Article

Simulation of closed timelike curves in the framework of an information-theoretic Darwinian approach to quantum mechanics

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Abstract: Closed timelike curves (CTCs), non-intuitive theoretical solutions of general relativity field equations can be modelled in quantum mechanics in a way, known as Deutsch-CTCs, to circumvent one of their most paradoxical implications, namely, the so-called *grandfather paradox*. An outstanding theoretical result of this model is the demonstration that in the presence of a Deutsch-CTC a classical computer would be computationally equivalent to a quantum computer. In the present study, the possible implications of such a striking result for the foundations of quantum mechanics and the connections between classicality and quantumness are explored. To this purpose, a model for fundamental particles that interact in physical space exchanging carriers of momentum and energy is considered. Every particle is then supplemented with an information space in which a probabilistic classical Turing machine is stored. It is analysed whether, through the action of Darwinian evolution, both a classical algorithm coding the rules of quantum mechanics and an anticipation module might plausibly be developed on the information space from initial random behaviour. The simulation of a CTC on the information space of the particle by means of the anticipation module would imply that fundamental particles, which do not possess direct intrinsic quantum features from first principles in this information-theoretic Darwinian approach, could however generate quantum emergent behaviour in real time as a consequence of Darwinian evolution acting on information-theoretic physical systems.

Keywords: quantum mechanical foundations, Deutsch closed timelike curves, Darwinian evolution

1. Introduction

Time is one of the deepest-rooted experiences in adult human beings. As such it has been a fundamental object of study in philosophy and physics from the antiquity to the present. Naively, we can try to define[1] time in a minimalist way as a concept that enables an observer to describe and measure the perceived physical fact that "the world changes". However, in this definition there is an echo of circularity as for most, if not all, definitions of time.

In Newtonian physics, time is an absolute, primary concept. But relativity theory demolished the notions of absolute time and absolute simultaneity, and, as a consequence, the flow of time, that shapes the first-person experience of an observer, appeared as an illusion. This paved the way to explore the possibility that time itself were not a primordial concept, but a derived one, and

[1] See Refs. [1] and [2] (and references therein) for a general and deep discussion of the problem of time.

contributed to the impulse of mathematizing and constructing physics in terms of more abstract primary concepts[2].

Quantum mechanics went beyond relativity concerning the difficulties in grasping the observer-independent reality of nature. The Copenhagen interpretation of quantum mechanics highlighted the absence of meaning in describing a system without referring to the results of a measuring apparatus. Thus, the reality of a system –the definite value of the intrinsic properties that characterized such a system-- could be affirmed only in connection with the actually performed observations by a classical meter.

Quantum mechanics also raised doubts about the validity of the classical principle of causality –i.e., that every event has an antecedent determined cause—and pointed at a possible intrinsic randomness as a fundamental feature of nature[3].

In addition, there was a central tension between quantum mechanics and relativity about the principle of locality[3] –i.e., the existence of a limiting velocity (the speed of light) for the propagation of an interaction through space—as was especially manifest in the experimental observations of non-classical correlations between entangled particles or Bell inequality violations[8].

Time seems to play a crucial role for the coexistence of both theories. For instance, backward in time causation [9-11] could explain Bell inequality violations preserving locality (see also Refs. [12] and [13]). And even in certain circumstances quantum mechanics can alleviate some of the problems that the theory of relativity brings about on the nature of time. One of these cases is the solution to the difficulties and mysteries in the concept of time supplied by assuming the many-worlds interpretation (MWI) of quantum mechanics [14] as analysed by Deutsch[15]. Another example is the resolution in the framework of quantum mechanics of the so-called *grandfather paradox* that appears in general relativity in those regions of spacetime for which closed timelike curves (CTCs) are possible mathematical solutions. The *grandfather paradox* reflects the logical inconsistency of those closed trajectories in which a time traveller could kill his own grandfather, therefore, making impossible his own existence. The resolution of the paradox in a classical framework [16] is generally considered unsatisfactory [17, 18] because it essentially requires suppressing by fiat the initial conditions of trajectories driving to the inconsistent solutions (enunciating a global principle of consistency that would prohibit the particular local solutions leading to inconsistency). However, a quantum model devised by Deutsch in order to analyse the closed timelike curves (D-CTCs) in terms of quantum information flows guarantees the existence of a consistent solution for all initial conditions.

The interest of studying CTCs in the framework of quantum mechanics resides not only in the solution of paradoxical results in this specific milieu, but also in the analysis of the interplay between relativity theory and quantum mechanics, and the deep implications on the nature, foundations and coexistence of both theories.

A set of studies have been developed on the special properties that quantum mechanical systems present near a D-CTC[4]. One of the most astounding results, which has been obtained by Aaronson and Watrous[20], is the computational equivalence of a classical and a quantum computer in the presence of a CTC. This result highlights the adequacy of the CTC scenario as testing ground to study the relationship between quantumness and classicality.

In the present article, it is analysed the possibility of simulating D-CTCs in the framework of an information-theoretic Darwinian approach to quantum mechanics (DAQM)[21-26] and its

[2] In fact, there was a previous loophole in Newtonian mechanics that pointed to the possible unreality of time in the time symmetry (reversibility) of the equations.

[3] See Khrennikov[4-7] for a modern resolution of the conundrum by getting rid of nonlocality from conventional quantum theory (considered as an observational theory, much like Bohr´s point of view) through reinterpreting Bell inequalities violations as purely showing the incompatibility of observables for a single quantum system.

[4] There are other quantum mechanical models different to that of Deutsch for the study of CTCs, e.g., see Lloyd[19], but in this article only the model of Deutsch will be considered.

implication for the progress in the understanding of the foundations of quantum mechanics. There are two specific concepts in this approach that play a central role in the theory. First, time is assumed to be, all the way down, a real fundamental magnitude in nature, in the sense that accepting the reality of time in its deepest meaning implies the possible change of the physical laws of nature, as extensively analysed by Unger and Smolin[27].

The second specific, crucial concept in DAQM is anticipation. If the previous anticipation by an agent of a future event or algorithm outcome actually coincides with such event or outcome in the future, then from the point of view of information, this situation might be operationally equated to backward in time causation. Anticipation is built on the capacity of a system to process information. And this capacity is assumed in DAQM as a fundamental property of matter. If information is central to physics, then it is natural to explore the possibility that matter possesses the capacity of processing information. Supplementing every physical system with an information space in which a methodological probabilistic classical Turing machine processes the information that arrives at the system turns physical systems into information-theoretic Darwinian systems on which natural selection might act as a metalaw driving the evolution of natural laws or regularities –the algorithms stored on the information space of every physical system that govern their behaviour-- and plausibly, as will be analysed within the article, generating quantum mechanical behaviour as result of an optimised information strategy.

Notice that in the present study it is not discussed the existence of real CTCs in the physical spacetime, but only the implications of the possible simulation of a CTC in the information space of a DAQM particle.

The aim of this article is to explore the possibility of inducing quantum behaviour for a physical system endowed with a probabilistic classical Turing machine through the simulation of a D-CTC on its information space, exploiting the theoretical equivalence between a classical and a quantum computer both with access to a D-CTC that has been demonstrated by Aaronson and Watrous[20]. In Section 2, a brief description of the D-CTC model is outlined. The characterization of a fundamental physical system in DAQM is analysed in Section 3. The simulation of a D-CTC on the information space of a physical system in the framework of DAQM is studied in Section 4. The plausible emergence of quantum mechanical behaviour from a sketchy mathematization of the dynamics of fundamental physical systems modelled as information-theoretic Darwinian systems in the framework of DAQM is discussed in Section 5. The conclusions are drawn in Section 6.

2. Deutsch quantum model for a CTC

The conventional studies of CTCs are framed in the geometrical analysis of these solutions of Einstein's field equations of general relativity for classical systems traveling along the spacetime[28]. Deutsch[17], adopting a different perspective, disregards the dynamics of the motion in the spacetime, assuming that the trajectories are classical and given, and considers traveling systems endowed with internal quantum mechanical degrees of freedom. Then, the physics of CTCs is analysed in terms of the information flows within a physically equivalent quantum computational circuit that models the interaction process. It is assumed that the interactions between systems are localized in the quantum gates. Therefore, the states of the systems stay unchanged between gates.

One of the meaningful elements suggesting to explore a quantum mechanical description as a possibility to solve CTCs paradoxes is that, by considering quantum mechanical systems, the space of states of the traveling systems is enhanced, including linear superpositions and mixtures[29]. Deutsch[17] then proceeds to demonstrate (Deutsch´s fixed point theorem) that in quantum mechanics is always possible to find a consistent solution for any possible initial condition in the presence of a CTC. In this way, the D-CTC model overcomes the unsatisfactory limitation imposed by the classical resolutions (e.g., see Lewis[16] and Novikov[30]) of the *grandfather paradox* in which the way out from the paradox basically consists in claiming a philosophical global consistency criterion that impedes by fiat the initial conditions that, although allowed by local physical laws, would conduct to physical contradictions.

The quantum circuit that represents in the model of Deutsch for a CTC the process for a particle that approaches the CTC is drawn in Fig. 1. Let us assume that the particle is a qubit. The particle that enters the CTC --see Fig. 1(a)-- in the quantum state ϱ(1) interacts in the quantum gate U with an older version of itself that has come out of the past mouth of the wormhole in the state ϱ(3). After the interaction, the younger version of the particle is in the state ϱ(2) and enters the future mouth of the wormhole as the older version of the particle in the state ϱ(4) leaves the CTC region traveling towards the unambiguous future. The process can be described in a "pseudo-time" narrative[5][18] from the intrinsic perspective of the particle following the timelike curve for which the proper time of the particle is increasing[28], with the number between parentheses for every state indicating the proper time order along the line. The model requires as consistent condition that the state of the younger system leaving the gate, ϱ(2), be the same as the state of the older system entering the gate, ϱ(3). That is to say, ϱ(2)= ϱ(3).

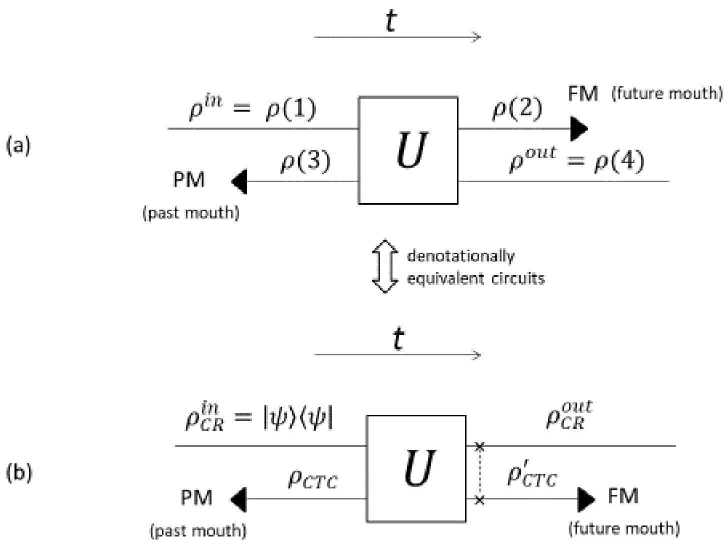

Fig. 1

Fig. 1: (a) Quantum circuit representing the model of Deutsch for a CTC. (b) Denotationally equivalent circuit. The description of circuits and the meaning of symbols are given within the text.

The circuit represented in the Fig. 1(a) can be conveniently transformed into a simpler denotationally equivalent circuit[17], Fig. 1(b), --for which the outputs of the transformed circuit are the same function of the inputs as in the original circuit, as defined by Deutsch[17]—by including a $SWAP$ gate after the original gate U, so that the interaction in the transformed circuit is given by $U' = SWAP \cdot U$. In this way the one-particle circuit is replaced with an equivalent two-particle circuit[31, 32] constituted by a chronology-respecting particle (CR) that interacts with another particle confined in a closed timelike curve (CTC). Now, the consistent condition in this equivalent circuit, Fig. 1(b), is obtained by requiring that the quantum state (ρ_{CTC}) of the chronology-violating particle that emerges from the past mouth of the wormhole in the closed timelike curve be the same as the state that enters the future mouth (ρ'_{CTC}):

$$\rho'_{CTC} = Tr_{CR}\left[U'(|\psi\rangle\langle\psi|\otimes\rho_{CTC})U'^{\dagger}\right] = \rho_{CTC}$$
(1)

where it has been considered that the chronology-respecting particle enters the gate in the pure state $|\psi\rangle$ (i.e.,$\rho^{in}_{CR} = |\psi\rangle\langle\psi|$) and the partial trace is over the Hilbert space of the chronology-respecting (CR) particle. Deutsch [17] showed (fixed-point theorem) that in the framework of quantum mechanics for a general interaction U' there is always at least a solution ρ_{CTC} of Eq. (1) for any initial state $|\psi\rangle$. This solves the *grandfather paradox*. An intriguing question of the model is the way

[5] This kind of account must be taken with care since it can be subject to interpretation[18].

in which nature has to manage in order to find the solution to Eq. (1). This problem is usually named the *knowledge paradox*, since the solution to Eq. (1) must be known at the same time as the state $|\psi\rangle$ enters the gate, i. e., before the interaction occurs. Deutsch[17] gives an answer to the *knowledge paradox*[6] in the framework of the many-worlds interpretation (MWI) of quantum mechanics. In our model, in the framework of DAQM, the *knowledge paradox* would be solved through the action of Darwinian evolution. This point is discussed in Section 5.

On the other hand, the state of the chronology-respecting particle that abandons the CTC region is given by the following expression:

$$\rho_{CR}^{out} = Tr_{CTC}\left[U'(|\psi\rangle\langle\psi|\otimes\rho_{CTC})U'^{\dagger}\right] \quad (2)$$

where the partial trace now refers to the Hilbert space of the particle trapped in the closed timelike curve.

The dependence of the output state ρ_{CR}^{out} on the input state $\rho_{CR}^{in} = |\psi\rangle\langle\psi|$ is non-unitary --since mixed states can occur on the CTC as solutions (ρ_{CTC}) of Eq. (1)—and nonlinear. This nonlinearity induced by the self-consistent condition –Eq. (1)— is the source [20] of the stunning computational efficiency that enables a classical computer in the presence of a CTC to reach the same computational performance as a quantum computer with access to a CTC.

3. Information-theoretic model for a particle in DAQM

The aim of this article is to analyse the relationship between classicality and quantumness under the light of the result of Aaronson and Watrous[20] in the unconventional scenario of a D-CTC. The model of Deutsch, as it has been briefly described in the previous Section, is based on the analysis of information flows in the equivalent quantum circuit that encodes the physical process for a quantum particle that traverses a CTC. Information is therefore a key ingredient and for that reason it seems justified to consider an information-theoretic model for physical particles in which information also plays a central role.

Not only is information a crucial concept in the D-CTC model, but also in the modern theory of quantum information and computation[33], and in recent perspectives in physics[34]. However, as Bell pointed out[35, 36], prior to introducing the concept of information in the description of physical systems, it seems necessary to specify two points: "About what information?" and "Whose information?". A basic answer to these two questions might be, namely, information is about the properties of physical systems and information is for physical systems. Therefore, if the emitters and receivers of information are physical systems –in particular, elementary physical systems as well--, then it seems reasonable to explore a scenario in which a particle is not a mere passive object that blindly transports information, but an active agent that receives, processes and generates information.

Bearing this in mind, we characterize in DAQM[21-26] a fundamental physical system i as a particle of mass m_i and position $\boldsymbol{X}_i(t)$ in physical space (see Figure 2). Every particle is methodologically supplemented with a classical Turing machine defined on an information space where a program P_i, which includes an anticipation module or subroutine A_i, and a random number generator R_i are also stored. At every run of the program, a carrier of energy and momentum is emitted by the particle according to the output calculated by the algorithm P_i. Particles interact absorbing and emitting these carriers that also transport information about the emitter to the absorber. This information consists in positions of systems. In this framework, the wave function ψ_i can be considered as a book-keeping tool that appropriately codes the data about the surrounding systems so that the program may calculate efficiently the self-interaction, i.e., the corresponding parameters of

[6] See Dunlap[18, 29] for a discussion on Deutsch's interpretation of the *knowledge paradox*.

the carrier to be emitted. In physical space, particles follow continuous trajectories and comply with the conservation of energy and momentum.

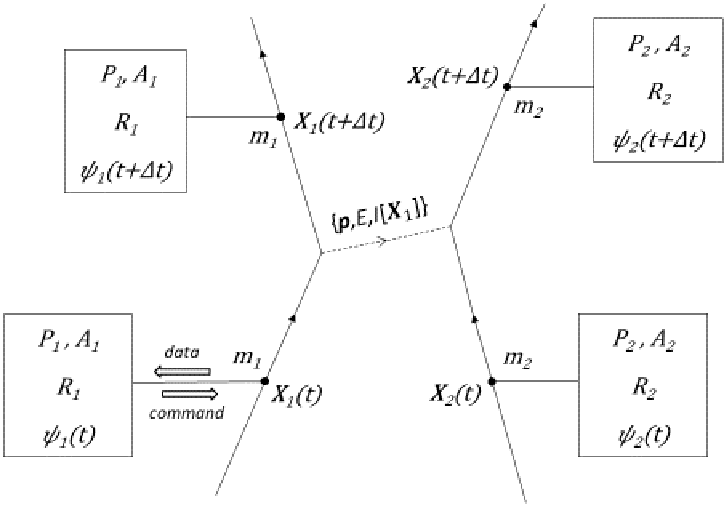

Fig. 2

Fig. 2: Representation of an interaction between two fundamental particles in DAQM. See the text for a detailed description and definitions of symbols.

It is assumed[7] that the program P_i that governs the dynamics of each particle simulates quantum behavior. The question arises whether this simulation, which is carried out on a probabilistic classical Turing machine, may be performed efficiently in order to be properly accomplished in real time. In the next Section, it will be analysed how the presence of the anticipation module A_i in the information space of the particle enables to simulate a CTC that would render the classical Turing machine computationally equivalent to a quantum one, therefore supplying the required efficiency to simulate quantum behaviour.

4. Simulation of a CTC on the information space of a particle in DAQM

Let us consider the information space of a particle i in DAQM. According to the model, the new, refreshed information about the surrounding systems that has arrived at the particle transported by the information carriers, which also convey momentum and energy, has been coded by the algorithm P_i into a probability distribution function[8] $\varphi_i(t)$ on the surrounding particles phase space. This function reflects the epistemic state of the particle about the locations occupied by the surrounding systems and their dynamics at time t. The wave function $\psi_i(t)$ of the particle can be constructed from the probability distribution function $\varphi_i(t)$ by the algorithm P_i . That probability distribution function $\varphi_i(t)$ enters the classical network G_i , which is schematically represented in Fig. 3, interacting with the second input φ_{CTC} that has come out from the anticipation module A_i of the particle. After the interaction, the output of the first channel is $\varphi_i(t+\Delta t)$, the anticipated probability distribution function of the surrounding systems at time $t+\Delta t$, and the output of the second channel is φ'_{CTC} that must equal the input φ_{CTC}.

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[7] A procedure by which these programs P_i might be developed in nature for the defined information-theoretic model of fundamental physical systems is analysed in Section 5.

[8] Note that in general this probability distribution function is a classical statistical mixture defined on the classical phase space of the surrounding particles.

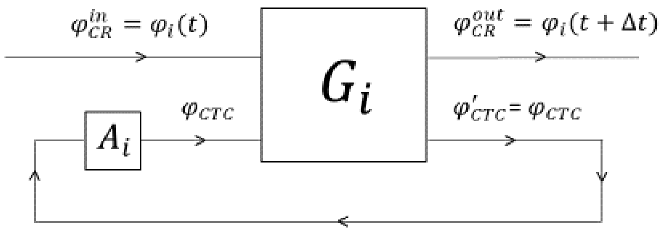

Fig. 3

Fig. 3: Classical circuit on the information space of a DAQM particle simulating a CTC. The definitions of symbols and the analysis of the circuit are contained in the text.

The program P_i , the anticipation module A_i and the network G_i are all of them classical elements that perform their task on a classical Turing machine as initially assumed. This means that, first, the program contains and applies the principles of quantum mechanics but on a classical processor, second, the classical anticipation module is able to find out the function that stays stationary after coming out from the second channel of the classical network G_i (i.e., it is able to find out the fixed point for the second channel of the network) and, finally, this circuit G_i correctly calculates as output of the first channel the function that allows the program to compute (on other module) the wave function $\psi_i(t + \Delta t)$ of the system at time $t + \Delta t$.

Notice that all the elements and functions in the circuit of Fig. 3 are classical. Therefore, it seems that this classical circuit would not be able to simulate a D-CTC as represented in Fig. 2, given that a quantum circuit with quantum states is apparently required. However, as shown by Tolksdorf and Verch[37] (see also Aaronson and Watrous[20]), the D-CTC model can be implemented on a classical network acting on classical statistical mixtures, since in order to ensure the existence of a fixed point for a map (the core of the model), the key mathematical properties are of statistical nature. In particular, the state space must be convex and complete[37]. In consequence, exclusive quantum properties are not necessary to carry out a D-CTC circuit.

Therefore, the classical circuit of Fig. 3 could simulate a D-CTC on the information space of particle i, provided that a procedure to obtain the objects P_i , A_i and G_i , whose characteristics have been defined in this Section, be specified. But if the classical Turing machine has access to a D-CTC, then according to the result shown by Aaronson and Watrous [20] this classical information processor would be computationally equivalent to a quantum computer and might induce in real time quantum behaviour on the particle.

5. Generation of the anticipation module A_i and the program P_i in the information space of a particle in DAQM

The characterization of a fundamental particle in DAQM [21-26] potentially endows these particles with the defining properties of information-theoretic Darwinian systems whose populations are then susceptible of evolution under natural selection[9]. It is assumed that at time $t = 0$ there is a

[9] For an introduction to Universal Darwinism and Generalised Darwinism, see Ref [38, 39].

distribution of particles that are exclusively governed by their respective randomisers. As time goes on, algorithms that progressively take control on the particles' behaviour are randomly developed as a consequence of the arrival of information at every particle. Different procedures[10] on the information space of particles mimicking those encountered in biological genetic systems might enable the variation of the control algorithms and their posterior selection and retention or inheritance through the populations dynamics of DAQM particles in physical space.

An open question in the Darwinian evolutionary theory is whether there is a direction for evolution, i.e., whether evolution is predictable in the long run. Complexity has been proposed in several occasions as a possible magnitude whose increase would determine the direction of evolution[40].

There is no general consensus[40,41] on the definition of complexity[11] in evolution. Among the multiple variations there is a contextual definition of "physical complexity", as it is named, given by Adami et al.[41] that characterises the genomic complexity of a biological system in terms of the information about the environment that is stored in the system for a fixed environment. It is then demonstrated[41] that, assuming this definition, according to the performed simulations, complexity must always increase.

In the present article another contextual definition, which is named "survival information complexity", is introduced. The essentials of the definition are summarized in that informationally the optimal strategy of any system at any environment would be maximising the anticipation and stealth capacities of the system. Thus, survival information complexity measures the capability of a system for optimising its information flows against survival. This definition does not directly contemplate structural characteristics of the physical constitution of a system.

Survival information complexity defined in this way does not automatically ensure a higher fitness in the short term. Other specific structural and functional traits or particular strategies may turn out more advantageous for survival in a concrete environment. However, in the long run, assuming an evolving environment, those populations that are informationally more complex, in the sense of the definition we have adopted, would have, in the end, a higher probability of adapting to the changing environment, therefore increasing their survival expectations, and, consequently, suggesting to identify the increase of "survival information complexity" as the property that determines the direction of evolution in the long run.

A system with information processing capabilities is then considered to be informationally more complex when, on the one side, it is able to anticipate the positions of its surrounding systems with greater precision, and, on the other side, it is also able to minimise the precision of the anticipation of its position by its surrounding systems through optimising the information sent outside.

Let us then define mathematically the survival information complexity $C(t)$ of a DAQM system 0 whose location is $\boldsymbol{X}_0(t)$ at time t by introducing two terms:

$$C(t) = C_a(t) + C_b(t) \qquad (3)$$

The first one, $C_a(t)$, measuring the capacity at time t of system $\boldsymbol{X}_0$ for anticipating the behaviour of the surrounding systems at a future time $t + \Delta t$, is:

$$C_a(t) = \frac{1}{N}\sum_{j=1}^{N} \frac{r_j^2}{\left(\boldsymbol{X}_j^0 - \boldsymbol{X}_j\right)^2} \qquad (4)$$

Where N is the number of systems that surround system $\boldsymbol{X}_0$; $\boldsymbol{X}_j$ $(j = 1,2 \dots N)$ are the positions that will really be occupied at time $t + \Delta t$ by the surrounding systems of system $\boldsymbol{X}_0$; $\boldsymbol{X}_j^0$ is the position that will be occupied at time $t + \Delta t$ by the surrounding system j of system 0 as

[10] Errors in the read/write operations in the Turing machine (the analogue of mutation in the genetic biological systems), transference or recombination of algorithms between particles, etc.

[11] Similar difficulties have been found in the definition of fitness[40] in Darwinian evolution.

calculated by system 0 at time t on the Turing machine of its information space; and, finally, $r_j^2 = (\boldsymbol{X}_j - \boldsymbol{X}_0)^2$ is the squared distance between the positions that will be actually occupied by system i and system 0 at time $t + \Delta t$ (see Fig. 4 for a visualization of an example for the definitions of real and calculated systems locations).

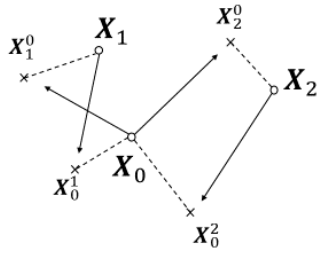

Fig. 4

Fig. 4: Actual positions occupied by three DAQM particles at time t+Δt are marked by small circles. The crosses represent the position at time t+Δt of the particles indicated by the subscript as calculated at time t in the information space of the particle indicated by the superscript. Dashed lines are drawn between the actual position of a particle and calculated positions. Arrows relate the actual position of every particle to the calculated locations on its information space of its surrounding particles that are relevant for computing the complexity of particle i=0. See the text for a detailed explanation.

Notice that in DAQM the location of a system is the physical property that is defined at any time, given that the trajectory is continuous

In the definition of survival information complexity $C(t)$, the second term, $C_b(t)$, that measures the capacity of stealth of the system 0 at time $t + \Delta t$ in a certain environment, is:

$$C_b(t) = \frac{1}{N} \sum_{j=1}^{N} \frac{\left(\boldsymbol{X}_0^j - \boldsymbol{X}_0\right)^2}{r_j^2} \tag{5}$$

Where N, as for the first term, is the number of systems that surround system $\boldsymbol{X}_0$; $r_j^2 = (\boldsymbol{X}_j - \boldsymbol{X}_0)^2$ is again the squared distance between the positions that will be actually occupied by system j and system 0 at time $t + \Delta t$; $\boldsymbol{X}_0$ is the position that will be occupied by system 0 at time $t + \Delta t$; and, finally, $\boldsymbol{X}_0^j$ is the position that will be occupied at time $t + \Delta t$ by system 0 as calculated by system j at time t on the Turing machine of the information space of system j.

More sophisticated definitions of $C(t)$ may be envisioned (e.g., including the integration over a meaningful interval of time or introducing a kind of anticipation depth or considering the response time of the information processor of the system) and certain technicalities should be further discussed (e.g., avoiding singularities by defining a minimum value for denominators; discussing the inaccessibility of certain magnitudes for system 0 at time t , what implies a delayed calculation of the quantity; the inherent difficulty of calculating the survival information complexity, except for models), but the given definition captures the central elements of the concept.

Now, let us schematically examine the way in which Darwinian evolution would imply the generation of the anticipation module A_i and the program P_i, which codes the mathematical quantum formalism, on the information space of a DAQM particle i, assuming that the increase of the survival information complexity $C(t)$ would determine the direction of evolution in the long term.

The maximisation of the first term $C_a(t)$ would directly induce the selection of those populations of particles that developed an anticipation module on the information space of the particles. Increasing values of $C_a(t)$ would imply more reliable anticipations of the configuration of the surrounding systems, and therefore increasing fitness of the system to its environment in the long term. As a consequence, those systems that developed anticipation modules with greatest values for their $C_a(t)$ terms would become the fittest with respect the capture of the environment information.

At the same time, increasing values of the $C_a(t)$ term would drive to the generation of the Hilbert space structure for the state space of the systems, since it has been analysed[42-46] that the Hilbert space structure optimises the information retrieval and inference capabilities of an information system, therefore leading to the improvement of the response time of the system that would induce an increase in fitness in the long run.

On the other hand, the second term, $C_b(t)$, maximisation plausibly brings about the dynamical postulates of quantum mechanics, that is to say, the Schrödinger equation and, in a Bohm-like style, the guiding equation for calculating the velocity of the particle from the wave function. Much in the like as for Bohmian mechanics, the Born rule might then be deduced from the dynamical postulates and a typicality criterion[47].

Notice that although DAQM can be considered a kind of generalization of Bohmian mechanics, however, DAQM is local as it is discussed in Ref. [26], in which Bell inequality violations in the framework of DAQM are analysed using a natural model for characterising entanglement in this theory.

Further work has to be done in order to give a detailed account of the mechanisms underlying the deduction[12] of the quantum mechanical postulates in DAQM. In particular, the role played by entanglement shaping the interaction between particles.

The plausible development of the modules A_i and P_i in the information space of DAQM fundamental particles subject to evolution under the main action of natural selection has been analysed. The emergence of quantum behaviour in such particles would be the result of Darwinian evolution acting on matter, "the survival of the fittest" in a universe of information-theoretic fundamental particles.

DAQM helps to explore the relationship between classicality and quantumness from another point of view, namely, the central role that information seems to play in the quantum theory. But this point of view is common to most modern reconstructions of quantum mechanics[48]. In many of these reconstructions [48], quantum systems are fundamentally characterized as carriers and processors of information. If this is an adequate representation of the world, and Darwinian natural selection might operate, then the appearance of the capability of projecting possible future configurations of the environment, the appearance of anticipation, would just be a question of time.

The second central characteristic of DAQM systems is that their properties are calculated in-flight on their information spaces in response to the interactions with other systems or to measurements in experiments. But this reflects Bohr's complementarity [4-7], from other perspective, the concept of objective indefiniteness[49] or in the saying of Peres[50] 'unperformed experiments have no results'.

Therefore, in-flight calculated properties and anticipation, both the two main elements associated to possess information processing capabilities, constitute, in addition to the intrinsic randomness

[12] See Ref. [21-26] for discussions on the deduction of the quantum mechanical postulates in DAQM.

supplied by the randomiser on the information space of every particle, the backbone of DAQM for explaining quantum behaviour in a natural way.

DAQM also explains in a remarkably natural manner the special adaptation and high-performance level of quantum computation for solving optimization problems and efficiently simulating quantum systems. As it has been analysed in this article, a fundamental particle in DAQM would be a classic-like system supplemented with information processing capabilities that would simulate quantum mechanical behaviour in real time by optimising its information flows through the action of Darwinian natural selection.

Finally, if matter as hypothesised in DAQM possesses an intrinsic property of processing information, then this built-in property would help to explain the speed of evolution in biology[51] that remains as one of the problems to be solved in biological Darwinism.

6. Conclusions

A mechanism has been described for the simulation of a CTC on the information space of a fundamental particle endowed with intrinsic information processing capabilities in the framework of DAQM. Assuming a new definition for information complexity, named “survival information complexity”, and that the increase of this magnitude points to the direction in which matter evolves in the long run, then the action of Darwinian evolution under natural selection on the populations of these DAQM fundamental particles would plausibly drive to the emergence of both an anticipation module, enabling the particle to drastically enhance its computational performance through the simulation of a CTC to which the information processor of the particle would thus have access, and an algorithm, coding the quantum mechanical rules, that would jointly induce quantum mechanical behaviour in real time to the particle.

Caption of figures

Fig. 1: (a) Quantum circuit representing the model of Deutsch for a CTC. (b) Denotationally equivalent circuit. The description of circuits and the meaning of symbols are given within the text.

Fig. 2: Representation of an interaction between two fundamental particles in DAQM. See the text for a detailed description and definitions of symbols.

Fig. 3: Classical circuit on the information space of a DAQM particle simulating a CTC. The definitions of symbols and the analysis of the circuit are contained in the text.

Fig. 4: Actual positions occupied by three DAQM particles at time $t + \Delta t$ are marked by small circles. The crosses represent the position at time $t + \Delta t$ of the particles indicated by the subscript as calculated at time t in the information space of the particle indicated by the superscript. Dashed lines are drawn between the actual position of a particle and calculated positions. Arrows relate the actual position of every particle to the calculated locations on its information space of its surrounding particles that are relevant for computing the complexity of particle $i = 0$. See the text for a detailed explanation.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

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Appendix A

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

Appendix B

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled starting with "A"—e.g., Figure A1, Figure A2, etc.

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