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Quantum computing architectures with signaling and control mimicking biological processes

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ABSTRACT

Earlier reports have described a quantum computing architecture, in which key elements are derived from control functions in biology. In this further continuing research, focus is on the signaling and control of a flow of qubits in that architecture, mimicking synapse signals and neurological controls. After a short description of that architecture, and of quantum sensing elements, it is first shown how the coloring of quantum particle flows, implemented as in mathematical colored algebras, can reduce decoherence and enhance the decidability of quantum processing elements. Next, after reviewing specific human biology functions, and exploiting experimental results on excitation modes in live animals, it is shown how to achieve separation of the quantum control & signaling signals. Technologies and designs from particle physics are discussed as well as open research issues towards a realization of a quantum computing architecture with decidable signaling.

1. Introduction

Despite continuous progress in microelectronics, computing and particle physics, little research has considered two disruptive dimensions, namely first the replacement of sequential instructions by biological process equivalents, and secondly such process implementations in quantum computing using particle physics interactions. Previously some empiric neuromorphic implementations have shown the way [1,2], without however exploiting quantum particles.

The proposed architecture resting upon the combination of these two dimensions, enables native spatiotemporal integration [3] or correlation [4–6], as well as powerful interference filtering, gating, splitting, crowding and other functionalities. Multilevel biological feedback is also commonplace. The realization of the combination by quantum particle and charge carrier interactions, has previously led the present project team to specify a biology inspired quantum computing architecture [7,8], including interfaces, storage of information, and programming.

While the present contribution is not devoted to architectural or technological realization details of the earlier proposed architecture (summarized below under Architectural features 1–7), the survey Section 2 reviews briefly relevant state-of-the art on sensors, hardware, and software components of quantum computing architectures to show afterwards the further capabilities offered by biological processes.

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To recap, this combined architecture [7,8] has the following features, to be refined later in this paper with focus on signaling and control aspects:

Architectural feature 1: The information processing is achieved by interacting particles carrying information and which follow propagation pathways. These massless quantum energy carriers propagate on these pathways alongside other energized particles. Carrier type specific elements for the deflection or collection get implemented on the pathways. Use of such different particle types helps achieve different delays when needed.

Architectural feature 2: Complex quantum gates, mimicking biological and physiological processes, and previously formally specified, help transform the flowing quantum particles. Examples of such complex gates to be discussed later are: differential operators, integral operators, deflection lattices, reflective processes, and others derived from biological functions

Architectural feature 3: Asynchronous signaling all through the pathways, and in sub-lattices thereof, is carried out by electrical-magnetic interactions, together with charge collector islands, which have been recently discovered [9].

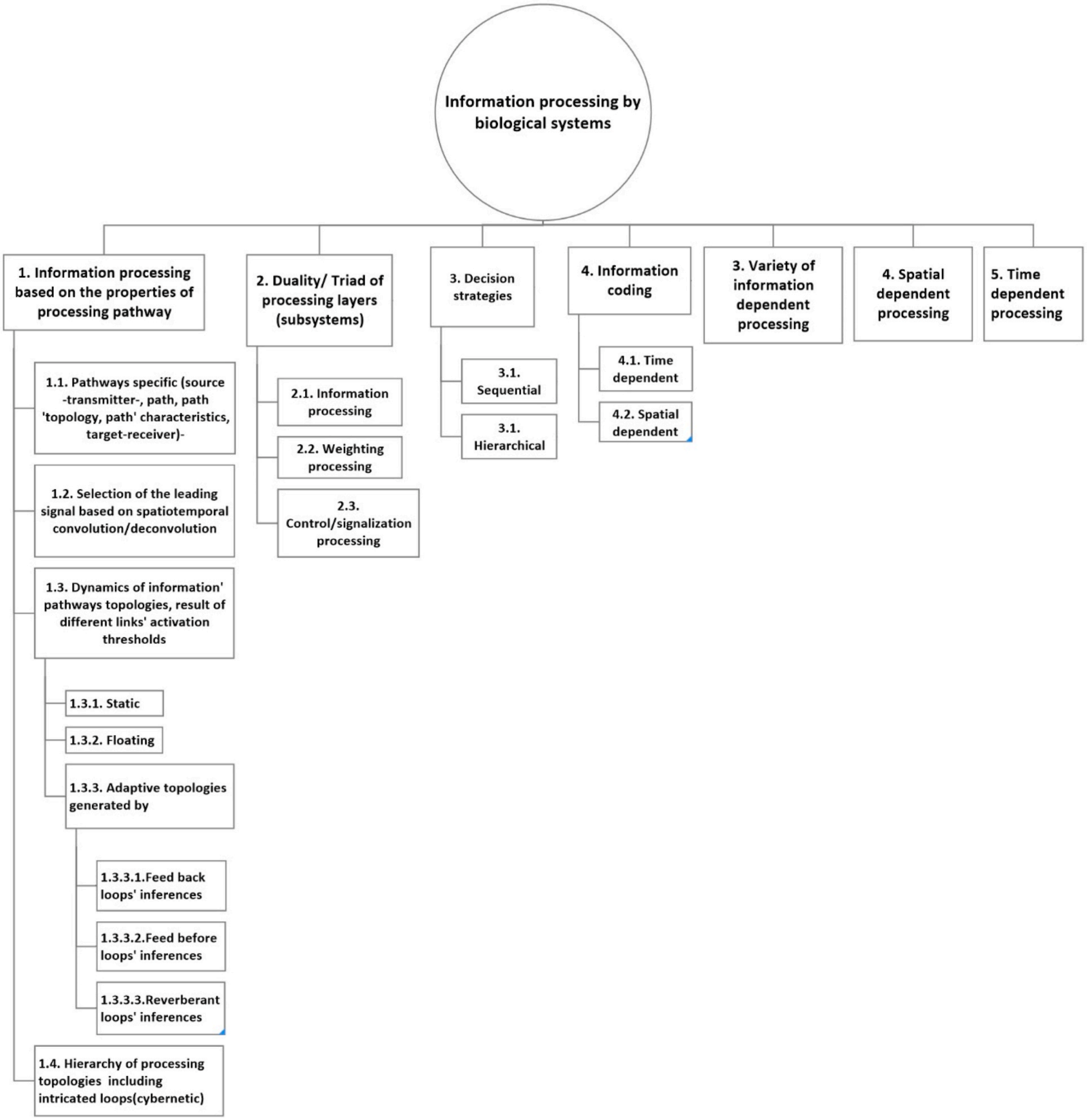

Fig. 1. Simplified ontological image of the information processing by biological systems, based on [11,12–17].

Architectural feature 4: Filtering of the charge carriers in the spatiotemporal domain is carried out by Moiré processing [5], or by structured resonator quantum gates.
Architectural feature 5: Quantum structures with resonance (like: quantum wells, and quantum dots), allow to realize quantum information storage, and they can produce single photons at high rates on demand [10].
Architectural feature 6: Input is by established very high data rate asynchronous quantum charge generation, and read-out is synchronous, both tied to the control functions.
Architectural feature 7: A quantum programming language (such as e.g., QML, QFC, QCL, QMASM, SILQ) serves the programming on a conventional digital processor with an interface, the photonic or RF outputs of which trigger the signaling and control.

In this paper the authors in particular focus on the control and signaling in architectures linked to quantum computing implementations with probabilistic information processing akin biological processes.

It is therefore necessary to compare and validate these Architectural features 1–7 against a thorough categorization of biological processes (see Fig. 1), although analyzing how they are realized in biology from the biochemistry angle is out of scope of this paper.

There are already several biologic/neuronal processes serving mimicity implementations [1,2] with specific elements having static and dynamic characteristics (sometimes named “plasticity” of neural networks or connectomes [11]), and specific processing functions. A classification of these can indeed be relevant; in fact, more of these plasticity features can be used together to improve the systems’ behavior, and they furthermore must be combined and tailored to enable controllability and stability. Also, one can try to identify similar topologies (static or dynamic) [18], and hierarchies [11] between biologic systems and computational implementations, which is an architectural aspect.

Each of these implementations [1,2] comes with specificities, one of which is the exploitation of the capabilities of biological processes; one such example is the spatiotemporal processing and spatial distribution of the computational resources [19]. The input signal domains are enhanced by preprocessing functions that involve filter implementations, mainly linear-logarithmic transformations, and the implementation of static or sliding activation thresholds. Using feedback and feedforward static or dynamic commutated topologies enable control and filtering functions, like in the case of a visual analyzer [20] that allows a lateral inhibition of optical nerves [21].

The specific signal propagation pathways inside biological systems are essential means for robust control and signaling, besides their role for pre-processing and information processing; the categorization of Fig. 1 helps select which types of biological pathways can serve as models for quantum processing control and signaling.

The emphasis in this paper is not about the technological realization of the required physical or engineering components, but on refining further the proposed architecture [7,8] through experiments and theoretical results, which, thanks to the advantages of neurological processes, can alleviate some of the pitfalls of current quantum computing realizations (uncertainty, entanglement, normalization, decoherence):

i *Entanglement*: When qubits interact with each other, and when besides their states cannot be specified as a product of the wave functions of independent qubits, one refers to entangled states.
ii. *Normalization*: Condition on the sum of the squares of the complex constants defining a quantum state decomposition (see Section 5): this raises issues at measurement stage (see Section 2.1.).
iii. *Decoherence*: The semi-group approach is referred to when defining decoherence in quantum computing [22]. Error generation is associated with the generators of a Lie algebra. This approach provides a comprehensive description, a special case of which becomes the spin-boson model. Decoherence effects are essential obstacles towards the achievement of the acceleration promised by quantum computers for classes of recursive algorithms such as [23–25]. To achieve decoherence, have been constructed quantum error correction codes (QECC) [26,27]: each qubit gets encoded into a large Hilbert space combining multiple physical qubits; this method is expanded upon in Section 5 using colored algebras. Such an “active” error-correction assumes that the most likely errors occur separately from a few select qubits and during reasonable time intervals.
iv. *Decidability*: In simple words, a formal language A is decidable if there exist an algorithm that can tell correctly in finite time if any given string w is an element of the language A, or not. There is thus a very close relation with coherence, the opposite of decoherence.

Already now, some prototype silicon photonic building blocks of the proposed architecture [7,8] have been realized; they should progressively get migrated to quantum flows elements or quantum gates in graphene or into AIN photonic building blocks. Instances of such building blocks include: (i.) ring resonators [28], (ii.) resonators with whispering gallery modes [29], (iii.) directional couplers [30], (iv.) grating couplers [31], (v.) slotted waveguides [32], (vi.) Mach-Zehnder interferometers with self-adjustment [33], and (vii.) photonic crystals [34]. These devices make it possible to build limited prototype versions. The MOQUASIMS project [35], has already achieved a quantum system able to capture moving photons by photonic means, and to maintain them in stationary atomic excitation states, providing an optical memory functionality. However, the manufacturing of such photonic building blocks raises formidable challenges. The architecture proposed in this paper by contrast would benefit to a significant extent from the exploitation of graphene and carbon-nano tube (CNT) materials which have more stable manufacturability, but also from a reduced complexity brought by efficient signaling and control.

2. Survey

2.1. Realization of signaling and instrumentation control in quantum computing systems

Although the focus of the present paper is, as already stated above, not on technological realizations underway of the elements of the proposed architecture, it is relevant to carry out a comparison with approaches taken towards the realization of signaling and instrumentation control in quantum computing systems. It is reminded that the quantum measurements are probabilistic and thus affected by deterministic as well as stochastic controls.

One function is the *control* (by direct modulation) of RF modulators (e.g., THz active modulators [36]) or modulated laser pulses (e.g., with acoustic-optic modulators) which modify the atomic energy levels of the particles used (e.g., trapped ions) at the level of the different types of quantum gates [37], and which operate on a specific qubit. In that case one must control and adapt with low latency and at high frequencies the frequency, phase and amplitude, besides pulse duration, as well as throughput of the modulators, in response to probabilistic quantum measurements. This is often enabled by the combination of synchronous detection and control systems, either separate [38], or integrated when possible into a single programmable system-on-chip (SoC) [39,40], leading to realization issues of qubit scalability, drift, stochastic memory access. A typical reconfiguration of the qubit gates must be executed in $<$0,1-1 μs.

A separate function is the *signaling* which is the use of signals for controlling communications between computing or communications elements. This may constitute an information exchange, driven eventually by protocols, concerning the establishment and control of a set of qubits; due to the use of quantum particles, it is by out-of-band signaling on a dedicated channel, which may use separate qubits and thus require separate controls as described above. Significant research by the authors [41] has tackled the control of the mean and variance limitations in the protocol-controlled interaction between stochastic packets carrying for example qubit measurements, while subject to direct-memory access or buffering besides acknowledgments, thus allowing to put probabilistic bounds on effects such as latency of the very high throughput interactions (several Tbit/s) between the control system and in the present context the set of quantum gates. Elsewhere, such a capability is already used in arrays of ASICs inside high-performance communications nodes.

Interestingly enough, biological signaling and control systems, such as lateral inhibition or attentive vision (see Section 2.2.), although at much lower throughputs, also exhibit mean and variance limitation controls, under higher goal-driven protocols with acknowledgments.

This reinforces the relevance of such biological signaling mechanisms on top of specific quantum computing realizations, with reconfiguration of the sets of calculating qubit gates (Architectural feature 2) being driven by higher level protocols, paving the way for deadline-based or soft real-time constraints [39].

2.2. Biological control and signaling

Despite the high complexity of biological processes, in this survey subsection, an attempt is made to illustrate, mostly through examples, the parallels between such processes, and some specific electronics or physics realizations, to help the reader towards the more detailed further Sections 3-7.

The processing that is done by the human neural system is topologically adapted to the reception, transmission, control, and reflection of information via cells, neurons, synapses, ganglions, and nerves interacting with different kinds of signals of a probabilistic and redundant nature [18,42]. It is important to observe the following, namely that biological systems already encapsulate the link between the status of neurons and time. The toponymy of the whole neural processing system and its dynamics, enables an exceptional capability to perceive jointly the internal and external realities, and act consciously upon them in individualized ways. Such perceptions and actions in their richness exceed the capabilities of most signal processing, computational and information handling models. Therefore, the experimental analysis of neural processes reveals some specific interactions and roles which may serve enhance the performances of such information processing models (see also Section 6.1.).

A very simple example is the *lateral inhibition*. This is the mechanism that allows an excited neuron to inhibit neighboring neurons, enhancing their mutual information contrast because of the dynamic adaptation of the afferent neural network, in conjunction (by back correlation) with the cortical reflection area [43,44]. The time constant of this adaptation process allows for the perception in vision of e.g., min. 24 images/s. This consists in a spatiotemporal and a dissemination phenomenon, which, combined with the phase delayed adaptation of afferent nervous networks, results in interaction means between different neurons placed at different hierarchical layers in the information processing. The thorough understanding of this property can for example help design a quantum gate control which enhances the qubit information in the presence of other interacting random particle flows.

It is already well known how neuronal synapses process the signals that cross it. The dosage of the quantities of chemical mediators generated because of the excitation signal, as well as their reaction speed at the level of the synaptic buttons, implements the function of temporary signal integration [4,12]. That functionality corresponding to the synaptic buttons together with the morphology of the neuronal dendrites, implements the spatiotemporal integration functionality of the set of signals converging to the respective neuron; this occurs in conjunction with the decremental propagation of the neuronal depolarization signals along each converging dendrite towards the neuronal perikaryon. At the level of the neural body (perikaryon), operates a sensitivity threshold, which, together with the spatiotemporal integration functionality, ensures a robust filtering of the set of signals converging towards the respective neuron.

The neural information processing system is characterized by a high structural and functional redundancy. Its topology is equally important from the system's point of view. The great variety of ganglion cells inserted along the signal propagation paths realize collectively multiplexing and demultiplexing complexes. Along the neural propagation paths of biochemical and electrical signals, the connection cells (ganglions) ensure the mixing as well as the mutual adaptation for sensitivity thresholds; these connection cells preserve the stability, "filtering" capacity, and reliability of neural processing [19].

Let us provide some additional examples, focusing now on some biological control and signaling processes which are relevant when a quantum computing system must have similar functionality:

Example 1: "Vision analyzer": illustrates the systemic complexity of signal processing, the coexistence of intercorrelated heterogeneous chemical and electrical biological processes, as well as the topology of the neural network that includes both afferent and efferent signal paths. Their existence together with the corresponding cortical reflection areas, toponymically similar to the structure of the retina, generates the phenomena of "lateral inhibition" described above and in Refs. [20,21]. The phenomenon of "lateral inhibition" illustrates the process of cortical "reflection" between different cortical areas and related visual pathways [36]. The reverberant processing of visual signals as spatiotemporally intercorrelated entities provides an essential functionality in visual perception for the variety of information received from the external environment (dynamics, spatiality, characteristic features, etc.) [11,12,45,36] (see also Example 3).

Example 2: "Allostatic load": This term covers the physiological consequences of chronic exposures to fluctuating or stronger neural or neuroendocrine excitations, which may occur following repeated or prolonged chronic stress [37,38]. Stability is achieved, or in other words, homeostasis of physiological processes is the consequence of the change in behavior. The allostatic load modifies HPA axis hormones and cytokines, and is adaptive in the short term. In this biological process, there are parameter variations, and, in essence, the variations anticipate the demands by changing the reference values corresponding to the feedback processes. This implies that the dynamically changing and self-updating specific parameters which get managed by a biological system, play a significant role in achieving the high stability, reliability, and adaptability of the responses in biosystems. Processes with prediction require each sensor to exhibit adaptability within their input range [46,47]. The "allostatic load" analysis suggests that stability in a quantum computing system can be improved by adding an appropriate predictive control element managed by signaling protocols.

Example 3: "Cortical reflections": The cortical area in the brain is known to be responsible for complex phenomena related to thinking, feelings, information valorization systems through rewards/pains, as well as their fusion that takes place at the level of the cortex [4,43]. We must emphasize that the processes mentioned above benefit from an intrinsic tool, revealed by the structural and functional mapping [44] of the afferent and efferent elements that form the propagation and processing pathways of signals. Some of these are loops in which the signals are reflected multiple times ("reverberant loops"). The "reverberant" loops function as simple clock generators, or for spatiotemporal filtering of signals [48]. The spatial and temporal mapping of the processed signals, and the labelling of the information processed plays an essential role in data structuring and storing processes. Maps of these zones have already been surveyed [44]. "Reflexive" function blocks mimic, even with limitations, some processing modalities identified at the cortical level. The signal interference processes are essential, but also the dynamic evolution of the signal reflection elements within the reverberant loops, which in fact could in physics be interpreted as Moiré type filtering [8].

Example 4: "Heart conduction system": A typical "hard encoded" control function (like Hardware in the Loop - HIL systems), is exemplified by the cardiac conduction system (CCS), based on signals' propagation delays through heart muscles. The muscles of the heart implement the control and at the same time the actuator system, all being supervised by nerves. The Hering nerve (which innervates carotid sinus), the cranial nerve IX, also the Ludwig depressor nerve, and finally also the vague nerves, all of them regulate the cardiac rate function of blood pressure and the oxygen concentration in blood, but all of which also have antagonist effects. The cardiac muscle group operations, correlated with the delays of the control signals due to their propagation, implement the main function of the heart, namely that of pumping the blood circulated in the body [49,50]. Also, the CCS illustrates a reliable, resilient, and hierarchical control architecture with fault-tolerance relying on the existence of multiple hierarchical redundant control nodes, which, in faulty conditions, activate generating functions such as a clock generator (sinoatrial, atrioventricular and Hiss bundles). The heart CSS, supervised by the sympathetic and parasympathetic neuronal networks, and the corresponding cortex control zones, forms a highly resilient and adaptive system. This suggests in a quantum computing architecture to use delay nodes, and the signaling protocols must serve as "hard coded" controls.

Example 5: "Haptic perception": In the context of body position or control of movements, the tactile system (or touch) is an especially interesting sensory system. On one hand, it illustrates the mapping strategy between the sensors placed on the skin but also internally inside the human body, and their cortical projection areas. On the other hand, this system illustrates the ways of coupling the tactile system with temperature perception, but also with rewarding information (pleasure/pain).

The "Haptic perception" illustrates also how the afferent sensing system is coupled with diverse muscular groups, and how these can identify force, torque, profile, and texture, to maintain or to change the body position or to control a complex body movement like gait. The specificity of such information processing, and perceptions of the external environment are presented in many papers [13,14,51].

Biological perception establishes a correspondence [13] between the receptors, the neural propagation pathways, and the relevant cortical projection zones; however, implementing such correspondences is currently out of range for current quantum gate design realizations (Architectural feature 2).

2.3. Mapping of biological control and signaling to quantum processing

Quantum computing technology as well as its theoretical basis have made significant progress using different approaches [52–55].

Several technology players are involved in a competition aiming for some hundreds of qubits cryogenically cooled processing elements; a 2-qubit SiGe processor was demonstrated [55] in which qubits have several milliseconds lifetime, compared to 10–100 micros in superconductive elements; eventually trapped ions processing elements will achieve a reminiscence of 1 min [54].

However, in terms of applicability beyond specific simple algorithms, quantum computers have exhibited less progress because of their specific limitations, mostly because of many technological challenges; also, about the requirements for migration/interoperability they still only exploit at best an approximated link between binary logic and qubit states [52,53] (see also Section 5). The mimicking of biological processes inside quantum processing architectures offers vast potential to go beyond algorithms rooted in mathematical feed-forward computations, in that they achieve the incorporating of much more adaptation.

Earlier papers [7,8] investigated an architectural path for quantum computing, utilizing simultaneously specific known biological processes alongside specific basic effects or phenomena in particle physics, to achieve a functional quantum system realization of these biological processes. A main advantage resides in a significantly more compact realization of the corresponding process functionality, compared to those based on recursive calculations; another advantage resides in exploiting the stability of biological processes in order to reduce quantum computational complexity and decoherence. Architectural building blocks were featured, and programming abilities were compared [8].

It was claimed that the corresponding biology-based functional pathways could be implemented following the Architectural features 1–7. As an example, an adaptive pump quantum functionality can be achieved with spatially distinct pathways, and by implicit delays in the control signal propagation, like those in CCS heart conduction (Example 4, Section 2.2). The relevant control nodes are the sinoatrial node, the Purkinje fiber terminations, the Hiss bundle, and the atrio-ventricular node; they constitute jointly an aspire-repellent pump, representing a fluid dynamics computational class. Another example to be pointed at to illustrate the claim, is the fact that protein strings do travel in parallelized controlled pathways, a property exploited in parallel bio-computer models designed to be like self-propelled biological agents [56].

The equivalent quantum processing building blocks consist in realizations involving quantum charge collector islands, besides propagation pathways (Architectural features 1–4); the conduction is then achieved by quantum particles moving in a ballistic mode and affected by deflection elements. The particle physics elements by which such deflections can be realized by spatial interferential processing include: lattice structures, a Berry cone, FET, or Moiré based sub-lattice computing [8,57] (as in Section 2.2 Example 3).

The proposed architecture can be extended by a mathematical construct, namely *colored algebras* [7]. Such algebras possess their labelled initial symbols, group structures, ring structures, operands, and some specific properties (such as: commutativity or non-commutativity, transitivity or non-transitivity, reflectivity, etc.). Just like each element has a color, quantum energy levels can represent values or intervals, allowing to formalize quantum particle interactions inside a functional block by classifying qubits by energy level attribute ranges. Thus:

> Architectural feature 8: A colored algebra with colors linked to the quantum energy levels (or intervals) of quantum states, can map, and categorize for signaling and control, the states carried by qubits whose quantum energies interact all along the pathways. In other words, the quantum energy levels become tags/colors used for signaling and control, eventually encoded as complex numbers or interval ranges, for specific signaling qubits.

It was also shown in Ref. [7] that such a correspondence has profound implications on improving decidability of the quantum calculations (see Section 1), which was earlier an open issue. This decidability in turn affects the control and signaling (see details in Section 5).

It should also be noted that such decidability by quantum energy levels coding indirectly also simply improves fault tolerance, like otherwise attempted with toric codes in multiqubit gates [58], in that faulty gates will be revealed by missing particle counts in specific energy attribute ranges provided by separate energy level instrumentation.

Experimental laboratory measurements on live mice and rats have been conducted to elicit their neurobiological pathway processing [7]. The scope was to study the nervous load (like in Section 2.2 Example 2) resulting from external physical excitation signals of different energy intensities, leading to biochemical effects measured ex-post on these animals. This has produced a characterization of the interactions along nervous pathways by changes on the neural synapses' metabolism, analog to quantum energy interactions resulting from quantum particle energy levels. This capability to relate the energy to information flows within the neural metabolism, is the subject of a patent by one of the authors [59]. These experiments reveal live reaction processes, which serve in turn to approximate quantum gate excitation levels, when a synapse functionality is represented amongst the complex quantum gates (Architectural feature 2).

This last result, as well as the requirements in real-time computing systems and communications networks, to synchronize excitations and their outcomes (Section 2.1.), creates the need to analyze in detail the signaling and control inside a biologically inspired quantum computing architecture, akin controlled synapse interactions able to conduct a diversity of functions. So far, in current quantum computers, it is still a sequential co-processor and I/O unit which triggers the interactions, in that the qubits & quantum gates only perform a specific calculation (of e.g., Toffoli cells, quantum Fourier cells, matrix calculations, etc. [60]).

The proposed architecture associates two different synchronization types, namely:

i) *Asynchronous processing*: it relies on the deflection of the quantum charge carrier pathways, combined with quantum particle accumulation at some dedicated porous islands serving towards charge accumulation or confinement (see Section 6.3.);
ii) *Synchronous processing*: once, at the level of the front-end processor, the signaling has activated all required functions and resources, the control path enables the program execution and parameter selection, as explained in Section 5.

The feasibility and implications of the specification of the new architecture summarized above are described below, and their results are embedded into the further on-going realization research focus (see Section 8).

3. Research question

The aim of this paper is to specify the signaling and control structure inside a biology inspired quantum computer architecture, when synchronization is to be achieved between quantum computations, while the controls, signaling and results may be asynchronous. This mimics the capability of a controlled network of synapses [61].

This paper shall not analyze in detail each signaling or control element inside the proposed architecture, nor the particle physics effects, biochemical and biology processes which have been utilized. It provides an encompassing vision of their interdependencies, and on how they can be integrated for the best quantum processing performances.

4. Synapse interactions and their implications for qubit interactions

This Section deals with how dis-entanglement and coherence (see Section 1) are maintained when a network of synapses, reacting to an asynchronous control, signals between synapses despite probabilistic signal values like in quantum computing.

The book [12] provides an overview of a biologic information processing system starting from the chemistry of cells, illustrating the role of synapses' plasticity in the information processing, learning and memorization. The cellular mechanisms generate structural changes that are illustrated by physiological and pathological processes. These can be seen as complex multiplexors and demultiplexers of neural networks “connectomes” [15]. The topologies of connectomes are illustrated both by the feedback but also by the feed-forward (before) connections [13–15]. The biochemical "plasticity" allows evolutionary topologies. All these changes inside the human body are also the result of a modulation of changes produced by the "limbic" system [16,17]. This function, as a weighting system, can generate a huge variety of biological system evolutions.

The recurrent changes produced in living systems, also called “sensitivity”, are mainly produced as a result of excitations received ("content") and not by the energy levels of information; this first property was initially put in evidence by von Bertalanffy [42] and proved in experimental studies [7,59]. In Ref. [7], experiments on mice have dealt with the biochemical effects of bits of information, by using selected pseudo-random video or audio signal excitations, and characterizing by biochemical measurements the adaptions of the mice to the excitation signals. It should be noted however that this research does not rely as in Ref. [62] on cell manipulation or synthetic biology, but solely on experimental measurements.

A second property demonstrated in these experiments [59] is to show that an experimental methodology can reveal the influence of some therapeutic drugs on living entities, respectively reveal the protective role played by these drugs, against excessive informational flows.

A first conclusion from Refs. [7,59], relevant for the realization of the bio-inspired quantum processing gates or functions, is the need to account for excitation uncertainties together with the drug adaptation inside synapse networks. This idea is also retained in Section 7.2.

A last elicited property pertains to the quantitative evaluation of the information content of the excitation signals. The randomization of signals serving as excitations for living entities, affects only relatively little the effects on them. We don't have the capability to determine how the living entities “interpret” the contents in the excitations. Also, this reactivity will always be specific to different species of living entities, and this diversity can be mirrored by a quantum pathway diversity inside a quantum processing architecture.

5. Decoherence reduction due to the color tagging of the particle flows

As a reminder, the measurement of a quantum state is probabilistic, and:

i. A state of a quantum system is specified fully by its state vector, the properties of which are: first uniqueness (accuracy matching to an arbitrary phase), and next normality.
ii. Any arbitrary state vector $|\psi>$ can be decomposed into an orthogonalized system of eigenvectors $|\psi(k)>$ of a physical particle flow (F), where: $|\psi \geq \Sigma\, a(k)\, |\psi(k)>$, and a(k) are complex numbers, such that the values $|a(k)|^2$ equal the probabilities of observing the system in the state $|\psi(k)>$. This measurement postulate is also called the “Born rule”.
iii. The state vector $|\psi>$ has its evolution described by the time-dependent Schrödinger equation.
iv. There is linear superposition of states.

Thus, the idea presented in Section 2.3. and through the Architectural feature 8, relies on the fact that a given colored algebra can represent the functional outcomes transported by different color tagged qubits (the quantum energies of which interact along pathways), via one specific functional block inside the proposed architecture, and thus that this block enables signaling. In this way, one colored algebra realizes the image of that functional block, and it can be used for signaling and low-level programming (like in Ref. [60]).

Architectural feature 9: The realization of the Architectural feature 8, is via the (color) tag assigned to each quantum state by a predecessor quantum gate and containing one or several eigenvector attributes $|\psi(k>$ of the predecessor state; one tag attribute is the quantum energy or a quantum energy interval. The tag can also include the output of a signaling protocol assigned by a signaling quantum gate. The tag can be a complex number.

These independent color tags embed the signaling affecting |ψ> at that time. The set of colors may eventually be finite according the the colored algebra specified. In Ref. [7] is shown the algebraic relation between the set of algebraic atoms of the colored algebra, and [63,64] showed that a computable atomic Boolean algebra (B) is decidable if the set of atoms is computable; this condition is satisfied if the set of colors corresponds to signal commands in response to the control flow of commands.

Furthermore [7,63,64], proves that for a computable colored algebra, and the coloring sequence thereof, the structure corresponding here to the quantum state interaction is *decidable* when the coloring sequence corresponds to a Gödel numbering [65]. It should be noted that a specification of the colors enabling decidability can be general, although they would be a specific discrete numbered set in any technology realization.

This design requirement implies that, despite the probabilistic distribution of the quantum states resulting from the quantum interactions, decidability can be obtained for it when the contributing signaling quantum states are color tagged as specified, the energy levels coming from the particle flow instrumentation (see Section 2.1.). More complex Lie algebras have been considered theoretically but with no link to signaling or control [66].

6. Implications for the control and signaling in the biological quantum computing architecture

This Section summarizes some of the consequences of the architectural design, mathematical analysis and of the biological experiments described above, to enhance the biology-inspired quantum computing architecture in Ref. [8].

6.1. Impact of the interactions of synapses

Obviously, random binary sound or video excitations of a rat's synapse [7,59] cannot reproduce the qubit interactions taking place inside the architecture studied here, if it was to be subject to sound or video excitation controls in an equivalent way. Combining Section 5 on colored algebras and Architectural feature 9, binary excitation sounds would be modelled by analogy first by a simple executable code, or by a signaling protocol output, while colored video excitation would be modelled by a waveform generator producing light color modulation output values. There are however some lessons to be learnt from this remote analogy:

- biological saturation occurs, but, due to feedback effects, it is not effected proportionally to the bit rates; the question is how to design a similar quantum gate functionality with similar feedback effects;
- in biology, the signal features (binary sounds, or long sequences of video signals) have a significant effect on the mice, in that video delivers the highest levels of excitation, with or without adrenaline injected to the animals during the experiments; this may lead by analogy to the hypothesis that long particle flows allow for the most extensive and salient processing in quantum gates mimicking synapses.

As shown in the further biological experiments [7] with the measured values of seventeen biochemical ketosteroid responses in the mice, these values are extensively affected by the exogeneous controlled mixes between the binary audio and the modulated video. This might correspond to a biological process accounting for the integral of the combined excitation information/content provided. This creates the supposition that the video modulation induces higher, and excitation adapted, sensitivity, meaning by analogy that modelling quantum architectures with detailed control & signaling using colored algebras, may allow to exploit wider sensitivity intervals if the quantum energy spectrum is large. This is especially important in engineering terms, in that more predefined quantum energy intervals instead can augment the needed particle source power and affect cooling requirements.

There are other implications for qubit interactions from the synapse interactions. In many ways, should be further researched the specific correspondences between the biochemical process constituents in a synapse control interaction, and the proposed color tagging of the quantum particle flows (described in Section 5), to reduce the size of the coloring sequence.

In addition, the quantum pathway processing reduces the commutation probabilities in the signaling, so the proposed solution based on biologic mimetics can surpass the thermal wall limits, permitting a significant increase in quantum processing energy efficiency.

6.2. Decidable quantum signaling

Using a group theoretic reasoning [67], the existence of decoherence-free (DF) subspaces of qubits has been demonstrated, using the projection onto symmetric subspaces of multiple copies of a qubit structure [68]. Construction of these subspaces was conducted explicitly for certain collective error processes in the spin-boson model [69,70].

By implementing the colored algebra as specified above in Section 5, decidability can be achieved, and it reduces decoherence at a given instant. But simultaneously, taking now an externally defined asynchronous sequence of commands or protocol outputs, and as the tagging signaling quantum gates will have their colored labels updated synchronously following the sequence of instants with decidability on the quantum interactions, then control and signaling are achieved together.

6.3. *Quantum pathways and synchronization error handling*

As presented above, the proposed quantum computing architecture includes a conventional interface processor to enable programmability, command interpretations and legacy (Architectural feature no 7). Otherwise, all quantum charge distribution, accumulation and decoding are along quantum pathways linking quantum functional blocks and complex quantum gates mimicking biological functions; the quantum pathways get modified by the signaling, and the quantum information by the functional computation blocks. The signaling protocols at this stage are specified and generated on the conventional interface processor interfaces with the signaling quantum gate(s).

Architectural feature 10: The quantum control path provides the asynchronous sequence of parameters and functions to be executed by the qubits and quantum gates dedicated to computations. The quantum signaling path activates/deactivates the network of quantum functional blocks and pathways using the signaling quantum gates.

At the physical level, the quantum pathways are assembled from three different types of particles areas:

- confinement areas for charge carriers, with signaling or controlling gates which emit charge carriers;
- collection areas for charge carriers, where quantum processing results get switched, measured, and synchronized (see Section 2.1.);
- propagation areas along which charge carriers diffuse and serving as principal quantum pathways; external control or signaling interference can happen at selected locations with charge collectors by the magnetic-electrical effect.

To achieve control and signaling of the processing, we realize the idea to interfere by magnetism with the inputs/outputs of the quantum functional blocks, and to update the signaling qubit tags, by controlling electrical fields at room temperature affecting magnetic fields [9]. A basic operation (e.g., writing a state attribute or tag) would by this effect consume less than 1 Atto-Joule, and this would correspond approximately to an energy density of 1. E−15 J/cm2. More precisely, some quantum functional blocks and signaling qubits may be interfered with by a spin effect, while others may become it by magnetic quantum pathway deflection. Such an approach rests on recent scientific breakthroughs achieving the electric field control of magnetism by electrical fields at room temperature [34,71]. A candidate material used for such an electrical field control is Bismuth Ferrite (BiFeO3), and its chemical substitutes; switching thin films thereof on a Si substrate can be tuned to become exchange coupled to either a spin valve or a magnetic tunnel junction, the switching voltage resting inside the 0,5-1 V range. Memory functions (Architectural feature 5) may be achieved by ferroelectric hysteresis of said spin valves, and amplification may be achieved by ferromagnetic resonance [72].

A different more futuristic approach to signaling realization is to strengthen the signaling flexibility by reshaping the atomic potential in quantum blocks by the phase Berry effect [73] into equivalents of Berry cones.

Therefore, and due to the randomness of the quantum states carrying signaling information, and despite coherence gains, synchronization errors may still exist at the level of the output qubit upon which measurements need to be done after prior computation of specific qubit interactions. To alleviate this problem, we suggest that a separate quantum pathway provides for the transmission from the output qubit of the sole signals received by it, to the quantum signaling gates or protocol processor for attribute updates. The content of this transmission should be limited to the decidability string of signaling colors, with a binary decidability flag as to synchronization being verified or not.

Thus, the proposed architecture mimics neurologic systems, and extends the traditional acknowledgment token sent by a receiving node to emitting nodes in router-based networks [41] or a Rapid IO standard packet interconnect.

7. Open research questions

While the present research addresses specifically the control and signaling in the proposed biological quantum processing architecture, it also helps to prioritize further research towards the detailed architectural design specification, layout, and realization, and to point at other relevant research results. The following represent some of the corresponding short term open issues:

1) *Complexity analysis*: As the proposed architecture requires for the signaling the addition of quantum gates for recording signaling labels and synchronization verification, the total realization requires more quantum gates than for quantum computation alone. However, the decidability gains resulting from the decidable signaling, will enhance the overall quantum measurement results. Some mathematical results related to quantum Kolmogorov complexity may help addressing the trade-off, in that the relative proportions of required signaling qubits can be controlled by a Kolmogorov bound linked to the noise-free Shannon encoding of the control signals [74].
2) *Biology*: Recent discoveries in neurobiokinetics [75] have shown that receptor cells like CB_1 can be actively modulated by novel drugs to inhibit addictions corresponding to excessive neural THC and metabolite activity levels, or the reverse. This suggests designing complex quantum gates, with much simplified functions compared to CB_1 cells, realizing controllable protocol sequences to modulate in discrete steps some quantum gates in case of detrimental particle over/under flows, where these quantum gates are some of those devoted to signaling.
3) *Compiler*: It is necessary to design a compiler able to translate a suitable computing language into code executable on the quantum computer, exploiting the generic quantum processing elements/biology inspired quantum gates, and possible customized one's, while managing dynamically the signaling color tags (Architectural feature 7). A challenge is not to rely on state superpositions with huge parallelization and very fast execution with errors, which are typical of quantum processing. Another challenge is to have the compiler support asynchronous controls alongside synchronous qubit execution; this capability is however largely achieved in

the Erlang.org [76] functional programming environment. A first prototyping case would have few input-output quantum gates and external interfaces, and would rely on one well characterized biological quantum gate functionality, selected from Examples 1–5 in Section 2.2., with attentive vision a prime candidate.

4) *Technology*: while the present paper is not about technology realization, each element of the architecture must be matched for feasibility against particle physics instrumentation and RF/optoelectronic/magnetic technologies, and some options have been mentioned here. This mandates improved nanotechnology manufacturing processes related to designing and stacking of graphene, carbon nanotubes, and ferroelectric layers having localized quantum charge accumulation islands (Architectural feature 5) [77]. Also, besides read in/out quantum gates, detailed measurements are needed of some quantum interactions along specific pathways. This may require eliciting a model based on confinement of some quantum particles, so that in fact their states become observable for a certain period and certain energy intervals. The buffer structure in the quantum signaling gate (Section 2.1; [41]) may be used for this purpose.
5) *Particle physics*: Recent research has focused on Majorana particles in terms of the superconductivity properties of different structured elements [78]. This research tried to better understand Majorana zero modes, which may realize potential zones for controlling the charge carrier displacement along a quantum pathway (Architectural feature 1, Section 1). For example [79], has investigated an implementation that allows for the reflection of the current on topological insulators. These efforts, together with the use of deflection of charge carriers in structured matter, represent elements that, aggregated in the future, will be able to generate computational structures like biological ones.

8. Conclusion

The proposed architecture described here is certainly visionary, and its realism hinges on the extent to which the large diversity of information processing, control and signaling tasks is not overwhelming the combinatorics and programmability of functions inspired from biology and embedded into this design. On the other hand, such functions by surpassing arithmetic or logic functionality, may simplify the overall complexity.

In response to the research question raised in Section 3, have been specified and characterized here theoretically (via the new Architectural features 8–10) the additional elements required for the control and signaling, with synchronization error recovery, in the presence of an asynchronous flow of controls, and synchronous quantum processing. It hinges upon combining qubit interactions akin networks of synapses, and a design-ready tagging of colored tags to the quantum states used for signaling.

Author contribution statement

L-F Pau; P.N. Borza: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

L-F Pau reports financial support, administrative support, article publishing charges, equipment, supplies, analysis, and travel were provided by the European Union. L-F Pau reports a relationship with European Union that includes: travel reimbursement. P N Borza has patent #Romanian Patent no 93122 (June 24, 1987) pending to Institutul de igiena si sanatate publica.

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