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Physical limits of computation and emergence of life

Abir U. Igamberdiev *

Department of Plant Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada

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Abstract

The computational process is based on the activity linking mathematical equations to a materialized physical world. It consumes energy which lower limit is defined by the set of Planck's values, i.e. by the physical structure of the Universe. We discuss computability from the quantum measurement framework. Effective quantum computation is possible via the maintenance of a long-living cold decoherence-free internal state, which is achieved by applying error-correction commands to it and by screening it from thermal fluctuations. The quantum Zeno effect enables coherent superpositions and entanglement to persist for macroscopic time intervals. Living systems maintain coherent states via realization of their own computing programs aiming them to survive and develop, while their non-computable behavior corresponds to a generative power that arises beyond combinatorial capabilities of the system. Emergence of life brings in the Universe a creative activity that overcomes the limits of computability.

Keywords: Quantum computation; Monad; Leibniz; Measurement; Coherence

1. Computability and its price

The basis to describe the Universe scientifically is a naïve and in fact paradoxical assumption that it is computable. The invention of mathematics by Pythagoras follows from his idea that the basis of the world is a number. In this approach, the numbers do not appear: they exist ideally before the existence of the created world. Facing the reality of the physical world, we have to admit, however, that in order to introduce numbers into real world, some action or "energy", which could be quantified *a posteriori*, has to be applied. Computation has its physical limitation, which belongs to the fact that any calculation action has a price (Liberman, 1989), e.g. the addition of one takes energy, and this energy cannot be reduced to zero value. This means that computability is limited: if the price of action is high, we have no physical capacity to control the process. Really, the fundamental constants of physics are the primary parameters for embedding computation into real world. Understanding the physical law means that it can be modeled by a kind of Turing machine, however, in the reality this machine is not external to the process but is embedded in the Universe.

If we divide space, ideally we can do this infinitely but the real physical space cannot be like this; proven by Zeno kinematic paradoxes, any movement in such space is impossible. For the division of space we apply a certain amount of energy, which cannot be infinitely small in a given real world. This determines the smallest space and time intervals defined (in our world) through the Planck's values. Below the Planck scale, the notions of space melt away. This means that in real physical world there is a materialized analogy to the infinitesimal (Leibniz, 1768), to quantify it and "hold" Zeno paradox. It is determined by physical impossibility to divide space

* Tel.: +1 2044746064; fax: +1 2044747528.
E-mail address: igamberd@cc.umanitoba.ca.

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or time below certain values. This idea of minimum measurement establishes a non-computable definition of the value that is needed to introduce another value in the real world. The quantum nature of the physical world is based on the introduction of a finite analogue to the infinitesimal acting as an indivisible real number, which sounds paradoxically. However, this paradox is held by the physical inability to reach infinity via finite means. This results in a fact that the physical world in quantified by intrinsic limitations in its computability. For Cosmos to be 'ever-living fire' (Heraclitus) there should be a certain Logos expressed as a set of fundamental constants. It is arbitrary (in the sense that it is not deducible from other basic principles) and hence semiotic in Saussurean sense (like the arbitrariness of the sign).

Really, Diogenes was not fully wrong by solving the kinematic paradox by walking: the physical (but not logical) impossibility of the infinite division of space in a given universe fixes the paradox and creates a set of physical laws via introduction of a minimum price of action for calculation. Considering fundamental constants we face the fundamental question of Einstein whether God had any choice in the creation of the world. If there is no choice we live in the best (the simplest in hypothesis and richest in phenomena) of all possible worlds a lá Leibniz despite of the fact of the common sense that it is not perfect (which can simply mean that it cannot admit all coexistences). If there is a choice, it could be realized in other universes, but the observability (and hence existence) of these universes has to be substantiated.

The Heisenberg's uncertainty relation 'energy–time' establishes the minimum limit for any action. The action (energy applied for a certain amount of time to fulfil any operation) cannot be lower than the Planck's constant value. Landauer (1967, 1986) and Wheeler (1982) pointed out that real calculations involve physical objects, so there will be fundamental physical limitations to what may be calculated in real world, which in turn imposes fundamental limitations on implementing the laws of physics. This is known as the Landauer–Wheeler principle of physical law. It claims that real calculations involve physical objects and take place in real physical universe, with its specific available resources. Fundamental physical limitations to what may be calculated in the real world in turn impose fundamental limitations on implementing the laws of physics (Landauer, 1967, 1986; Wheeler, 1982). Liberman (1979, 1989) introduced the same idea independently as the 'minimum price of action' principle. The fundamental limitations of computation in the Universe correspond to the imposition of the physical laws in the given observable world. The Planck's quantum is a unit that defines a limit to which the world can be computed (Conrad and Liberman, 1982).

The Universe is finite due to several limits of observation propagation, one of which is a causal horizon limiting the volume of space within which information may propagate in the time t since the origin of the Universe, $\sim(ct)^3$. Another limit is the maximum rate of elementary operations $2E/\pi\hbar$, which would be attained by an ideal quantum computer (Margolus and Levitin, 1998). This limit is linked to the rate of quantum measurement (observation propagation) (Igamberdiev, 1993, 2004). The Margolus–Levitin theorem implies that the minimum tick length of a clock with energy E is $\Delta t = \pi\hbar/2E$. Further limit appears because the information must either be stored or erased in a finite number of physical degrees of freedom (Lloyd, 2000, 2002). All limits are combined in the form of Bekenstein (1981) bound: $kER/\hbar cS \geq (1/2)\pi$, where k is the Boltzmann's constant, R the size of the system (assumed spherical) and S is the entropy. This limit is saturated for the case of a black hole, which may be regarded as a perfect information processing (or erasing) system. It allows estimation of the maximum number ($\sim 10^{123}$) of elementary operations since the Big Bang (Davies, 2005).

2. Monads as computability units

The computability principle in the physical world is introduced via some sort of spontaneous activity brought by elementary units linking mathematical equations to a materialized physical world. These units we define "monads" following Leibniz (1768). A self-moving monad realizes computation by establishing its logical set embedded into the world via the price of action. The programs of all monads define the spatio-temporal physical world while the program that a single monad runs simulates it. The physical world is defined via a basic principle called 'pre-established harmony' (Leibniz, 1768), which is simply a condition satisfying a possibility of reflection of a whole external world to individual internal programs of monads (Nakagomi, 2003a). We suggest later that it is the perpetual activity of solving the semantic paradox that generates what Leibniz called the "pre-established harmony". The harmony does not exist independently of monads. It comes as a possible solution in the physical world and the Planck's quantum plays a role in establishing the existing version of the pre-established harmony. The monadological approach developed in this paper is not exactly isomorphic to what Leibniz introduced initially but it has a similarity with the original monadology in its conceptual basis. Leibniz by himself in his letters and unpublished works developed ideas that are not identical to his original monadology. For example, in his unpublished logic, he considered a condition for a phenomenon to be existent if it is in a harmony with a higher number of phenomena than some other potential event. This is close to our understanding of the perpetual activity of solving the semantic paradox. In the paradigm discussed here, the pre-established harmony is a result of this perpetual solving activity rather than of something divine and given *a priori*. The Planck's quantum forms a major condition for the spatio-temporal representation of monads' projections and exposition to the outer world.

Monad in Leibniz's sense can be considered as a logical basis for the physical world and represents as an embodied logical machine. Each monad computes its own algorithm, performs its own mathematical transformations of its qualities, independently of all other monads. Monads are self-powered: the power that causes the changes is due to the internal logical structure or, more precise, to the perpetual solution of the semantic paradox. Its relative solution has a creative power in the embodied world. We can say following Leibniz that the primary substance is not a number but it is an activity that introduces number. Existence is equivalent to the embodied number which realizes its computational activity and this activity is attributed to a single substance (monad) which observes itself in the world. Observability from the quantum mechanical point of view means a possibility to perform multiple quantum measurements in such a way that their results are compatible and can form a pattern which corresponds to our trivial sense of absolute space–time common to all beings.

This space–time is really a relation but for observability criteria it should meet the criteria of universality upon certain limits (established by the theory of relativity at the upper limit and by the quantum mechanics at the lower). In other words, the external space–time will appear as a medium suitable for coexistence of monads. It cannot afford coexistence of everything possible, but it should allow coexistence of maximal possible things: not every set of monads is a possible world, since every possible world must be coordinated (symphonic): some programs cannot be implemented into bodies, and some bodies cannot coexist with others. The set of fundamental constants (Planck's values) defines and introduces the condition of pre-established harmony to our world. Really, these constants correspond to observability of the world but they may change over some kind of meta-evolutionary process in which the history of decisions made by monads is generated (Nakagomi, 2003a). Pre-established harmony is developed: it is a process of fitting monads together through the actualization of monads' programs that generates a spatio-temporal world. This world develops in a way that the events actualized via monads' program interact and form an actualized pattern.

We can re-formulate the causality principle based on the monadological approach. A monad's internal decision to perform a calculation procedure is the initial cause, which is viewed as an event that can be evaluated externally (via the spatio-temporal representation). According to Leibniz, monads are self-sufficient internally, they have no windows to look through toward outside. Really, there are no windows to perceive the other's self, but the internal program of a monad harmonizes its spatio-temporal representation in the world in itself, like modeling this window. If we turn to physics, we explore an external world generated by the spatio-temporal representation of monads. The window to this world is actually the window to monad's own spatio-temporal representation, so it is not a real window. But it helps evaluate the monad's possibilities of governing in this physical world.

In other words, monad is a unit that makes a decision to perform quantum measurement. This decision does not necessarily mean consciousness, but it means some original elementary *Wille* that produces decoherent output, i.e. *Vorstellung* (in Schopenhauer's terms). Only when all decisions are held in a prolonged coherent medium where a higher monad rules others, a possibility for consciousness arises. In other words, monad is not a physical unit, but a basic semiotic structure that defines a physical event. A monad is characterized by a system of qualities that can be viewed as a system of equations, i.e. a computational program that the monad runs. The qualities of monads serve as a logical basis for the spatial structure of the physical world via putting mathematics into motion. Monads are all symmetrically coordinated but none acts on any other (Steinhart, 1997). However, their bodies, i.e. the patterns on their spatio-temporal representation, act on one another.

3. Coherent states and computation

The main condition for applying computation to the physical world is that it should be stably performed. In such complex systems as biological organisms, to proceed with a high precision of the output, biochemical processes should preserve quantum coherence over a time of the order of a second (Igamberdiev, 1993). This is achieved by the structural organization of macromolecular components constituting living systems. A reaction region enveloped in an enzyme molecule is partly screened from the van der Waals-mediated thermal interactions with the rest of the cell. Similarly, the histone wrapping of DNA might serve to shield coding protons from decoherence (Davies, 2004). Organisms exploit thermodynamic gradients by acting as heat engines to drastically reduce the effective temperature of certain macromolecular complexes (Matsuno, 2006). The effective temperature of the coherent state of the actomyosin complex was calculated (from emitted quanta) as near 10^{-3} K (Matsuno and Paton, 2000). Thus, the actomyosin complex can be regarded as a black body at temperature 1 mK when the temperature is read from the profile of the radiation spectrum (Matsuno, 2006). In the processes associated with mind, the effective temperature can be even much lower.

The long-living quantum coherent state is embodied into a robust quantum heat engine feeding on quantum decoherence that supports the coherent state (Matsuno, 2006). The coherent state with very low temperature is delocalized within this engine, which operates between its "body" temperature of ~300 K and the temperature of delocalized coherent state which is $<10^{-3}$ K. The screened regions forming decoherence-free subspaces can also be shielded by error-correction (Nielsen and Chuang, 1997). When a system couples very strongly to its environment through certain degrees of freedom, it can effectively freeze other degrees of freedom by a sort of quantum Zeno effect, enabling coherent superpositions and even entanglement to persist (Kay and Pachos, 2004). The situation is that unexpectedly long decoherence times exist in biological systems allowing the maintenance of internal quantum states (IQS).

If the calculated values of millikelvin range of the effective temperature within biological macromolecules and their networks can drop down to the scale of tens or hundreds nanokelvin, they can avoid Boltzmann statistics inherent to macromolecular systems (Davies, 2004). Probably the screening from thermal interactions together with error-correction can drop internal temperatures down to such low values (Davies, 2004; Igamberdiev, 2004). The effective temperature of the actomyosin complex was calculated according to the time of its conformational relaxation and the amount of quanta emitted (Matsuno and Paton, 2000). But the ATP-linked actomyosin processes function to support more subtle coherent phenomena of maintaining living system entity. Really there should be processes in living systems (particularly in long-size microtubules of nervous system) (Hameroff and Penrose, 1996; Hameroff, 1998) that correspond to emitting much less quanta and hence to supercold effective temperatures orders of magnitude below that calculated by Matsuno and Paton (2000).

What happens when the temperature drops down to such low values? We approach a state described by the Bose–Einstein statistics and likely present in the regions of the Universe shielded from the temperature of microwave background radiation of the Big Bang, which currently is 2.725 K. Such shielded states exist at the edge of the black holes or gravastars (Mazur and Mottola, 2004). Gravastars are quark stars representing a gravitational version of Bose–Einstein condensate, which is all composed of an identical wave function (Silverman and Mallett, 2001). It consists of particles created in pairs out of the vacuum near the edge of the black hole being the place where the four fundamental forces come together (Garay, 2002). According to the current views on Hawking radiation from black holes, the internal states associated with the black holes are shielded from the background radiation, so they keep independence from the common thermal bath of the Universe. This allows maintenance of coherent states and has a similarity to the existence of the self, which is shielded by error-correction allowing its long-living existence in spite of possible decoherent events at high temperatures.

Delocalized states can also be modeled in supercold fluids (Fedichev and Fischer, 2004; Fischer, 2004). Sound waves are trapped in these areas of moving fluids like light in black holes (Leonhardt et al., 2002, 2003; Barcelo et al., 2003). The string theory indicates that black holes may not actually destroy the information about how they were formed, but instead process it and emit the processed information as a part of Hawking radiation. If the picture is correct, the black holes could in principle be programmed: one forms a black hole whose initial conditions encode the information to be processed and extracts the answer to the computation by examining the correlations in the Hawking radiation emitted when the hole evaporates (Giovannetti et al., 2004). Although the information processing in black holes takes place at extremely low actual temperatures (nanokelvin range), the entropy slightly increases and this leads to the increase of the horizon of a black hole. The two general rules can be applied to the information processing in black holes: the one is the generalized second law of thermodynamics, and the other is the cosmic censorship hypothesis (Davies et al., 2002).

When we turn to living organisms, the basic biological principle can be formulated in a way that it is a living body (robust heat engine) that shields and error-corrects the internal quantum state (IQS) via organized decoherence patterns. This state exploits an internalist non-Boolean logic containing no law of the excluded third: we can make decisions and abolish them before they are actualized. In the actualized world, the Boolean logic is operating which implies the law of excluded third. An activity of choosing in the field of potentialities, which is associated with the measuring device, represents an agency that implements it. If we consider internal measurements or Penrose's "objective reduction", we anyway introduce a kind of a measuring device-based spontaneous selection within the potential field. Again, monads have no windows in a certain sense, so they are "logically" shielded from the excluded third but their representative projections are selected on the basis of a choice between the alternatives.

Fröhlich (1983) viewed biological activity as a result of collective vibrations of electric dipoles in biomacromolecules. From the quantum mechanical point of view, an IQS (quantum "Bohm pilot-wave") is attached to these vibrations (Bohm and Hiley, 1993). It governs Fröhlich-like vibrations via the Hamilton–Jacobi force with the minimum price of action of the value of Planck's constant. The relevant particles are electrons and protons whose spatial displacement controls the conformations of the protein molecules. The idea of living system performing quantum computation (via controlled decoherence patterns at body temperature) requires that there should be no collapse or decoherence whilst the computation is in progress (Mensky, 1992, 1997). The low-energy Bohm quantum qualia pilot-wave (defined here as IQS) (Bohm and Hiley, 1993) is supplemented by a direct back-action of the material modes of the macromolecules on its attached pilot-wave.

The coherent long-living quantum states in biological systems explicit themselves in a phenomenon of emission of weak coherent light discovered by Gurwitsch in early XX century (Gurwitsch, 1923; Gurwitsch and Gurwitsch, 1959). It is worth to note again that the emission of quanta during actomyosin contraction allowed calculation of effective temperature of its internal coherent state (Matsuno and Paton, 2000). Recently a strong evidence of ultraweak photon emission was demonstrated (Popp et al., 2002). This emission is a kind of a similar phenomenon as the Hawking radiation from the black holes (Barcelo et al., 2004) and it may serve for unification of the processes taking part in different subsystems of a biological system (synchronization of individual coherent states), i.e. serve as a kind of informational field as originally proposed by Gurwitsch (1923). The internal quantum state of a living system is a subtle individual subatomic structure and ultimately can be reduced to a complex pattern of vibrating strings, which exhibits itself via a visible classical body-like structure.

4. Finite velocity of quantum measurement

The phenomenon of actualization corresponds to a reflection from the set of potentialities into the set of actualized elements in the frames of a self-referential process (Igamberdiev, 1993, 1998, 2004). For its description only spatial relations are insufficient: the irreversible time flow separates the references to the whole (the set of potentialities) and to its finite actualized model. The choice of a definite set of quantum reduction parameters is determined within the system by its consistency and optimality. An increase in complexity occurs simply as a result of perpetual solution of the computation paradox (Matsuno, 1995). The evolution, viewed as an internalist continuous measurement in the system "living organism plus environment", becomes its own cause, a universal property of our world.

Computation is related to the basic metamathematical action, which defines the structure of physical world and provides a possibility of its observation, i.e. of internal activity that detects the rest of the world. Metamathematical actions related to the physical action of detection (quantum measurement) are thoroughly analyzed in the works of Gunji's group (Gunji et al., 1997, 2004). Kauffman (2001) pointed out that the perception is related to a generation of a fixed point in the self-reference process, but not to a reflection of something completely externally independent. This detection can take place via a kind of a state that is embedded into physical world as a self-operating device performing quantum measurements. The structure of the potential field of the internal quantum state implies simultaneous existence of contradictory statements. Actualization of this potential state ends up this self-contradiction realizing one possibility from many. This actualization defined as quantum measurement, should occur with finite velocity, otherwise it will contain contradictory statements at the same moment of time (Gunji et al., 1997; Gunji and Ito, 1999).

Physical limits of the rate of measurement (finite velocity of observation propagation) can be calculated based on the Heisenberg energy–time uncertainty ratio. The maximum rate of elementary operations as calculated from this ratio is $2E/\pi\hbar$ (Margolus and Levitin, 1998). The strength of electromagnetic interaction, e^2/r, determines the minimum amount of time $t_{flip} = \pi\hbar r/2e^2$ it takes to perform a quantum logic operation on the two particles (Lloyd, 2000). The minimum time it takes to perform such an operation (t_{flip}) divided by the amount of time it takes to send a signal at the speed of light between the bits $t_{com} = r/c$ is a universal constant, $t_{flip}/t_{com} = \pi\hbar c/2e^2$, where $e^2/\hbar c \approx 1/137$ is the fine structure constant α (Lloyd, 2000). The fine structure constant was initially introduced as a fundamental measure of the electromagnetic interaction between bosons and fermions such as photons and electrons. In the case of interacting single photon and electron, the speed of the quantum logical operation will be retarded at least by $\pi\hbar c/2e^2 \approx 215$ as compared to the speed of light. It was an original idea of Kozyrev (1991[1963]) that the "time flow" (which is really the uniformly observed rate of decoherence in the physical world) occurs with the velocity that lower than the speed of light by the value linked to the value of the fine structure constant.

Recent finding has shown that the value of fine structure constant changes over time. Really it slowly increases over cosmological timescales, by less that 10^{-5} over the past 6–10 billion years (Davies et al., 2002). This means that the velocity of quantum computation is decreasing as the speed of light is decreasing too in the line of a general decrease of the basic uniform rate of decoherence ("time flow") with the evolution of the Universe. Davies et al. (2002) suggest that the generalized second law of thermodynamics can explain this decrease as event horizons of black holes may only decrease if there is a corresponding increase in the conventional entropy of the black hole's environment. This also assumes that a more basic (than the set of fundamental constants) non-changing scale invariant linking the physical world and computable laws operating in it should be introduced. This invariant reflects a correspondence between the internal logical structure of a monad and a uniform external time–space which is formed by all monads. It can be reflected in some basic ratios between the microscopic and macroscopic parameters of the Universe (Alpher and Gamow, 1968; Kafatos et al., 2005) initially proposed by Dirac (1937) that reflect the pre-established harmony. It also means that the pre-established harmony develops by a kind of indeterminable process of adjustment of monads (Nakagomi, 2003a,b). The monad corresponds to a unit having its own calculus. It establishes a harmony with other monads via an open process of interactions of its spatio-temporal projection with the projections of other monads. This may be different from the original monadology but it shows that the "pre-established harmony" is not a divine principle but it rather has its own history of fitting together.

The velocity of quantum measurement propagation is retarded for the reductions involving holding of the coherent state (Braginsky et al., 1986; Igamberdiev, 1993, 2004). For the enzyme molecule in action, the collapse time (corresponding to the substrate turnover rate) (Igamberdiev, 1993; Matsuno, 1995) is usually 10^{-3} to 10^{-1} s, which corresponds to the millikelvin scale of the effective temperature. If the life span is $\sim 10^9$ s as for advanced living systems, this corresponds to a much lower scales referring to the Bose–Einstein statistics of cold quantum superfluid (Fischer, 2004). This state cannot be a single molecule state, but it can be shielded within a kind of a net uniting the whole cell or even the whole body. Both powerful shielding from the external influence and powerful error-correction should prerequisite the maintenance of this state. Error-correcting routines are working analogues of Maxwell's demon, getting information and using it to reduce entropy. The thermal load of correcting large numbers of errors indicates operation at a slower speed than the maximum allowed by the laws of physics. Error-correction requires certain machinery and an input of energy to keep the coherent state non-disturbing. Maxwell's demon (Leff and Rex, 1990) in this case is associated with the quantum measuring device to eliminate the possibilities of undesired quantum reductions.

The finite velocity of observation propagation collapses into the fractal structure (Gunji et al., 1997; Gunji and Ito, 1999). Simple modes of such collapse involving summations of the results of preceding and current measurement lead to the structures containing the golden section and the golden wurf limits as described in my previous paper (Igamberdiev, 2004). Other possible (and more complex) structures are presented in the works of Gunji's group describing both morphogenetic (Gunji et al., 2004) and behavioral (Migita et al., 2005) patterns taking place in the course of perpetual 'solution' of the measurement paradox. This solution corresponds to a fixed point (number x that makes $f(x) = x$) of the infinite recursive process and appears as a semiotic sign used as an instrumental tool marking whole system's behavior.

5. Emergent properties in complex systems

Life is an emergent phenomenon. I suggested earlier a definition of life as 'a self-organizing and self-generating activity of open non-equilibrium systems determined by their semiotic structure' (Igamberdiev, 1996, 2001). This definition is developed from the Aristotelian understanding of life as a body's feeding, growth and decline reasoned in itself (*di'ayton*) (Aristotle, *De Anima* 2:1, 412a). In other words, life is the embodied metamathematical activity of the self. Via application of its own calculus, the self is generated and maintained via error-correction and opens into the infinite process of emergent evolution.

A new solution appearing during the evolution of a formal system (if it is complex enough) cannot be obtained in a recursive combinatorial way. While in very simple systems combinatorial possibilities are limited, there should be a threshold above which a new solution cannot be obtained computationally (Davies, 2005). It is likely that even in such complex systems as the chess game, computation in principle can be achieved while living systems arise at the threshold when non-computable solutions are unavoidable, i.e. a causal openness arises in the systems exceeding certain threshold of complexity. This threshold corresponds to a minimum level of complexity when emergent behavior appears. There is a wish to quantify this threshold for the emergent behavior as Davies (2005) suggested. He considers emergent a system that selects from possibilities exceeding informational capacity of the Universe (10^{123} bits) and finds these solutions in biological processes starting from the conformational activities of macromolecular components of living systems. This makes sense if we consider that monads reflect (simulate) in some sense the whole Universe but definitely needs further substantiation.

The values memorizing the emergent behavior are the statements about the system (which corresponds in the logical calculus to Gödel numbers) and emergence is the activity generating these statements (Igamberdiev, 1998). In sufficiently advanced formal logical systems, Gödel numbers are introduced to define statements about the system itself. In the systems having their own logical calculus as in living organisms with their digital internal genetic description, a new solution (e.g. behavioral or evolutionary) is memorized in a way that new formulae are generated to signify these solutions. If we consider logical calculus of a monad, its creativity can be related to a power of forming Gödel numbers. The complementarity between logic and physics means complementarity between the open process of generation of Gödel numbers and the emergent phenomena.

Really there should be several thresholds in growing complexity. At the lowest level, all transformations are obtained by a combinatorial way. There is no emergence at this level and the system is fully computable: classical computation has enough power to model all possible transformations. With a certain approximation, the growth of inorganic crystals can be described in such a way, however, some effects even in inorganic world can be understood only via a collapse of the wave function and exceed the limits of classical computation (Penrose, 1989). The next level is assembly based on sorting from enormous amount of possible states that occurs in the potential field. A finite solution comes via framing of the set of potential states.

As Davies (2005) mentions this threshold has something with exceeding informational capacity of the universe. Definitely, folding and self-assembly of biomolecules appears beyond this threshold. This level corresponds to a pre-biotic world before a minimum biological unit is formed. Formation of this unit corresponds to overcoming another threshold: a mixture of biopolymers becomes a system capable of generating Gödel numbers, i.e. statements about functioning of the system itself. In other way, it means appearance of encoding in the system when one type of biopolymers serves as a matrix for reproduction of another and also itself. We define this system as a hypercycle following Eigen and Schuster (1979) with the emphasis of the logical aspect of self-reproduction (Igamberdiev, 1999a). Evolution of hypercycles via passing several thresholds (formation of eukaryotic cell, of multicellular organization) comes to a point when a system becomes able to designate itself as belonging to the whole (potentially) infinite world. This is a point where consciousness arises (Igamberdiev, 1999b) and social evolution begins.

Everywhere, in the case of emergent behavior, the newly generated structure is put into correspondence not to the previously existing reality, but to the changed reality non-recursively modified after the inclusion of this structure in it. The developing (evolving) systems realize the reflection to the emergent area (area which is not defined before). These systems are living as they introduce computation into the physical world while the physical systems obey mathematical constructs but do not embed metamathematical statements. Body limits of living systems are established by their quantum properties. The 'quantum recipe for life' (Davies, 2005) governs possible chemical recipes. The Margolus–Levitin limit based on the Heisenberg's energy–time uncertainty ratio actually defines the rates of velocities in living systems. Davies (2004) analyses velocities of actomyosin motor and transcriptional machinery and finds that the size and mass of interacting molecules perfectly corresponds to limitations applied by the Margolus–Levitin principle.

6. Internal quantum states and the problem of self

We define monad as a unit that introduces computation. It has a spontaneous activity attributed to its "self". Schrödinger (1945) was the first who suggested that the nature of self is quantum mechanical, i.e. the self is a state beyond quantum reduction, which generates emergent events by applying quantum reduction externally and observing it. Liberman (1979, 1983, 1989) suggested that the internal self refers not to molecular but to certain quantum structures. Really, the shielded area of the IQS can be a place of making decisions (emergent phenomena). When we approach very small distances, few orders of magnitude larger than the Planck's length, e.g. intranuclear distances (<10^{-25} cm), we enter the area of "local freedom" where the interactive forces are decreased. Quarks move at such small distances independently but cannot separate from each other: their interaction force does not decrease with the distance. We come to the concept that perception and decision-making phenomena are physically possible as shielded from decoherence in a kind of the Bose–Einstein condensate state (Marshall, 1989). In other words, the self non-locally resides inside the quantum state while the locality of space resides outside. The action of the self has its framed output located in this external space.

Inside the regulatory system, its internal volition-based (quantum reduction implying) behavior occurs in a way that the external observer describes via a probability (wave) function. The cause of such a behavior always arises to a non-computable decision of the controlling system (monad) preceding a control. When we formalize such decision-making (living) system, we transform it into a program for a macroscopic computer without any internal point of view and freedom of will. However, internal measurements occur by internally attached observer (Bohm's pilot-wave) and are non-computable. They may be evaluated from the time future, i.e. from the perfection of their final cause. Unstable quantum superposition collapses according to the uncertainty principle $E = \hbar/T$, where E is the energy of the superposed system, $\hbar$ the Planck's constant, and T is the coherence time until reduction. The energy of a superposed system is inversely related to the time T until self-collapse. The result of collapse may be estimated from the time future as being compatible to a larger number of existing events than an alternative result, in correspondence with the unpublished (in his life time) logic of Leibniz (Font and Jansana, 2001).

With the appearance of consciousness a device evolves that detects the rest of the world (Gunji and Kamiura, 2004). The consciousness and social human being appear when the meaning of a whole is encoded in the semiotic system as a Gödel number (Igamberdiev, 1999b). A human being thus can model a picture of the reality as something external but in which he is embedded. Measuring this reality means that, both the measuring object and the measured reality are perpetually changing. This determines social development of the mankind in which the embedding actual infinity means the beginning of social evolution (Igamberdiev, 1999b). Really, a body appears as a sign for the self, while the stable "framed" objects are formed as symbolic entities of the external reality, in Peircean sense, in the course of recursive participation of the observer in the world (Kauffman, 2001) and fixed points are used as semiotic signs of living activity.

The molecular-based body of organism with Gödel numbers encoded in the genome is linked to the attached internal quantum state. Until the organism is alive, it keeps a connection to this state. When the connection is lost, potentially it may reappear spontaneously in a creative act as another space–time unit harmonically embedded into the infinite Universe of monads. The anthropic principle is a direct consequence of such a structure of the world. Human minds can see the truth or falsity of their non-computable statements and can intuitively solve certain machine-unsolvable problems (such as Gödel's problem of recognizing the consistency of arbitrary sets of axioms or Turing's halting problem for Turing machines). The consequences of such incomputability are the Saussurean arbitrariness (contingency) of sign (Saussure, 1965[1911]), the idea of Chomsky (1965) of indefiniteness in generative mechanisms as a requirement for the explanation of semiotic creativity and the notion of Kolmogorov (1965) on the randomness defined as sequential incompressibility.

We observe ourselves as being embedded into the whole world simulated via our internal computation. This means that we observe the world from the black hole-like coherent state and our perceptions (of color, sound) are quantum phenomena linked to macroscopic processes such as wavelengths, sound waves, etc. At the quantum level, there will be no division on subject and object and our perceptions arise as polarizations of the quantum state generating the observed pictures (Liberman, 1989). The human thought and any decision-like activity of living beings can be described as a non-computable process of generation statements about the system (Gödel numbers), which makes it computable (Gunji et al., 1997; Gunji and Ito, 1999). The system as a whole selects whether the statement is true. Such mathematical process (generation of Gödel numbers and their selection) has a general analogy in the background physical reality (actualized world), which is the quantum mechanical reduction, occurring as an internal measurement. Life emerges to incorporate basic computation principles and in the course of evolution to overcome physical limits of computability of the world.

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