallels between quantum processes and neural-network-processes. Several mathematical analogies will now be discussed.

4.1 Neuronal-State-Vector ⟷ Quantum Wave-Function

In neural network theory the state of the system of neurons is described by $q(\vec{r},t)$ which denotes the activity of an individual neuron (located at $\vec{r}$) at time t. *Neuronal patterns* $\vec{v}$ are special neuronal configurations $\vec{q}$ which represent some information. In quantum theory the state of the quantum system at location $\vec{r}$ and time t is described by the wave-function $\Psi(\vec{r},t)$ [23].

4.2 Neuronal State Is a Superposition of Neuronal Patterns ⟷ Quantum Wave-Function Is a Superposition of Quantum Eigen-Wave-Functions

A neuronal configuration $\vec{q}$ may be described as a linear combination of neuronal patterns $\vec{v}_k$ ($k = 1, \ldots, p$ where p is the number of patterns represented simultaneously in the combination). Similarly, a wave-function Ψ can be described as a linear combination of eigen-states ψ_k ("quantum patterns"):

$$q(\vec{r},t) = \sum_{k=1}^{p} c_k(t)\ v_k(\vec{r}) \quad (1)$$

$$\Psi(\vec{r},t) = \sum_{k=1}^{p} C_k(t)\ \psi_k(\vec{r}). \quad (2)$$

4.3 Ortogonality and Normality

Both sets of vectors, $\vec{v}_k$ and ψ_k, have the properties of ORTHOGONALITY and NORMALITY.

4.4 Coefficients of the Series: Synergetic Order Parameters ⟷ Quantum Probability Coefficients

C_k are the quantum probability coefficients and c_k are the neural order parameters. In the linear combination each pattern is represented by a corresponding coefficient. The coefficients describe how much a specific pattern is represented in the actual state of the system, or how probable it is that the corresponding pattern will be recalled (reconstructed, explicated from the superposition of many patterns). Thus, the time-dependent coefficients encode quantitatively the *meaning* of their patterns. They describe how strong a role a given pattern has in contextual system-dynamics. Mathematically, coefficients describe projections (in terms of scalar products, in Hilbert space, for example):

$$c_k(t) = \langle \vec{v}_k, \vec{q} \rangle = \iint v_k(\vec{r})^* q(\vec{r},t) d\vec{r} dt, \quad (3)$$

$$C_k(t) = \langle \psi_k, \Psi \rangle = \iint \psi_k(\vec{r})^* \Psi(\vec{r},t) d\vec{r} dt. \quad (4)$$

Asterisk denotes the operation of complex conjugation. If variables $\vec{v}_k$ or ψ_k are real, we may delete the asterisk.

4.5 Spatio-temporal Integration of Neuronal Signals $\longleftrightarrow$ Feynman's Version of the Schrödinger Equation

The dynamical equation for one neuron is essentially a spatio-temporal integration of signals from all other neurons which are connected to that neuron. So, the state of a neuron at position $\vec{r}_2$ and time t_2 is given by J-weighted summation of all signals and the whole history of signals[1]:

$$q(\vec{r}_2,t_2) = \iint J(\vec{r}_1,t_1,\vec{r}_2,t_2) q(\vec{r}_1,t_1) d\vec{r}_1 dt_1 \tag{5}$$

where $J(\vec{r}_1,t_1,\vec{r}_2,t_2)$ is the strength of an individual synaptic connection. J's may be the transmissions of real synaptic connections between two neurons (spatially separated, but realized at the same time) or correlations between states of different neurons at different times, represented at least virtually.

In non-relativistic quantum mechanics the dynamical equation is the Schrödinger equation which is here written, analogously to the neural equation (5), in Feynman's form [19]:

$$\Psi(\vec{r}_2,t_2) = \iint G(\vec{r}_1,t_1,\vec{r}_2,t_2) \Psi(\vec{r}_1,t_1) d\vec{r}_1 dt_1 \tag{6}$$

where $G(\vec{r}_1,t_1,\vec{r}_2,t_2)$ constitutes the Green function or propagator of a quantum system [2]. The propagator G is a matrix which describes a parallel-distributed transformation of the whole system from an initial state to the final state. The system transforms itself into a new state by exhibiting numerous internal interactions between its constitutive "quantum points" (some mathematical "basic elements" of the system). Informationally, such a transformation ((5) or (6)) is *association*.

[1] t_2 is always greater than t_1—because of the "arrow of time".

4.6 Encodings of Pattern-Correlations: Synaptic Transmissions $\longleftrightarrow$ Green Functions

The kernels of dynamical equations (5) and (6) are given as a *correlation* function. The transmission of an individual synapse is determined by the Hebb learning rule as a correlation between its two neurons participating in various patterns $\vec{v}_k$:

$$\begin{aligned} J(\vec{r}_1,t_1,\vec{r}_2,t_2) &= \sum_{k=1}^{p} v_k(\vec{r}_1,t_1)\, v_k(\vec{r}_2,t_2) \\ \text{or} \quad J(\vec{r}_1,\vec{r}_2) &= \sum_{k=1}^{p} v_k(\vec{r}_1)\, v_k(\vec{r}_2). \end{aligned} \tag{7}$$

Similarly, the Green function [2] is given as a sum of auto-correlations of individual "quantum patterns" ψ_k:

$$\begin{aligned} G(\vec{r}_1,t_1,\vec{r}_2,t_2) &= i\sum_{k=1}^{p} \psi_k(\vec{r}_1,t_1)\, \psi_k(\vec{r}_2,t_2) \\ \text{or} \quad G(\vec{r}_1,\vec{r}_2) &= i\sum_{k=1}^{p} \psi_k(\vec{r}_1)\, \psi_k(\vec{r}_2). \end{aligned} \tag{8}$$

4.7 Relativistic Analogy

Analogy of Subsection 4.6 can be extended to relativistic domain as well. In the relativistic case the role of G is realized by the $S-matrix$ [2]. Its elements are:

$$\begin{aligned} S(\vec{r}_1,t_1,\vec{r}_2,t_2) &= -i\sum_{k=1}^{p}\sum_{j=1}^{2} \psi_k^j(\vec{r}_1,t_1)\, \psi_k^j(\vec{r}_2,t_2) \\ &\quad \text{if} \quad t_2 > t_1; \\ S(\vec{r}_1,t_1,\vec{r}_2,t_2) &= i\sum_{k=1}^{p}\sum_{j=3}^{4} \psi_k^j(\vec{r}_1,t_1)\, \psi_k^j(\vec{r}_2,t_2) \\ &\quad \text{if} \quad t_2 < t_1. \end{aligned} \tag{9}$$

There is, of course, an essential difference between equations (7) and (8): the later one includes the imaginary unit i. That prevents us from claiming that a quantum system is a very complex sort of "neural network". Here we shall not enter into discussion of the role, backgrounds and origins of the imaginary nature of quantum equations. We shall also not discuss any possible proposals for a replacement of complex-valued quantum equations with a system of real-valued equations which would support the search for further analogies with the neural-network-theory. In spite of this we are able to argue that there are very interesting functional and mathematical *analogies* between quantum and neural levels, although they are not perfect.

In neural networks the *correlations between patterns* are important for memory. In quantum mechanics the *phase differences between different parts of the wave-function* are important [3]. They control the time-evolution of probability distribution involving *interference* of the contributions of different stationary eigen-wave-functions. Thus, *changing the phase relations between eigen-wave-functions* is analogous to the *learning*-process in neural networks where synaptic correlation-matrix "absorbs" new pattern-correlations. This is also similar to holography [35].

4.8 Neuronal-Pattern-Reconstruction ⟷ "Wave-Function Collapse"

The most important neuro-quantum analogy is the following. Pattern-reconstruction in a neural network

$$q(\vec{r},t)=\sum_{k=1}^{p} c_k(t)v_k(\vec{r}) \Longrightarrow$$
$$q(\vec{r},t_0)=v_{k_0}(\vec{r}) \qquad (10)$$

is very similar to the "collapse of the wave-function" in a quantum system

$$\Psi(\vec{r},t)=\sum_{k=1}^{p} C_k(t)\psi_k(\vec{r}) \Longrightarrow$$
$$\Psi(\vec{r},t_0)=\psi_{k_0}(\vec{r}). \qquad (11)$$

For reasons presented in section 3 this is a very important feature of cognitive processes. Processes (10) and (11) are both a result of the influence from the system's *environment*. The environment selects those neural/quantum pattern which is the most similar (or is correlated) to the state of environment.

Neural-pattern-reconstruction and wave-function collapse are results of a transition from the *implicate order* [2] (with latent, implicit, inactive, potential information only) to the *explicate order* (carrying manifest, active, realized information) [5]. The implicate order represents a combination of very many *possible* states or processes. It is analogous to a set of so-called "parallel worlds" or parallel sub-branches of the general wave-function proposed by Everett [11]. Explicate order, on the other hand, represents a state or process which is at a moment physically actualized—it is "chosen" from a set of potential (implicate) states, or is a result of their optimal "compromise".

4.9 Fourier-like Analysis

A short calculation, presenting correspondence rules between above equations, can be performed first for the neural case (12), and then for the quantum case (13):

$$q(\vec{r}_2,t_2)=\iint J(\vec{r}_1,t_1,\vec{r}_2,t_2)\; q(\vec{r}_1,t_1)\; d\vec{r}_1 dt_1$$
$$=\iint\left(\sum_{k=1}^{p} v_k(\vec{r}_1,t_1)\; v_k(\vec{r}_2,t_2)\right)\; q(\vec{r}_1,t_1)\; d\vec{r}_1 dt_1$$
$$=\sum_{k=1}^{p} v_k(\vec{r}_2,t_2)\left(\iint v_k(\vec{r}_1,t_1)\; q(\vec{r}_1,t_1)\; d\vec{r}_1 dt_1\right)$$
$$\Longrightarrow \quad q(\vec{r},t)=\sum_{k=1}^{p} c_k(t)\; v_k(\vec{r},t) \qquad \text{or}$$
$$q(\vec{r},t)=\sum_{k=1}^{p} c_k(t)\; v_k(\vec{r}). \qquad (12)$$

In the last step we have used definition (3) for time-dependent patterns (Eq. 12, last row, left). For stationary case we delete the time integral and get Eq. 12, last row, right. On the other hand,

[2] Bohm's term.

$$\Psi(\vec{r}_2,t_2) = \iint G(\vec{r}_1,t_1,\vec{r}_2,t_2)\ \Psi(\vec{r}_1,t_1)\ d\vec{r}_1 dt_1$$

$$= \iint \left(\sum_{k=1}^{p} \psi_k(\vec{r}_1,t_1)\ \psi_k(\vec{r}_2,t_2)\right) \Psi(\vec{r}_1,t_1)\ d\vec{r}_1 dt_1$$

$$= \sum_{k=1}^{p} \psi_k(\vec{r}_2,t_2) \left(\iint \psi_k(\vec{r}_1,t_1)\Psi(\vec{r}_1,t_1)\ d\vec{r}_1 dt_1\right)$$

$$\Longrightarrow \quad \Psi(\vec{r},t) = \sum_{k=1}^{p} C_k(t)\ \psi_k(\vec{r},t) \quad \text{or}$$

$$\Psi(\vec{r},t) = \sum_{k=1}^{p} C_k(t)\ \psi_k(\vec{r}). \tag{13}$$

4.10 Dynamics of the State Functions

The following version of dynamic equations can be derived from the above neuro-synergetic equations (here somewhat generalized):

$$\dot{q}(\vec{r}_2,t_2) =$$

$$= \iint \left(\sum_{k=1}^{p} \lambda_k v_k(\vec{r}_1,t_1) v_k(\vec{r}_2,t_2)\right) q(\vec{r}_1,t_1) d\vec{r}_1 dt_1$$

$$= \sum_{k=1}^{p} \lambda_k v_k(\vec{r}_2,t_2) \left(\iint v_k(\vec{r}_1,t_1) q(\vec{r}_1,t_1) d\vec{r}_1 dt_1\right)$$

$$\Longrightarrow \quad \dot{q}(\vec{r},t) = \sum_{k=1}^{p} \lambda_k\ c_k\ v_k(\vec{r},t) \quad \text{or}$$

$$\dot{q}(\vec{r},t) = \sum_{k=1}^{p} \lambda_k\ c_k\ v_k(\vec{r}). \tag{14}$$

We have inserted a generalized version of the Hebb rule (7) into the time-dependent equation (5). λ_k is the so-called *attention parameter* of the pattern $\vec{v}_k$, and is an eigenvalue of the matrix J with eigenvectors $\vec{v}_k$. In the second step we have used the definition (3) for time-dependent patterns. For stationary case we could delete the time integral.

On the other hand, we can make the following quantum calculation starting from the time-dependent Schrödinger equation with the Hamiltonian operator $\hat{H}$:

$$i\hbar\ \dot{\Psi}(\vec{r},t) = \hat{H}\ \Psi(\vec{r},t)$$

$$= \hat{H}\left(\sum_k C_k\ \psi_k(\vec{r})\right)$$

$$= \sum_k C_k\ \hat{H}\ \psi_k(\vec{r})$$

$$= \sum_k C_k\ E_k\ \psi_k(\vec{r}). \tag{15}$$

In the last step we have used the stationary Schrödinger equation $\hat{H}\ \psi_k(\vec{r}) = E_k\ \psi_k(\vec{r})$ where E_k is the energy-eigenvalue. We thus obtain

$$\dot{\Psi}(\vec{r},t) = -\frac{i}{\hbar} \sum_{k=1}^{p} E_k\ C_k\ \psi_k(\vec{r}) \quad \text{or}$$

$$\dot{\Psi}(\vec{r},t) = -\frac{i}{\hbar} \sum_{k=1}^{p} E_k\ C_k\ \Psi_k(\vec{r},t) \tag{16}$$

where E_k has a similar role as λ_k.

4.11 Uncertainty Principles and Duality

In the neural network theory there are *uncertainty principles* (Daugman [8], Gabor [26]) which are similar to the famous Heisenberg uncertainty principles of quantum mechanics. An interesting neural analogy of the Heisenberg uncertainty principle is represented by an *inability of simultaneous determination of patterns in the system of neurons* $\vec{q}$ and of *patterns in the system of interactions* (or connections) J. We are unable to *explicate* a pattern in a system of neurons, and to *explicate* a pattern in the system of connections at the same time. Only one pattern which is temporarily realized in the system of neurons is explicated. All the others are present only *implicatedly* (implicitly) in the system of interactions, or in the dynamics itself, respectively. This is similar to the cognitive situation; we can be aware of one pattern only which has been extracted from memory. Other memory patterns remain unconscious and implicit.

Thus, the so-called *position (x-) representation* of quantum theory can be approximated by the system of neurons $\vec{q}$. The so-called *impulse (p-) representation* can, on the other hand, be associated with the system of interactions J which regulates all transformations of the network-state.

Although only some basic mathematical analogies were presented here, numerous other parallels can be found between the neural and the quantum processing. They show that there may be a subtle "division of labor" and an isomorphism-like relation and cooperation between the neural and the quantum levels. These levels may be in a sort of *fractal*-relationship. The first main difference between the physical and psychophysical processes is that *the quantum system itself is not intentional* (does not carry any mental information), but *mind-brain is intentional* (carries specific mental contents). The second difference is that *the quantum system itself does not have a relatively independent environment, but brain does.* Therefore the brain models its macroscopical environment in a specific and flexible manner by *using the biological neural network as a macro-micro-interface and a (subconscious) preprocessor* for an unified *conscious experience which involves neuro-quantum coherence.*

5 Super-Computers Exhibiting Multi-Level Coherence

We have argued that mind-like processing needs neural or/and quantum virtual structures (attractors). There is no reason why complex computers would be unable to form virtual structures. Indeed, every collective state of a complex system may constitute a specific gestalt (a specific virtual unity) which cannot be reduced to the state of constitutive elements of the system alone. The problem is the formation of a specific isomorphic (e.g., fractal) multi-level coherence. The practice of computer simulations of neural nets shows that we can govern the artificial neuronal level implicitly by regulating the artificial virtual level explicitly. If our *dynamical equations for neurons and synapses regulate the patterns only, the attractors always accompany the neural dynamics implicitly!* Neural dynamical equations (represented in the computer program) are differential equations (with local range of validity), but attractor-structures may be mathematically described by variational calculus (with global range of validity). We do not necessarily need both mathematical descriptions—one is sufficient. Thus, we may organize one level and the others will automatically follow. This is the reason, why the *reductionist approach usually works for all practical purposes*, and this is a chance for advanced system-based artificial intelligence.

Conventional computers and human analytic mind are limited by the Gödel theorem. On the other hand, the human mind is able to synthesize different levels, which refer to each other, into a coherent whole. The mind is also capable of synthesizing a thesis and an antithesis simply by "not taking the difference too seriously", by "making a compromise", by merging incompatible informational subspaces into a higher-dimensional space, by transcending the hierarchy of well-defined levels using a process of restoration of symmetry (like in spectroscopy after turning magnetic field off). Actually, all sufficiently complex systems are capable of symmetry-breaking (formation of differentiated structures) or symmetry-restoration (integration of different aspects into a coherent unity or gestalt); they can also be artificial.

It is true that human mind is also not able to solve the liar paradox. It is not able to integrate the concepts of liar and his self-referential sentence into a static (stable) solution, but it is able to "think about it". So, the reaction of human mind to such paradoxes is not decay of the model-structure (except in schizophrenic minds), but formation of a dynamic coherence. The resulting coherent state is quasi-stable and only temporary, but useful for ever-changing life-situations, because it is adaptive.

Artificial consciousness of hypothetical quantum computers of the future will, of course, never be identical to human consciousness. It will be only a model of human consciousness, but it may be a good replica, identical for all practical purposes due to Turing test. The hypothetical artificial consciousness will (at least for a very long time) be only an extension of human consciousness, always coupled to it. Humans will still project their conscious interpretations into the performance of their replica-machines. The physical states of these hypothetical machines will be informational only due to the coding-rules given by humans. So, computer-consciousness will not be autonomous, because its contents will always be interpreted by humans - until these futuristic computers-robots would become self-maintaining. Till then, we cannot talk about "real" computer-consciousness in any case, because involvement of human informational interpretations necessarily means "projection of *human* consciousness" into computers. So, as long as computers will be our tools they will merely be a sub-branch of human consciousness, an isomorphic co-processor.

6 Conclusion

It was shown that associative or attractor neural networks and quantum networks realize similar collective dynamics. Our computer simulations [34] of neural networks realize efficient information processing. Using presented mathematical analogies with quantum networks, we can try to establish similar information processing in quantum systems also.

Neuro-quantum parallelism may thus represent the crucial element of natural and artificial informatics.

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References

[1] D. Amit: Modeling Brain Functions (The world of attractor neural nets); Cambridge Univ. Press, Cambridge, 1989.

[2] J.D. Bjorken, S.D. Drell: Relativistic Quantum Fields; chapter 6: Propagator Theory; McGraw-Hill, New York etc.

[3] D. Bohm: Quantum Theory; Constable and Co., London, 1954.

[4] D. Bohm: Wholeness and Implicate Order; Routledge and Paul Kegan, London, 1980.

[5] D. Bohm, B. Hiley: The Undivided Universe (An ontological interpretation of quantum theory); Routledge, London, 1993.

[6] F. Brentano: Psychology from an Empirical Standpoint; Routledge and Kegan Paul, London, 1973.

[7] Y. Burnod: An Adaptive Neural Network: the Cerebral Cortex; Prentice Hall, London, 1990.

[8] J.G. Daugman: Uncertainty relation for resolution in space, spatial frequency, and orientation optimized by 2-D visual cortical filters; Journal of Optical Society of America A **2** (7) (1985) 1160.

[9] P.C.W. Davies, J.R. Brown (Eds.): The Ghost in the Atom; Cambridge Univ. Press, Cambridge, 1986.

[10] D. Deutsch: Quantum computation; Physics World (June 1992) 57-61.

[11] B.S.DeWitt, H.Graham (Eds.): The Many-Worlds Interpretation of Quantum Mechanics; Princeton Univ. Press, Princeton, 1973.

[12] E. Domany, J.L. van Hemmen, K. Schulten (Eds.): Models of Neural Networks (Series "Physics of NN"); Springer, Berlin, etc.

[13] A. Goswami: Consciousness in Quantum Physics and the Mind-Body Problem; Journal of Mind and Behavior **11**(1) (1990) 75.

[14] H. Gutfreund: From Statistical Mechanics to Neural Networks and Back; Physica A **163** (1990) 373-385.

[15] H. Haken: Synergetic Computers and Cognition (A Top-Down Approach to Neural Nets); Springer, Berlin etc., 1991.

[16] H. Haken: Advanced Synergetics (Instability Hierarchies of Self-Organizing Systems and Devices); Springer, Berlin etc., 1987.

[17] H. Haken, M. Stadler (Eds.): Synergetics of Cognition, Springer, Berlin etc., 1989.

[18] S.R.Hameroff: Quantum coherence in microtubules: a neural basis for emergent consciousness? ; Journal of Consciousness Studies 1(1) (1994) 91–118.

[19] B.J. Hiley, F.D. Peat (Eds.): Quantum Implications (Essays in Honour of David Bohm); Routledge, London, 1987.

[20] J.J. Hopfield: Neural networks and physical systems with emergent collective computational abilities; Proc. Nat. Acad. Sci. USA **79** (1982) 2554–2558.

[21] T. Kohonen: Self-Organization and Associative Memory; Springer, Berlin etc., 1984.

[22] A. Krogh, R.G. Palmer, J. Hertz: Introduction to the Theory of Neural Computation; Addison-Wesley, Redwood City etc., 1991.

[23] L.D. Landau, E.M.Lifšic, (V.B. Berestecki, L.P. Pitajevski): Lehrbuch der theoretischen Physik, Band III: Quantenmechanik / Band IV: Relativistische Quantenmechanik; Akademie-Verlag Berlin, 1967, 1970 (English ed. also).

[24] M. Lockwood: Mind, Brain and the Quantum; Blackwell, Oxford, 1989.

[25] B. MacLennan: Information Processing in the Dendritic Net; Report 2^{nd} Ann. Behav. and Comp. Neuroscience Workshop, Washington, 1992.

[26] B. MacLennan: Gabor Representations of Spatiotemporal Visual Images; Tech. Report CS–91–144, 1991.

[27] J.L. McClelland, D.E. Rumelhart, PDP research group: Parallel distributed processing (Explorations in the Microstructure of Cognition)—vol.1: Foundations, vol.2: Psychological and Biological Models; MIT Press, Cambridge (MA), 1986.

[28] R. Penrose: 1) The Emperor's New Mind (concerning Computers, Minds, and Laws of Physics); Oxford Univ. Press, London, 1989. 2) Shadows of the Mind (A Search for the Missing Science of Consciousness); Oxford Univ. Press, Oxford, 1994.

[29] P. Peretto: An Introduction to the Modeling of Neural Networks; Cambridge Univ. Press, Cambridge, 1992.

[30] M. Peruš: Neural Networks as a Model of Brain Processes; Anthropos **5–6** (1993) 146-177 (in Slovene).

[31] M. Peruš: Concepts of Holistic "Models" of Consciousness (Bohm's Quantum Implications, Holograms and Neural Networks); J. Critics of Science **174** (1995) 11–22 (in Slovene).

[32] M. Peruš: Analogies of neural and quantum processing—Consequences for cognitive science; in: P. Pylkkänen, P. Pylkkö (Eds.): New Directions in Cognitive Science, Proceed. Int. Conf., Lapland/Finland, 1995 (pp. 115–123).

[33] M. Peruš: Synergetic Approach to Cognition-Modeling with Neural Networks; in: K. Sachs-Hombach (Ed.): Bilder im Geiste (pp. 183-194); Rodopi, Amsterdam/Atlanta, 1995.

[34] M. Peruš: All in One, One in All (Brain and Mind in Analysis and Synthesis); DZS, Ljubljana, 1995 (in Slovene).

[35] W. Schempp: Bohr's Indeterminacy Principle in Quantum Holography, Self-adaptive Neural Network Architectures, Cortical Self-Organization, Molecular Computers, Magnetic Resonance Imaging and Solitonic Nanotechnology; Nanobiology **2** (1993) 109.

[36] J. Šlechta: On a Quantum-Statistical Theory of Pair Interaction Between Memory Traces in the Brain; Informatica **17** (1993) 109–115 (and other ref. within).

[37] J. Šlechta: 1) The Brain as a "Hot" Cellular Automaton; 2) On Molecular Foundations of the Thermodynamics of the Thought Processes in The Brain; Proc. 12^{th} Int. Congress on Cybernetics, Namur, 1989 (pp. 862–869; pp. 870–877).

[38] J. Šlechta: On Quantum-Statistical Theory of the Brain—Brain as a Generalized Laser; in: J. Rose (Ed.): Cybernetics and Systems (pp. 919–924); Thales, Lytham St. Annes, 1987.

[39] E.J. Squires: Quantum theory and the relation between the conscious mind and the physical world; Synthese **97** (1993) 109.

[40] H.P. Stapp: Quantum Propensities and the Brain-Mind Connection; Foundations of Physics **21**(12) (1991) 1451.

[41] A. Stern: Matrix Logic and Mind (A probe into the unified theory of mind and matter); North-Holland/Elsevier, Amsterdam etc., 1992.

[42] A.P. Železnikar: On the Way to Information; The Slovene Society Informatika, Ljubljana, 1990.