Veiled Nonlocality and Quantum Darwinism

Subhash Kak

ABSTRACT

The disparate fields of quantum mechanics and neuroscience come together in the act of observation. Quantum mechanics is a nonlocal theory but the expectations of our cognitive systems are local. The principle of veiled nonlocality appears to direct not only logic and design of experiments but also the manner in which experimental data is analyzed. The principle preserves the naïve classical view of the universe that is consistent with locally realistic models; it also sees underlying similitude between biological and physical processes. One of these similitudes is that of proliferation of stable states in an interaction between quantum systems in analogy with the survival of the fittest of biological evolution. This paper investigates this idea of quantum Darwinism.

Key Words: nonlocality, information, evolution, quantum theory, quantum Darwinism

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Introduction

The idea of information plays a central role in current theories of physics, whether it is quantum theory itself or black-hole thermodynamics. Information is seen as the elemental stuff of reality as in the slogan: *It from Bit*. But it is overlooked that information is a classical concept; it is related to choices that confront the observer. These choices can only be made within the framework of the nature of reality in the mind. In other words, giving centrality to information is to let the observer into the room, even though this is not acknowledged.

In classical physics also the observer lurks in the shadows. Here the future of the system can be estimated given the initial conditions and the assumption that the computations are made by an observer who is located outside of the system. But there is a problem when we conceive of a system that includes a sentient observer as a sub-system. For classical mechanics to be universally true, this requires that the behavior of the observer must also be viewed as being completely predictable which negates the idea of free will. Since the act of observation requires making a choice, either observers and the observation process lie outside of classical physics, or it must be assumed that this choice is illusory.

The situation is essentially the same in quantum mechanics. An unobserved system evolves deterministically by the Schrödinger equation and, therefore, there is no room, *a priori*, for agents making choices within it. If the process of observation is seen as the interaction of two physical systems by the process of

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decoherence, that also rules out free choice. This interaction as unfolding of the entanglement between the system and the apparatus (or the observer) into a statistical mixture of classical pointer states by the environment (Zurek, 2003; Zeh, 2013) has circularity built into it since we expect it to evolve preferentially into the classical states (Kastner, 2015). It also doesn't address the question why the system and the apparatus are separate given the universe itself has an evolving state function that overarches the evolution of the subsystems.

If one were to view the process of observation from the perspective of the human observer, one confronts the problem of how the observation mapped into the activity of its neural correlates gets recognized within the brain of the individual. It is fine to assume that events being observed lead to the firing of specific neurons in the brain, but there is no explanation of how this activity that may be located in different parts of the brain leads to the corresponding experience. The conscious observation cannot be located in a specific physical system even though the data that it is based on is within the brain (Kak *et al.,* 2014c). If the brain is viewed as a neural machine, its response to a stimulus is determined by its current internal state and therefore it cannot act freely. Nevertheless, most individuals believe that they make choices even if it is only the choice of what to focus on amongst infinity of possibilities at each instant of time. If these choices are random, then how does larger human behavior have coherence and meaning?

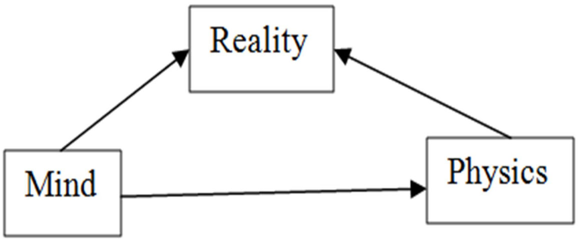

Figure 1. Reality apprehended directly and perceived through the lens of physics.

Shift the focus from the observation to the physical correlates of it, one needs to analyze how these correlates are put into different parts of the mental picture. In classical physics, it is believed that the intuitions of the particle and the wave can be used in a consistent manner although there are complications due to relativity. There is no agreement on this process in quantum mechanics. Its multiplicity of interpretations arise from the difficulty of conceiving of the same "object" in terms of the mutually contradictory intuitions of particle and wave in different situations. Single objects also produce interference patterns in the double slit experiment, therefore some kind of a wave phenomenon is taken to be at the basis of particles that is masked by the mathematical formalism that requires complex probability amplitudes to be associated with individual objects (Feynman, 1985), or it is assumed there is a pilot wave accompanying the particles (Bohm, 1984). There are further problems related to discreteness (Zeh, 2010) as well existence of virtual particles. Last but not the least, in consideration of measurement the observer is both a part of the experimental system and outside of it. The difficulties are sometimes expressed in the idea that reality is veiled (D'Espagnat, 2003) or that there is a deeper implicate order that is more fundamental than our intuitions of space and time (Bohm, 1980).

Here we do not wish to consider the larger question of interpretation of quantum theory and will focus only on the matter of nonlocality. Although quantum mechanics is a nonlocal theory as expressed, for example, in the property of entanglement between remote particles, it is viewed to be consistent with the no-signaling theorem according to which no useful information can be sent to remote places. Experiments to investigate nonlocality have been designed, but imperfections in the experiments leave various loopholes permitting explanations based on local realistic theories (Brunner, 2013). As shown in Figure 1, we approach reality either directly through our cognitions or mediated through physical representation. In both these approaches, the nature of the cognitive lens plays a central role. We proposed that a *principle of veiled nonlocality* (PVN) (Kak, 2014a) is necessary to explain why we don't have loophole-free experimental evidence in support of nonlocality in spite of many research efforts. According to PVN, which is stronger assertion than the non-signaling theorem, the loopholes will never be closed and experimental verification of nonlocality that excludes local realistic explanations will not be found.

In this paper we discuss further the implications of PVN and also investigate the question of quantum Darwinism which is the idea that the interaction between a quantum system and its environment leads to the survival of certain specific states.

Limits to Knowledge

That nonlocality cannot be reconciled with the philosophical position of realism was the argument made by Einstein, Podolsky, and Rosen (EPR) (Einstein *et al.,* 1935). Einstein supported the ensemble interpretation in which the quantum formalism provides results for an ensemble and not for a single measurement. Another realistic theory is that of de Broglie and Bohm in which the particles are guided by the wavefunction. This eliminates the problem of the wavefunction collapse but it does so by introducing hidden variables associated with an objective wavefunction that can never be measured directly.

It was shown by Bell that for a pair of entangled particles measurements made independently in three different directions by Alice and Bob lead to constraints on probability that are different than for the classical case (Bell, 1964; with new discussion by Kak, 2013b). Bell's theorem is taken to mean that results of quantum theory cannot be matched by introducing a set of objective local hidden variables. Although loophole-free evidence in favor of Bell nonlocality does not yet exist, it is generally agreed that experimental results rule out hidden variable theories. On the other hand, the realists offer the possibility that the collapse of the state function of two remotely situated entangled objects will leave some trace in terms of local process explanations that will call for a theory that goes beyond current quantum theory ('t Hooft, 2009; Vervoort, 2013).

When two particles are entangled and they are spatially separated, the particles are each in a mixed state. The measurement of one in a particular orientation leads to an identical result in the remote location if it is carried out in the same orientation. If the measurements are made in different orientations, the quantum system gives results that are different from the classical case.

By the no-signaling theorem, the "instantaneous" collapse of the wavefunction of an entangled particle by the measurement on its twin particle at a remote location cannot be used to send useful information, but experiments on nonlocal correlations continue to have loopholes and therefore they cannot be considered as definitive tests of nonlocality. The two principal loopholes are those of detection and locality.

The detection loophole addresses the fact that although derivation of the Bell Inequality assumes binary outcomes, say 1 and -1, in reality a third outcome of "no-click" is associated with the observations. Furthermore, as practical detectors are not perfectly efficient, the "no click" data cannot be left out as being anomalous under a fair sampling assumption. For the low detection efficiency case, the experimental results can be explained by a local realistic theory (Brunner, 2013; Christensen *et al.,* 2013; Santos, 2004; Santos, 2013).

The locality loophole addresses the possibility that a local realistic theory might rely on some type of slower-than-light signal sent from one entangled particle to its partner. Furthermore, the measurement choice on one side should not be correlated with that at the other. This has also been variously called the "freedom-of-choice" and the "measurement-independence" loophole.

One can argue that the problems of understanding quantum theory are a consequence of the "reductionist" language employed to explain the observations. According to the positivist view, quantum theory concerns our knowledge of reality and not the structure of reality and one can only speak of a probabilistic final result that is a function of the initial conditions. From another perspective, matter at the microscopic level is not "physical" and mathematics is the only reality. In such a realistic interpretation, nonlocality should have measurable consequences.

In principle, macroscopic systems may also be quantum and it seems reasonable to take measurement process to be decoherence caused by the environment and, therefore, there is no need to seek the agency of consciousness in the transition from the quantum to the classical world, as was suggested by scientists such as Wigner and Stapp (Wigner, 1967; Stapp, 2007). On the other hand our conception of the universe and its laws and our analysis is a result of the capacities of our cognitive systems (Carter, 2011). Although it is possible that the classical agents of our mind are based on quantum collectives (Kak, 2013a), we cannot negate the fact that the world of perceptions is at the basis of our knowledge and this world has a classical form.

Those who are dissatisfied with the idea of collapse of the wavefunction in the orthodox view (Copenhagen Interpretation, or CI) have sought new way of looking at things. These include the Many Worlds Interpretation (MWI) that privileges the mathematical wavefunction over the knowledge that can be inferred from it. MWI takes the Born probability distribution to be literally true and, therefore, postulates *other worlds* (constituting the ensemble) that, together with our own, validate the observations. More recent versions of MWI take a somewhat different tack (Tegmark, 1998) and the wavefunction of the universe is now taken as the starting point in the consideration of reality.

If one wished to aggregate the different interpretations of the wavefunction into two groups, one can classify based on whether it has independent ontological reality or if it only has epistemological significance in terms of providing knowledge related to outcomes of an experiment. These are the ontic versus the epistemic views of the wavefunction and they are fundamentally the positions of realism versus positivism. If the wavefunction has ontological reality, then it is conceivable that an experiment will show the nonlocality, but if the wavefunction only encodes information about outcomes then it is unlikely that nonlocality will be revealed.

In the formalism of quantum theory, observable quantities are represented by Hermitian operators, and their possible values are the eigenvalues of these operators. Interaction with the environment (which could be the measurement apparatus) reduces the wavefunction to one of its component states and it is the outcome associated with the application of the measurement operator on the state. From the philosophical perspective the jump may be viewed as not taking place in the physical world but rather in our knowledge of the system. Physically, the reduction is viewed as decoherence precipitated by the environment (Zurek, 2003; Zeh, 2013).

Other less popular interpretations are consistent histories, many minds, quantum Bayesianism, transactional interpretation, and modified dynamics. The consistent histories interpretation is based on the criterion that the probabilities for each alternative history obey the rules of classical probability while being consistent with the Schrödinger equation. The many-minds interpretation brings in subjectivity in the MWI by proposing that the distinction between worlds should be made at the level of the mind of the individual observer. According to the quantum Bayesian interpretation, when an observer updates the state assignment nothing changes in the external world, only the observer's expectations related to the subsequent experience of the world changes and therefore there is no measurement problem. The transactional interpretation describes a quantum interaction in terms of a handshake between forward-in-time and backward-in-time waves. Each of these comes with its own philosophical problems that appear to be more severe than the problems with the orthodox Copenhagen view. Beyond these interpretations is the view that there is a deeper yet-to-be-discovered theory that agrees with the quantum theory in the microscopic world and the classical theory in the macroscopic world.

According to PVN future experiments will be unable to bridge these loopholes and demonstrate nonlocality that cannot be explained by a local realistic theory. Veiled nonlocality does not suggest a local realistic basis to quantum theory. Our mind operates by the classical picture and it uses artifacts wherever necessary and the principle makes the classical picture of reality remain consistent. But it leaves open the possibility that nonlocality can leave traces that can be measured.

Consider now a known wavefunction that has been prepared in the laboratory. It has extension, that is, it is described across space and time. Since this extension collapses into a local attribute, what is the process by which this collapse takes place and might this be apprehended by our instruments? The principle of veiled nonlocality ensures that we will be able to advance local explanations for the process or ascribe the results to coincidences. The veiling of the nonlocality occurs due to decoherence and noise and the fact that the assumed state function represents knowledge about the system in a collective sense for an ensemble of such particles.

Homology between the Psychological and the Physical

The problem of measurement is connected to basic issues associated with the inner and the outer. There is an undoubted homology between the two because any cognitive process must leave a corresponding trace in the brain. The world of material things is causally closed and, therefore, any subjective state must have an objective counterpart. In the CI, the collapse of the wave function requires a "cut" (*Schnitt* in German in the words of von Neumann) between the microscopic quantum system and the observer. Due to the homology between the inner and the outer, it does not matter where this cut is placed. In the words of von Neumann:

> That this boundary can be pushed arbitrarily deeply into the interior of the body of the actual observer is the content of the principle of the psycho-physical parallelism -- but this does not change the fact that in each method of description the boundary must be put somewhere, if the method is not to proceed vacuously, i.e., if a comparison with experiment is to be possible. Indeed experience only makes statements of this type: an observer has made a certain (subjective) observation; and never any like this: a physical quantity has a certain value (Von Neumann, 1932/55).

CI is the view of the universe with the observer in the privileged position and MWI is the view of the universe as a thing. In CI the wavefunction represents the knowledge of the experimenter, whereas in MWI the wavefunction is the complete reality. If CI is the subjective view, MWI is the objective view. The inside-out and the outside-in are like the complementary wave and particle viewpoints already considered in CI. Both these positions are consistent within each of their narratives but these have important consequences for our understanding of the larger reality.

In the outside-in view of MWI observers are only correlates of brain activity and in this it is similar to a conception of reality as nothing more than a collection of *things*. In such a picture, there is no room for minds with agency and the whole universe operates as a giant computer. This appears to have support in the view that brain activity appears to precede the "choice" made by the agent (Libet *et al.,* 1983).

To return to the question of homologies between subjective and objective states, the question may be asked how can the one influence the other? Observe that the epistemic and the ontic views are not that apart if it is noted that knowledge is contingent on the brain and the brain cannot make sense of the world if it did not already possess knowledge. If we grant the ontic view that reality is mathematical, we are also indirectly privileging the idea that this mathematics can only make sense to mind (Figure 2).

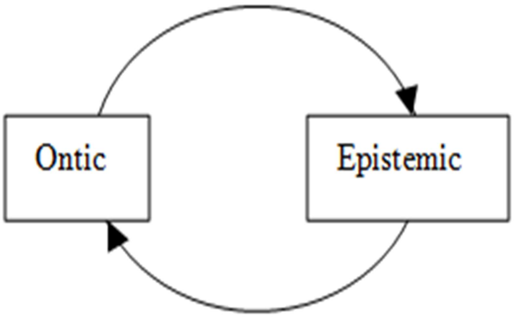

Figure 2. The ontic and the epistemic grounding each other.

In the epistemic view, the ultimate observation cannot be located in any physical module of the brain owing to the neuroscience problem related to the homunculus, and must, therefore, lie in space that is not material and, therefore, outside of the circle of causality. One can, in principle, argue that it is from this space that the observer guides the unfoldment of the universe by the quantum Zeno effect (Misra and Sudarshan, 1977; see also Kak, 2007). This provides the possibility, at least to the philosopher of mind who is looking for space where human agency might be located, for an acausal influence on a process.

Whither Quantum Darwinism?

Zurek presents the idea of quantum Darwinism to explain the emergence of the classical world based on unitarity alone (Zurek, 2009). He claims that this solves the problem why classical states are robust and remain unperturbed by measurement. The basic idea is to see measurement as an interaction between the system *S* and its environment *E* that leads to the singling out of the eigenvectors (pointer states) of the environment in such a way that the phase relations between the pointer states are lost (Zurek, 2003). In this interaction, the state of the system is represented by the reduced density matrix ρ_S which is obtained from the composite state Ψ_{SE} of S and E by tracing out the environment:

$$\rho_S = Tr_E \left| \Psi_{SE} \right\rangle \left\langle \Psi_{SE} \right| .$$

The loss of the phase information leads to classical or probabilistically additive behavior.

In this view there is nothing that distinguishes *S* from *E* and therefore it implicitly leaves out the special role of observer in the measurement process. Since classical observations are repeatable, Zurek brings in the classicality of the observation process indirectly by assuming that correlations between fragments F of the environment E and the system are considered to account for the repeatability associated with the classical states. In quantum Darwinism, these fragments are taken to be independent and, therefore, each of these fragments as an observer will get the same information about the system, leading to classical repeatability.

The idea of a computation determined by the environment is not, in itself, surprising. Consider ants in random motion on a mountainside so that some are able to reach the mountaintop. The fact of having reached the top cannot be ascribed to the intention of the ant, but rather to the nature of the environment. It is in that sense that the environment reduces the dynamics of the system. But if the environment itself is random, no such discernible "computation" can occur.

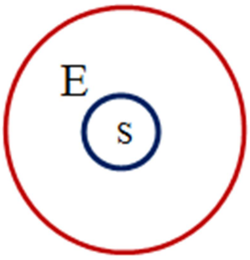

Figure 3. Universe viewed as System (S) and Environment (E).

Zurek asserts that the mutual information *I* between the system *S* and the fragment *F* of the environment, available through decoherence, will satisfy:

$$I(S:F) = H_S + H_F - H_{S,F}$$

where the H functions represent the corresponding entropy values. He claims that states of *SE* contain almost all (all but δ) information H_S about *S* in small fragments f_δ of *E*. This implies a redundancy of $R_\delta = 1/f_\delta$ in obtaining (1-δ) of information from the very many fragments. He concludes that "Large redundancy implies objectivity: The state of the system can be found out indirectly and independently by many observers, who will agree about their conclusions. Thus "*Quantum Darwinism accounts for the emergence of objective existence.*" (Zurek, 2009)

This argument contradicts the notion of one universe with its wavefunction that evolves as a single system that is implicit in unitarity alone dynamics assumed by Zurek. It needs the postulate that subenvironments of the environment are independent (redundancy paradigm of Figure 4) and there exist independent observers (who constitute collections of subenvironments) both of which are contrary to the idea of a single wavefunction.

Figure 4.(a) The environment E divided into 7 subenvironments; (b) fragments are aggregations of subenvironments and each has nearly complete information (after Zurek, 2009).

Kastner criticizes the idea that Zurek's "einselection" (environmentally induced superselection) can explain stable pointer states and she claims that it suffers from circularity of logic. According to her:

> The] problems is not so much a lack of observer-independence as it is a *failure to account for the initial independence of the environment from the system it is measuring*. That is, even if it is true that the system's only correlation with the environment is via the interaction Hamiltonian, and the environmental systems are randomly phased with respect to each other, these conditions cannot be explained from within the Everettian account: in that account, random phases are fictions. And these conditions are crucial to 'deriving' decoherence and the appearance of classicality in the no-collapse, unitary only Everettian picture. Thus, in that picture, apparently *de facto* classicality is crucial to deriving classicality. (Kastner, 2015).

Kastner's critique is compelling. Others have likewise criticized the claim that unitarity alone is sufficient to explain measurement. The very definition of subsystems comes with ambiguity since the partition can be done in a variety of ways that are dependent on what the observer is interested in (Zanardi, 2001) Fields argues that the idea of quantum Darwinism requires an extra-theoretical assumption (Fields, 2010).

Clearly, the multiplicities of views on the measurement problem arise from the differing interpretations of the quantum formalism. Measurement seen as decoherence (Zeh, 1970; Joos and Zeh, 1985; Zeh, 2013) has the virtue of consistency but it leads to a variety of paradoxes like the information paradox (Penrose, 2007) and as Kastner argues it cannot explain how classicality arises.

Nevertheless the question of quantum Darwinism, where the system together with the environment evolves into preferred states remains interesting. If unitarity alone is insufficient, what else might be needed for this to be possible? In order to advance this discussion further we reexamine the ideas of information and of observers that are fundamental to a consideration of the measurement problem from the perspective of quantum computability theory.

Observer and Information

In extension of our self-understanding as biological organisms, an observer is a physical system but he or she is not described exclusively as a physical system for there may be other states such as emergent states that should be counted. To the extent that machines that are used to make observations are physical systems, they are extensions of human agents. The agent is further associated with internal states and a cultural context. Although some physicists believe that all phenomena must be reducible to physics, others have suggested that one needs different kinds of descriptions. Popper and Eccles believed one needs three different worlds, each with its own language, to understand reality (Popper and Eccles, 1984). In their classification, World 1 is the world of physical objects and states, World 2 is the world of subjective states such as thoughts, memories, and emotional states, and World 3 is knowledge in an objective sense. These worlds deal with outer sense, inner sense, and culture and spirit (or self), respectively. Eccles even argued that the self-controls the brain (Eccles, 1991).

In any event, information requires an observer for whom the prior expectations are changed once a message has been received. The central idea here is that of computation of global states and an underlying structure of data within which the message must he examined. An observer cannot analyze data without models and expectations on measurements. The observer, therefore, must not only belong to Eccles Worlds 1 and 2, but also World 3. The observer must have complex stable structures that are entangled not only within its subsystems but also with the environment. This implies that the assumption that the environmental systems are randomly phased as assumed by Zurek is not valid. What is true of the external environment is also valid of the internal environment (structure) of the observer. The claim can be made that whatever is observed is based on the cognitive systems that have the capacity for such observation. As argued in the beginning of this paper, one may also take particular characteristics of reality to be a consequence of the nature of the cognitive system of the human agent.

There are many ways to look at information. More commonly, we view scientific information or knowledge within the context of specific areas that allows us to understand relationships between variables, find laws, and make predictions, where some of the phenomena are deterministic and others are random. Another perspective is to consider the nature of the language in which knowledge is expressed. Different areas of science have their own specialized languages and across fields the languages are not always consistent. This inconsistency points to the gaps that exist in our understanding of reality.

Interpretations of quantum theory provide a bridge between the formalism and intuition. A valid question to ask is if an interpretation can be checked for consistency within itself and the larger philosophical framework of quantum theory. The orthodox interpretation acknowledges a split between the quantum mechanical process and its measurement: the evolution of the system is unitary and the measurement is non-unitary and this embodies the intuitions related to the nature of the physical and the psychological worlds. The unitarity alone idea encapsulates the philosophical view that ultimately all human behavior will be reducible to machine-like behavior.

Now consider a point of comparison of the above with the classical world. Note that even though the three-body has no general analytical solution, measurement is not normally a problem in the classical world because of the clear hierarchical distance that exists between the observer and the system on which the measurement is being made. In computer science, the observer sits beyond and above the system examined by him. Thus in Figure 5, classes 1, 2, and 3 may be based on the size of the system and an example of this is the nation (class 1), the city (class 2), and the human observer (class 3). Clearly what happens to a member of C has little influence on the dynamics of class 2, and so on.

Now if we anthropomorphize the members of the three classes in a different kind of a system, then A who sits above B can observe the latter, so long as it is isolated from other systems in its own level (such as C) and the interactions with systems in the lower levels (such as D, E, and F) are small enough to be taken as background noise. In computer science or in machine theory also, the observer or the controller is hierarchically situated above the system.

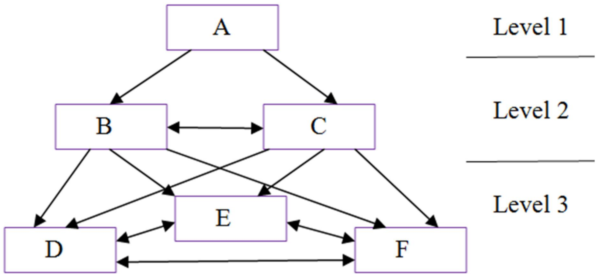

Figure 5. Universe with three hierarchical levels.

A classical system can be observed since it can be isolated from other systems – and from the observer – due to the local nature of interactions. In contrast, interactions in quantum mechanics are nonlocal, which forebodes new problems in the very process of observation in a universe that is purely quantum mechanical. At the quantum mechanical level, a system cannot be described in terms of clear hierarchies such as that of Figure 5. For example, an electron or a photon can be entangled with an atom (Volz *et al.,* 2006).

Computability in a tangled hierarchy. In the absence of a clear hierarchy and in the presence of nonlocal interactions, subsystems cannot be isolated within a system. Such isolation is essential for the observer to recognize his or her own identity and this requires some knowledge of the environment in advance.

If systems cannot be completely separated before the observation begins, observation will be impossible. From another perspective, the need for global states (related to World 3 aspects of observation) in the observation process implies that the measurement of one system by another by unitarity alone cannot be reduced to the Turing machine formalism.

A quantum Turing machine (QTM) is an abstract machine, which enlarges the classical model of a Turing machine by allowing a quantum transition function. In a QTM, superpositions and interferences of configurations are allowed, but the controllers running the quantum algorithms and inputs and outputs of the machine remain classical (Deutsch, 1985; Bernstein and Vazirani, 1997; Kak, 2014b); an example of this is quantum teleportation that requires sending some information on a classical channel. Without postulating a higher level measurement process (which cannot be quantum) the completion of the computation cannot be determined.

A purely quantum Turing machine cannot halt due to the continuing unfolding of its dynamics. From this perspective, unitarity alone cannot lead to measurement.

Conclusions

We have argued that while collapse of the state function in quantum mechanics is best described as a nonlocal process, this nonlocality is veiled. Probability constraints that exclude local realism explanations for quantum phenomena have loopholes in practical implementations. This has important implications for quantum information processing. In practical terms, it favors the view that the wavefunction represents our lack of knowledge rather than the reality. Any evidence in favor of naked nonlocality would support the view of the wavefunction as complete description of physical reality.

Nonlocality lies outside the framework of classical science and, therefore, its actual occurrence is problematic in making sense of the world. Veiled nonlocality saves us from this difficulty. It also creates the space in which human agency sees its actions as consistent with classical explanations. No wonder, there exist echoes of the idea in ancient philosophy and mathematics.

We would also like to draw a parallel of quantum Darwinism with the problem of measurement (or recognition) in neuroscience. It is no doubt that the incoming sensory signals are correlated with activity in specific regions of the brain just like the correlation between the system and the environment. But how this activity leads to measurement cannot be resolved within the framework of brain states since it leads to the homunculus problem.

Quantum Darwinism appears to embody the philosophy of random evolution even if one were to concede that "einselection" leads to the survival of the most proliferated states. Darwinism is supposed to encapsulate standard evolutionary framework in which new variation arises through random genetic mutation, inheritance occurs through DNA, and natural selection explains adaptation that makes organisms become well-suited to their environments. More recent research shows that "physical development influences the generation of variation (*developmental bias*); the environment directly shapes organisms' traits (*plasticity*); organisms modify environments (niche construction); and organisms transmit more than genes across generations (*extra-genetic inheritance*)" (Laland, 2014). This complexity in biological evolution appears to call for a corresponding complexity in our conception of observers that will be achieved only if we are prepared to concede not only processing of local information but also global states. Such global state processing is not possible in unitarity-alone models.

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