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Non-locality in the Science of the Millennium

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Abstract

The most recent experimental evidences of Quantum Physics and the new theoretical considerations connected to them have paradoxically questioned the basic founding principle of the scientific method, called the local realism principle. The main consequence of this cultural revolution is the need for a different approach to complexity in the world view through a phenomenon that I have called quantum synchronicity.

Quantum synchronicity is a phenomenon that is associated with the principle of cause-effect and tells us that in the quantum world there is an intrinsic correlation between systems, not attributable to a recognizable and expressible physical interaction, which means that a quantum system, and in general the entire universe, cannot be traced back even in principle to a set of separable parts, which can be defined locally and interacting only according to causality. The non-local quantum vision has its laws, potentials and limits, which we are learning to know and use for our evolution. The possibilities are largely yet to be explored, and range from technological applications, such as the quantum computer that is almost ready to be commercialized with immense implications in information management, to a revolution in looking at our essence and the world that contains us as inseparable elements.

Keywords: Local realism principle, quantum synchronicity

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Introduction

The first attempts of commercializing prototypes of quantum computer have started (Arute 2019). Quantum computer is a complex macroscopic object capable of functioning according to the laws of quantum mechanics (Feynman 1982; Devoret 2013; Leggett 2004; Nielsen 2000). The realization of quantum computer (CQ) first of all demonstrates that quantum mechanics laws also work in everyday life, although they are not normally directly visible to the way of seeing limited by our usual mental capacities (Bohm 1980). The possible use of CQ normally advertised is to process quantum information to make classically inconceivable calculations, but then the emphasis falls on the classical information that can be extracted from this colossal ability to process information. This classical information, while important, is very little when compared to the worldview revolution entailed by quantum computers. In this text, I invite the reader to become aware of the all-round awareness revolution that follows the new discoveries of quantum physics, and to use the new, emerging “intelligence” to address the challenges of such an evolution. The phenomenon of quantum coherence in macroscopic systems and entanglement has been supported by a large amount of experiments (see for instance Arute 2019; Chiorescu 2003; Emary 2014; Gerlich 2011; Hackermuller 2004;

Nakamura 1997; Wan 2016), opening the door to large-scale scientific speculations, both from an applicative point of view and from a philosophical and ethical point of view. It is important that the whole humanity, and not just a narrow scientific oligarchy, becomes aware of the possibilities that are opening up with these new discoveries and the related worldview.

Among other things, the recent developments in Quantum Physics undermine one of the most radical founding principles of the classical scientific method, called the local realism principle, and therefore require a profound revision of the scientific method by extending it to phenomena not directly measurable at the local level. Locality is a way of conceiving physics that attributes reality only to physical systems that can be defined through the measurable characteristics in the immediate surroundings of the system itself. Any other distant object cannot contribute to the reality of the local system. The interactions are also local, the presence of which can be measured in the immediate vicinity of the systems under consideration. In a local and mechanistic vision, reality is always separable into elementary parts, possibly interacting more or less intensely. This is the basis of classical scientific reductionism.

Non-locality, on the other hand, indicates that distant physical systems can be related in an inseparable way, to form a single quantum system. This correlation is not measurable at the local level, but means that the overall system cannot be separated into simple elements without losing its essential feature. As an intuitive, evocative example of what I mean, we know that a living organism cannot be separated into parts without losing its essential feature, which is life. We can then say that "vitality" is a non-local phenomenon, and as such it cannot be defined in classical physics. Similarly, quantum entanglement and synchronicity are non-local phenomena.

As opposed to classical reductionism, I would like to call the principle of non-locality at the basis of a new method of scientific investigation a "synchronic principle". The current scientific paradigm based on reductionism has been dominant since the Enlightenment, and places knowledge at the service of the immediate needs of humanity (real or presumed as such), neglecting or underestimating the effects that the use of new technologies have on the rest of the nature. As an undesirable side effect, technological development has thus contributed significantly to the recent global social and environmental crises. The main reason for this long supremacy is that this worldview allows for immediate material gains and economically profitable knowledge production, with a minority class of investors holding the controlling power. However, the awareness of having to verify how, in the face of short-term profits, reductionist technologies influence the ecosystems and complex systems with which they interfere, is increasingly spreading, first at the level of the cultural avant-garde and now in an increasingly widespread form. This type of approach to the interconnections of complex systems must be multidisciplinary and not local in nature, and I hope that academic institutions will soon open up to the holistic approach, as required by our new understanding. Science naturally realizes that most natural phenomena are of a complex type, meaning by this a system consisting of a very large number of elementary components interacting in a non-linear way, and therefore not deterministically predictable, whose collective properties are not simply attributable to the sum of the properties of the individual constituents. All biological systems, atmospheric phenomena, and in general all mechanical systems whose evolution is determined by non-linear equations that can lead to chaotic solutions are complex systems. Famous is Edward Lorenz statement: "The flapping of the wings of a butterfly in Canada is enough to cause a typhoon in Brazil the next day", indicating with this that it is enough to change the conditions by a trifle boundary to arrive at completely different solutions in mathematical models subject to non-linear equations.

The classical and deterministic scientific method is not applicable to these systems subject to chaotic solutions, as it cannot produce reliable predictions. Alternative mathematical methods are therefore being sought to be able to determine, at least in probabilistic terms, the possible evolutions of the system. This has created a new discipline in the scientific field that we can call the science of complexity, which has recently undergone great development. However, even for the study of complexity science starts from an approach based on the principle of local realism and of cause-effect, albeit trying to consider a complex circularity of causality relationships: it is hypothesized that in complex systems the simple elements influence each other through cause-effect relationships inextricable in their circularity characteristics, making the overall system inseparable into simple elements without losing some of its essential characteristics.

The synchronic principle introduces a new, I would say revolutionary, element in the approach to complexity, linked to the possibility of "non-mechanistic choice" that complex systems can have in their evolution. This possibility, which with anthropomorphic terms we could venture to call "conscious choice", is present in correlated systems through quantum synchronicity, and could be much more generally widespread than we can hypothesize in a reductionist paradigm.

Orthodox science is still tied to the reductionist approach that most scientists follow, consciously or not, as a widely accepted general theoretical paradigm to determine the design of research and even what is an acceptable research topic. An ideology of scientific progress is followed as a cumulative system of knowledge that grows steadily, drop by drop, in a single direction. The history of science teaches us that when anomalies are discovered that do not fit the dominant model, at first one tries to underestimate their revolutionary significance, then the tension grows as the evidence of new effects increases until one is forced to accept the revolutionary consequences of new discoveries. The dogmatic aspect of previous knowledge then falters and shatters. Thus a great leap forward in awareness is produced in the service of truth. In this way, modern science was born, and in particular quantum physics, as a quantum leap in stark contrast to the dominant paradigms at the time in which it was born.

The revolution that is approaching in the transition from the hegemony of the reductionist to the holistic approach envisages this type of discontinuity and offers us the opportunity for another great leap forward in human awareness. Scientific reductionism has brought us this far, and we must be grateful to it for the great progress achieved that have produced an abundance of material resources that cannot be compared with any previous historical era. But now the time has come to renounce the hegemony of reductionism, not to renounce the tools of the scientific method that work on a material level, but to integrate them in the service of a broader vision based on the synchronic principle. The question now is: what will be the new organization of science based on a synchronic principle? How can reductionist knowledge be integrated into a holistic hegemony?

In the first part of this article, I propose a synthesis of quantum synchronicity and the emergence of the classical worldview from the quantum model. In this synthesis, told without using any mathematical formula, I have no claim to be complete or original, but rather to be as clear and simple as possible without trivializing the concepts. In the second part I mention through some simple examples how quantum synchronicity can intuitively manifest itself in daily life, and I invite an integration between art and science in a new vision of the world that values the holistic principle towards the millennium community.

Of course, the field of investigation is very new, and we do not yet know the revolutionary consequences that a different approach to scientific knowledge can bring to everyday life, but in my opinion, an opening to new possibilities is already necessary right away.

Considering quantum mechanics as a theory adhering to physical reality simply means accepting that our possibility of knowing the world from a local point of view is severely limited. From a broader point of view, what appears to a local view as "very small quantum effects", often paradoxical, instead have dramatic consequences on the non-local conception of the world, and the phenomena that we are currently capable of considering in the classical scientific method are only the tip of an iceberg, the submerged part of which is immensely larger than that observable at first glance.

But there is no need to fear this submerged part whose effects begin to emerge in our most sophisticated experiments. These effects of Quantum Physics, if reported in our daily life, can be the guideline for a change in human awareness towards a different way of conceiving individual and collective happiness, to produce a change of direction in our personal choices towards a real development, globally sustainable, and to live life individually in a fulfilling way. Each individual can make her contribution, and each individual contribution has consequences on the collective global system that can be very relevant. Individuals can fully regain confidence in the power of their choices, without necessarily feeling like a small insignificant part of a huge system, whose inertia seems to be completely beyond the control.

In this regard, I like to conclude this introduction by making my own the statement of Richard Buckminster Fuller, the great American architect and stylist, pioneering advocate of sustainable development:

> "Think of the Queen Elisabeth: the whole ship and its helm. And then to the fact that there is a little contraption, called the trim-tab, correction flap. It is a miniature rudder, and it is the movement of that small fin

> that creates the pressure that causes the rudder to rotate. It requires almost no effort.”

So I told myself that the little individual can be a trim-tab in the big ship that is the global eco-system of life on earth!

1. Entanglement and Synchronicity

Entanglement is a mathematical consequence of the expression of quantum states in terms of vectors in Hilbert’s complex space: it can be seen mathematically that if we have two or more particles, alongside particular cases in which the collective state can be separated into independent states concerning the single parts, in the vast majority of cases there are collective, tangled states that do not allow the individual parts to be separated even if they do not physically interact with each other. The quantum universe is interconnected through a classically inexplicable mechanism and not directly detectable or attributable to interactions between objects, to which Schrödinger has given the name of “entanglement”.

The entanglement state is the mathematical representation of a phenomenon in which the quantum state of two or more physical systems depends on the quantum states of each of the systems that make up the whole, in a way that an action on one of the components causes an effect immediate on the state of the overall system, regardless of their space-time distance.

Albert Einstein branded the oddities predicted by quantum mechanics relating to entanglement phenomena as “spooky actions at a distance”.

Albert Einstein himself, together with two co-authors, Boris Podolsky and Nathan Rosen, demonstrated in 1935 that quantum mechanics violates the principle of local realism through the mechanism of entanglement.

Rather than giving up this principle underlying all classical scientific thought, deeming it absolutely indubitable, Einstein stated that quantum mechanics is an incomplete theory and that it should be supplemented with hidden variables. These hidden variables should take into account the information necessary for the local realism principle to continue to apply, but are not contained in the quantum theory which would therefore be incomplete. The apparent non-locality of nature predicted by quantum theory would therefore be due to the impossibility of acquiring all the information necessary to describe a microscopic system. The argument is known as the EPR paradox (acronym for Einstein Podolsky Rosen 1935).

In quantum physics entanglement is a very general phenomenon, which affects every complex system up to and including the universe itself, as will be discussed later. However, its break with classical thought by now deeply rooted in our belief system, which imagines reality made up of separable parts, is so disruptive that it is difficult to visualize its scope, if not at an intuitive level. In fact, this whole text is an introduction to trying to figure the effects of entanglement (which I will later call quantum synchronicity) in our view of the universe. From a communicative point of view, entanglement can be described in the simplest possible case, i.e. the case of only two elementary particles distant from each other, albeit correlated to form a single system described by a single wave function not separable into parts. This is also the example that led Einstein and the other pioneers of quantum physics to introduce (and often critically consider) the concept of entanglement. So let’s try to understand in the simple case of two particles what the difference between a classical and a quantum correlation consists of.

Suppose we have two classic particles of different color, say two marbles, one white and one black. We place the two marbles in a closed box, extract them one at a time and, without looking at the color, give them to two observers who then move away from each other. Later, when the two observers are very far away, we ask them to observe the color of the marbles. It is clear that the two measures are related: if one observes the black marble, at the same time it can be assumed with certainty that the other has a white marble, and vice versa, even without carrying out the measurement directly or communicating in any way with the other. Obviously we do not find anything strange in this, since the correlation of the measures is linked to their past history, which is precisely traceable: the different marbles were delivered to the two observers from the beginning, and from that moment the result of the future measure was set, even when the measure had not yet been carried out. We only lacked the information that came later with the observation, but the “reality” of the two marbles can never be questioned: one of the two has always had the white marble and the other the black; there is no need for the measure to fix the two marbles in a defined color.

The situation is completely different in quantum physics. The two marbles in the black box are indistinguishable and quantistically related: both may manifest as a white or black marble at the time of measurement, but their quantum state before measurement is a coherent superposition of the two states, where the choice has not yet been carried out. Both quantum marbles coexist in the two states. There is also a correlation between the two marbles, which in turn form a unique quantum system described by a single state consisting of a superposition of "entangled" states of the two particles. We know with certainty that if one of the two manifests itself as white at the moment of measurement, the other must necessarily manifest itself as black, or vice versa, but the "reality" of the marbles is not determined except at the moment of measurement through the collapse of the wave function. If you measure one of the two, its quantum state instantly "collapses" to a given value, and the state of the entangled particle also instantly collapses, whatever its distance from the first. In that case, it is as if information on the quantum state of one particle has been communicated to the other with a speed greater than that of light (instantaneously, to be precise).

In reality there is only one state of the particle system, and this is not separable into the states of individual particles. Quantum mechanics is a non-local theory, and the quantum universe cannot be separated into individual constituents.

Rather than accepting this state of affairs that quantum theory suggests, Einstein preferred to hypothesize that the two entangled particles were correlated from the beginning through hidden variables, for the moment unknown to us, so that if one of the two manifested a state l the other should manifest the complementary state even without exchanging information: similarly to how it happens in a classical correlation of the type described above, only through a more complex and yet to be determined mechanism. For Einstein, therefore, the correlation is formed at the moment in which the particles interact and, when they move apart, each of the two already exists in a defined state that we cannot know unless we carry out the measurement. In this way, the local realism principle can be saved: the description of the system given by quantum states would be correct but incomplete, and the apparent violation of the locality principle would arise from our ignorance of the variables necessary for a complete description of quantum systems.

The EPR paradox generated a debate on the interpretation of quantum mechanics, initially between Niels Bohr, a keen supporter of the "orthodox" quantum vision, and Einstein, a supporter of the incompleteness of quantum mechanics and the principle of local realism. The dispute continued even after the death of the two great scientists, between the promoters of the two interpretations. The debate could last so long because it is very complex to think and carry out an experiment that establishes the fall of locality principle. This type of experiments became possible only many years later, starting from the 1970s (Freedman 1972; Aspect 1981; Weihs 1998), but unambiguous evidence of the need to renounce local realism could only be found very recently with various experiments (Giustina 2015; Hansen 2015; Kneee 2016).

It should be clear from what has been said so far that the quantum nexus that connects two distant systems (which are often called Alice and Bob) is of a-causal type, i.e. there is no cause and effect relationship between the two systems.

Without a causal link, the result of the measurements that Bob takes is not affected in any way by the measurements made at the same time by Alice: Bob cannot know if Alice has actually carried out the measurement, or vice versa.

In the EPR paradox it is not possible to think that the result obtained by Alice is the cause of the result obtained by Bob: there is no cause and effect mechanism that causes the correlation. It is impossible even to establish whether the event concerning Alice's measure or the one concerning Bob's measure happened before.

We are assuming that Alice and Bob are far away at the time of the measurement, far enough that nothing traveling with the speed of light or less can depart from Alice when she takes the measurement and arrive at Bob when he does the same thing, or vice versa. In such a situation, it does not make any physical sense to ask which event happened first. According to the theory of relativity, I can find reference systems in which Alice is described making the measurement before Bob, but I can find reference systems where the opposite happens, and also I can find a frame of reference where events happen simultaneously. Whatever Alice does cannot be the cause of something happening to Bob.

In reality, Alice and Bob are not two separate systems connected through some "exotic" mechanism, but are the same inseparable, non-localized quantum system.

The a-causal quantum link does not contradict the cause-effect principle, but is complementary to it: through entanglement it is hypothesized that, alongside causality that acts in the direction of the progression of time and connects phenomena that occur at different times through a cause-effect relationship, there is a principle that "merges" the phenomena that occur at the same "time" but in different "spaces", between which no type of causal communication is possible.

Without causality, the word "time" must be in quotes, because the principle of cause and effect is fundamental to distinguish time in the usual way as past and future. This "time" instead describes a concept of synchronicity, through which the quantum system as a whole manifests itself in evolution without a specific cause and effect relationship between the parts, without a necessary consequentiality between past and future. It is clear that these concepts of "time" and "space" I am referring to here are very different from Einstein's concept of space-time.

The reality of quantum entanglement can be verified with particular experiments, through a statistical comparison of measurements made in several distant laboratories.

In 1964, John Stewart Bell, a British physicist who worked at CERN, demonstrated that local realism was expressed in mathematical terms by a series of inequalities, which have gone down in history as Bell's inequalities (Bell 1964). These inequalities link together, in statistical terms, the preparation of the experimental apparatus and the measurements obtained by two or more experimenters in different places, in the context of a correlation based on a causal principle. Now, according to Bell's proof illustrated in his theorem, inequalities are violated in processes based on quantum entanglement, and in general in any non-local theory.

Bell's theorem is an elegant and viable way to experimentally test local realism. Since then, dozens of experiments that refer to Bell's theorem, able to measure in the laboratory–or rather, in pairs of laboratories–have been carried out, experimentally demonstrating the violation of inequalities and highlighting the existence of a non-local quantum correlation (Ansmann 2009; Aspect 1981; Freedman 1972; Giustina 2015; Groeblaker 2007; Hansen 2015; Weihs 1998; just to cite some of the them).

The violation of the local realism principle manifests itself in the EPR-Bell experiments in which we are able to relate coincidences of measurements that occur in separate spaces without there being a cause-effect correlation between the parts. In this case, synchronicity manifests itself as a deviation from the law of chance that we would expect in the classical case. To understand this, we can give a very simple example taken from everyday life: it is as if we rolled many times two "entangled quantum dice" and we find that, despite each of the dice has taken every number between 1 and 6 with equal probability, the sum of the two numbers are always the same, say 7. Therefore, although observing each dice individually (local observation) we would not find anything strange, the correlation between the two measures (non-local synchronicity) cannot be the result of chance but indicates that there is an "invisible" and classically unexplainable relationship between the two events.

These are the simplest cases of entanglement between two quantum systems.

In more complex cases, the correlation can lead to situations that cannot be exemplified in a classical representation. Of course the level of entanglement between quantum systems can vary: in some cases it may be extremely high, or even the maximum possible, and involve a large number of particles, in other cases less strong, but in any case it always implies that the events that occur are significant of a certain correlation that cannot be traced back to any observable interaction between the parties. The experiments relating to Bell inequalities carried out so far refer to simple systems, such as pairs of electrons or "entangled" photons, or qu-bits, which we can call EPR-Bell experiments, but the proof of the non-locality it is indirectly verified even for more complex systems, so that entanglement is now an accepted and used phenomenon, especially in quantum information. In the quantum computer the level of correlation between quantum bits is the basic principle of its functioning. In reality we will see later that entanglement must conceptually extend to the whole universe.

As paradoxical as it may seem to the rational mind, quantum physics envisages an inextricable interconnection between events in space and time, which includes observers, through a single quantum state, the manifestation of which takes on a specific form only at the moment of observation. This implies that every local action has an impact on the whole related system, which however does not have a directly visible effect at the local level.

2. The Emergence of the Classical World from Quantum Theory

The paradoxical aspects of reality which the experiments conducted on microscopic objects oblige us to accept, have often been considered as belonging exclusively to a vision of the world valid only on very small scales, that is to say in the atomic or sub-atomic world, or in very particular conditions. According to this idea, there is a substantial difference between how the classical world that we commonly experience behaves and the described reality of quantum theory. In other words, there are two distinct models of reality, one classical and one quantum, which function in radically different ways, described by completely different physical laws. For the proponents of this hypothesis, there must be a physical process that allows the two worlds to be clearly separated. The collapse of the wave function due to the measurement has often been interpreted in this sense: as a physical process of a fundamental nature that necessarily transforms a quantum state, described by a coherent superposition of classically incompatible states, into a single classical state, the one that we experience in everyday life. Whatever way the measurement is made, the result will inevitably be a classical state anyway, obeying the logic of the classical world.

According to the statistical view of the theory, the mathematical formalism of quantum mechanics does not describe “physical reality”. What it does is to provide an algorithm for calculating the probabilities for events as consequences of our experimental interventions. However, the world may be such that it cannot always identify a reality independent of our experimental activity. Consequently a vision of “objective” reality, that is, which exists independently of our subjective perception, would be impossible.

In other words, in the statistical interpretation of Quantum Mechanics (Ballantine 1970) the possible existence of an objective reality independent of what the observers perceive is not denied; this “objective reality” is simply not directly accessible to our experience since each of our observations substantially modifies the natural course of events.

I believe that most exponents of statistical interpretation would argue that since “collapse” is not a physical process for them, no “dynamic description” of it is needed. Collapse is something that happens in our description of the system, not in the system itself. Likewise, the time dependence of the wave function does not represent the evolution of a physical system. It only describes the evolution of probabilities for the results of our potential experiments on that system. This is the only sense of the wave function in the extreme statistical interpretation.

What to say now about the evolution of a macroscopic object: can it be described by a quantum state? In reality, nothing prevents it, as long as the forecasts we get are consistent with the results of the observations.

Let us examine the famous Schrödinger’s cat paradox seen from this perspective (Schrödinger 1935). Here is the “paradox”: a cat is in a closed box, where a photon is sent through a polarization filter. If the photon passes through the filter, then an ampoule containing a deadly poison opens. If, on the other hand, the photon is absorbed by the filter, then the bulb remains closed. The presence of the deadly poison in the box is therefore linked to a properly quantum process, described by a superposition of states, and therefore the “classic” state of the cat must be in a logically inconceivable superposition of “alive cat” and “dead cat” at the same time. However, if we do not attribute a measurement independent reality to the wave function, the paradox disappears. A quantum physicist stays outside the lab and calculates the cat’s wave function. According to him, the cat is in a coherent superposition of states, simultaneously alive and dead in equal measure. But there is nothing paradoxical about this wave function; it represents only the greatest possible knowledge of the state of the cat obtainable outside the closed box. Reality cannot be known until one looks inside the black box containing the cat and the ampoule. If we open the box and observe we will always find the cat either dead or alive. Looking from inside the box, as soon as a detector was activated, the cat’s status changed. Some time later, the physicist peeks into the box: thereby he gains new knowledge, and thus changes the wave function he uses to describe the cat.

From this example, it is clear that in this interpretation a wave function is only a mathematical expression for the calculation of probabilities and depends on the information of whoever is doing the evaluation of the various possibilities. In this way there is no paradox. Instead, attributing an objective reality to quantum states leads instead to a series of "quantum paradoxes" (for a review see Ballentine 1970).

This interpretation appears completely consistent, as long as it is integrated by a premise that constitutes the fundamental aspect that underlies the hypothesis of the collapse of the wave function as a non-physical process and is taken for granted in the statistical interpretation of quantum mechanics. We can formulate this premise by stating that for macroscopically distinguishable quantum states there can be no interference effects. If this is always true, then the quantum superposition between macroscopic states must be absolutely indistinguishable in every possible experiment from a classical statistical superposition. Only with this premise when we observe Schrödinger's cat we will always find it either alive or dead (with relative probabilities that can be calculated through the knowledge of the wave function), but never in a state of interference between the two possibilities. In the statistical interpretation, interference phenomena between macroscopic quantum states are not admissible, as the wave functions do not have a corresponding element of reality associated in the physical world, but serve only to calculate the probability that an observation produces one or the other possible result.

Until the late 1970s it seemed that no experiment could ever have the resolution needed to detect macroscopic quantum interference effects, even if it existed. From the beginning of the eighties until today, however, the possibility of macroscopic quantum effects has been highlighted in a series of increasingly convincing experiments (it is impossible to mention all the experiments: see for instance Chiorescu 2003; Friedman 2000; Martinis 1987; Mooji 1999; Nakamura 1997; Rouse 1995; Silvestrini 1997). Faced with the possibility of the superposition of macroscopically distinguishable quantum states, a theoretical investigation began at the same time to investigate this aspect (Caldeira 1981; Zurek 1981). Some theoretical physicists have tried to hypothesize models to describe the transition from the quantum world to the classical world, using exclusively the formalism of quantum mechanics. Quantum de-coherence theory (Zurek 2003) is one such model, considered valid today by most physicists and widely used to describe quantum mechanical experiments at the macroscopic level (Devoret 2013; Leggett 2004; Myatt 2000).

3. Quantum De-Coherence

Let us now try to mention the guidelines that underlie the theory of quantum de-coherence, in order to understand its scope and limits. Since macroscopic objects are made up of microscopic particles, all of which obey quantum mechanics, there should be a way to connect the classical world and the quantum world, macro and micro reality. We have seen that the traditional interpretation of quantum mechanics answers the questions regarding the definition of the state that manifests itself in the observed reality through the measurement process, a special process that cannot be traced back to the other rules of quantum mechanics.

The theory of de-coherence develops completely within the orthodox quantum formalism, and therefore uses the concept of measurement. In the theory of de-coherence privileged observers are not allowed, but every system can be considered both as an object to be observed and as an observer (Fields 2016).

Complex systems, made up of an incredibly large number of elementary components, can therefore be observed from parts of the system itself: in a sense, macroscopic systems can measure themselves, causing the collapse of the wave function and the emergence of the classical world, giving up a part of the information of the complex system as a whole. The information obtained in this process defines classical reality.

The mathematical theory of classical de-coherence, pioneered by Caldeira and Leggett (1981) and by Zurek (1981) independently, is a quantitative model of how this transition from quantum physics to classical mechanics occurs, and involves systems that make local measurements on themselves. The basic consideration is that every macroscopic object can never be completely separated from the environment. The degrees of freedom related to the environment are seen as a system of observation of the macroscopic object on which attention is being drawn (Zurek 2003). Our universe is therefore divided into two parts: the system we are considering, which is treated with quantum mechanics, and an environmental component, which is treated statistically. When the environment is coupled to the system, a part of the quantum information that the system transfers to the environment is lost, while the considered system loses its quantum coherence and over time becomes a statistical mixture, justifying the success of the statistical interpretation of Quantum Mechanics .

Now I try to visualize how the de-coherence occurs with a simple example that uses the phenomenon of interference through a double slit. So let's imagine conducting an experiment through a double slit using complex quantum objects, consisting of a large number of elementary components; this macroscopic object is inevitably interacting with the environment. One can imagine using large molecules made up of a large number of atoms (Gerlich 2011; Hackermuller 2004), or even more macroscopic objects. In the case of simple systems, such as electrons or photons, an interference pattern will appear on the screen, which is a consequence of the coherent superposition of quantum states in which electrons (or photons) pass through both slits simultaneously. This figure, however, disappears if we add to the experiment a measuring apparatus capable of identifying the trajectory followed by each electron, to become a classical statistical mixture in which there is an equal probability that each particle passes through a slit or through the other. In the case of complex molecules (and macroscopic objects in general) it happens that the particles interacting with the environment leave a "trace" of their passage in the environment. This trace provides information on the trajectory followed by the molecules even without the presence of a specific measurement apparatus, destroying the interference figure and collapsing the wave function in a classic mixture. This information is dispersed into the environment and may not be accessible to the experimental physicist, but it still exists and produces the phenomenon of de-coherence.

It is important to keep in mind that de-coherence is inherently a local phenomenon. That is, if we consider our entire universe, the system plus the environment, from the point of view of quantum mechanics, the classical effects do not emerge. Rather, for the emergence of "classicality" we need to focus attention on a particular component, and neglect the quantum information that has to do with the environment.

A great advantage in formulating the theory of de-coherence is that the mathematical apparatus allows to calculate the time in which the coherent quantum effects disappear, called the de-coherence time. This time turns out to be extraordinarily short in the vast majority of cases, thus justifying the fact that the superposition of macroscopically distinct states is not observed in everyday life. In some particular systems, however, paying particular attention to separating the system from the external environment, the de-coherence time can be long enough to allow laboratory measurements that highlight the superposition of states in macroscopic systems. These measurements, although confined to rather particular systems, nevertheless have an extraordinarily important significance, both from an applicative and a conceptual point of view. From an application point of view, they have opened up the possibility of a new discipline, called quantum information, which includes the phenomenon of quantum computing with the possibility of building quantum computers in the coming years, based on elementary bits of a quantum nature. Such a computer will have the potential to process quantum information with absolutely unthinkable perspectives for classical information, many of which are yet to be discovered but certainly extraordinary (Arute 2019; Feynman 1982; Nielsen 2000; Preskill 2018).

From a conceptual point of view, macroscopic systems showing quantum coherence effects indicate that there is no classical world and one quantum world described by different laws, but there is only one quantum universe in which the logical paradoxes we have discussed are real (Bohm 1980).

Since the theory of de-coherence predicts that the observable states of any system interacting with a surrounding environment will appear in a very short time classic to the observers who are present in that environment, it is considered by many to be an explanation of the apparent "classicality" of the observable states.

From a mathematical point of view, de-coherence theory is simply an application of quantum theory to the system-environment interaction. When we carefully examine the calculations of de-coherence, it is immediately clear that the mathematical methods provided by the theory of de-coherence are applicable in practice only if supplemented by classical assumptions. In particular, we must assume that during the interaction with the environment the system considered can be defined separately. A hypothesis of this type can only be an approximation in quantum mechanics, since the phenomenon of entanglement dynamically and inseparably binds all interacting degrees of freedom. The calculations of the de-coherence also involve the hypothesis that the observer does not obtain any information from the environment; this assumption is often rendered mathematical by assuming that the dynamic variables of the environment can be treated using classical statistical mechanics.

If we omit the classical assumptions and instead assume that quantum mechanics is a theory of general validity, the mathematics of de-coherence simply describes how the phenomenon of entanglement spreads in the environment.

In a quantum view, entanglement with the surrounding environment does not remove quantum coherence from a system; rather it couples the system and the environment in a way that quantum coherence expands to their joint state, also including the observer. The phenomenon described by de-coherence therefore does not cancel quantum coherence, but diffuses it into the environment, demonstrating that in quantum mechanics separate systems are only an approximation.

This is an inconceivable concept for our classical belief system that underlies our usual way of interpreting reality, but it is what recent experiments seem to confirm.

4. A Quantum World

Now I want to try to describe how we should interpret the quantum world in case we attribute a physical correspondence with reality to the mathematical formalism of the theory. This is the position that for me best suits the most modern and sophisticated experimental evidence.

The fundamental concept that introduces quantum theory is quantum connection, entanglement. The quantum world is an inextricably interconnected world. It is not separable into limited, temporary and re-identifiable entities that can be considered independently of each other. Our idea of separate independent systems that persist over time is, from a quantum point of view, only an approximation (Fields 2016). It is often a good approximation, good enough to allow for daily experimental testing in the laboratory, with uncertainties better than one part in a billion. This only means, however, that it is a good approximation for us, in our way of seeing things: we define the systems that we believe to be separate in space and time, and these are the systems for which the approximation is good. How does it work? What allows us to define the systems that appear to us to be separate? (Wheeler 2014). The phenomenon of entanglement shows us that any separation between observer and world (i.e. all the rest of the universe that is not an observer) is somehow arbitrary: the world itself can be considered as the observer (and therefore in this subdivision the observer becomes the world), and in general can contain infinite other observers, since any subset of the universe can be considered as an observer. The only entity that has an absolute existence, persistent over time albeit with changing forms, is the universe in its totality.

What we call “observer” is therefore a subset of the universe, arbitrarily chosen, which exchanges information with the rest of the universe. As a limited system it can exchange and store a limited amount of information. As we know from computer science, information is contained in the fundamental elements, which are called bits, two-state elements that can only take on two possible values, 0 or 1. Any type of information that a classical observer shares can be expressed as a string finished with “classic” bits. A computer in fact operates completely in a binary language through the creation and/or destruction and storage of a limited number of “classical” bits. Even the text I am writing right now is nothing more than an ordered string of bits that can later be decoded and interpreted by the reader, who in this way gives it meaning. With the evidence of the possibility of superposition of macroscopic states, we must assume that in fact information is coded by qu-bits. A qu-bit is a two-state system that can exist in an arbitrary coherent superposition state of classical states zero and 1. It has now been seen that a qu-bit cannot be duplicated (Zurek 1982) and that a single quantum bit in an unknown state cannot be described by a countable sequence of classical bits (for a review see for instance Nielsen 2000). In a quantum world, any limited subset of the universe cannot therefore receive, store, and exchange information through quantum bits. Therefore, our way of representing the world through classical information, be it a text, a thought, a mathematical formula, a complex theoretical system or any other shareable classical representation, cannot be a complete representation of the quantum reality. Hence the paradox of measurement in quantum theory, and all the other paradoxes we have mentioned in previous chapters. It can also be assumed that quantum theory is the most efficient logical system for managing shareable information that comes from a wonderfully complex and interconnected world, in which any subdivision into limited and independent subsets is completely arbitrary. The extraordinary agreement that quantum theory shows with an enormous amount of experiments conducted with great accuracy seems at the moment to support this hypothesis.

From another point of view, however, we now know that the information that we are capable of processing according to a classical and shareable logic is a very small part of the quantum information that describes the totality of the universe. The reason why we can scientifically agree on the occurrence of objective and shareable phenomena is simply that in the scientific method we consciously decide to focus our attention on a very limited part of phenomena.

This may perhaps be useful according to the classic logical view of interpreting the world, but in reality we must be fully aware that what cannot be understood according to this logic is immeasurably greater than what is shareable. Perhaps the time has come for the human mentality to become fully aware of this reality by opening ourselves to new forms of research. The scientific method can then continue to constitute the support for the resolution of practical problems, but the excessive emphasis that our culture gives to materialism and to the scientifically demonstrable aspects of reality, sometimes denying the existence of what is not scientifically demonstrable, it is not justifiable even within our current scientific knowledge.

I am convinced that a new world can emerge from the new quantum awareness that is forming in the process of global evolution, with humanity more responsible for its choices.

5. Quantum Complexity, Evolution, and Synchronicity

The reality that is the object of scientific research, and in general of all human knowledge, is characterized by a remarkable complexity which in the classical scientific vision appears to us as due to the complex interaction of an extremely large number of simple elements. This was the guiding principle of the scientific method, which schematizes reality through the interaction of a few simple microscopic elements such as quarks and leptons—which then combine in various form. Then, gradually increasing the complexity, they form simple molecules and then more and more complex systems until reaching chains such as the DNA that underlies every living process. The molecules in turn interact through chemical-physical phenomena related to energy and thermodynamic exchanges until they manifest the complexity of the entire universe starting from very few simple elements (37 are known, including leptons, quark, bosons, and gluons, with a symmetry between matter and anti-matter elementary particles) and four fundamental interactions.

Entanglement does not deny causality, but associates with it a different a-causal correlation not observable at the local level, which we have called “synchronicity”. Another term that we could use to indicate entanglement is “organicity”, that is, something that makes a related system organic, that is, not attributable to the simple sum of its parts and the interactions between them, as we can guess to happen in biological organisms in which the whole acquires a unique and unrepeatable identity.

In our observation of complex phenomena we can intuit that causality and synchronicity coexist, even if one of the two phenomena may appear to us more or less predominant. In general, causal relationships are more easily identifiable and measurable because they can be described in terms of cause-effect, to which our rational mind is more adapted. However, it is easy to recognize that the principle of cause and effect alone is not sufficient to explain many complex phenomena, and in particular organic phenomena. For example, in biology we can explain how the chemical-physical processes sustain life in an organism, but the beginning of life remains shrouded in mystery. To put it in a phrase attributed to the Nobel Prize in Chemistry, Ilya Prigogine that I made mine:

> “The probability that a macroscopic number of molecules will be assembled by chance to give rise to the highly ordered structures and coordinated functions that characterize living organisms is practically zero. The idea of the spontaneous genesis of life in its present form is therefore highly improbable, even on the scale of the billions of years during which prebiotic evolution took place.”

On the other hand, we now know that entanglement (whose experimental evidence did not yet exist at the time of the quoted sentence by Prigogine) plays a fundamental role in the collective behavior of complex macroscopic systems.

Here I want to give an example taken from everyday life to express my thoughts about how a collective trend of a complex system can be associated with local relationships, and how synchronicity can be indicated in an evolutionary key, in the sense of probabilistic process indicated by Prigogine.

I think many have observed the collective figures that flocks of hundreds (or even thousands) of black birds called starlings sometimes perform in the skies of our cities. The movements of this set of separate individuals appear to us so harmonious and synchronized that it leads us to think that there is an "intelligence" guiding the group, a leader from whom the synchronized movement originates. There have been many scientific studies to try to understand how these collective movements can be explained in physico-mathematical terms (see for instance Attanasi 2014). The study of this type of collective dynamics is an interesting example because it is a moderately complex system (a few hundreds or thousands of elements can appear a lot, but it is nothing compared to the complexity of billions of billions of elements that synchronize in biological systems) and allows to find solutions that are currently unapproachable in more complex systems. The result of these studies is in some ways surprising, because it shows that there is no need for any leader to perform these complex synchronized figures, but it is enough to hypothesize local relationships between the elements. Each individual has no awareness or vision of the overall flight of the system, but is aware only of the motion of the first neighbors (generally 6 or 7) and starting from these is following some simple rules to move accordingly: first of all, they avoid colliding in flight with the neighboring birds, but at the same time they try to maintain cohesion with the group so as not to find himself isolated. Finally each individual tries to align with the first neighbors. With just these three elements of "local interaction" we can explain the synchronized collective motions that we observe as a whole. Furthermore, it can be seen from the mathematical models how the system, while apparently moving in a chaotic way, can maintain a high degree of global coherence. This coherence can be described in analogy with the phase transitions at low temperatures of superfluid helium or superconductivity. These latter phenomena, which require elements of quantum physics to be described, derive from the combination of a purely local phenomenon and synchronicity.

Cooper coupling in a standard BCS superconductor is indeed the result of "local" interactions (range ~ 1-2 angstroms), but the resulting correlations extend to several thousand angstroms and are manifestly entangled at least as regards the degree of freedom of spin. The behavior of superfluid 4-He helium can instead be explained on the basis of the Bose-Einstein condensation. Both phenomena constitute a quantum phase transition associated with a collective quantum state.

To understand how the combination of a local phenomenon and synchronicity could intervene in the probabilistic terms indicated by Prigogine we must understand the evolutionary function of these collective motions: in the event that the group is threatened by a predator, a movement must originate to decide in which direction to escape. The information spreads quickly to the whole system through a particularly effective and reliable mechanism that makes predation rather difficult. The hidden purpose of this collective behavior is therefore linked to the evolution and survival process of the species which individuals are not directly aware of, but which they instinctively follow. This species intelligence linked to evolution is specific to the group, and is the result of natural selection.

Now Prigogine's statement comes into play: if the process of natural selection were to act completely at random, the probability that such a finalized collective behavior would be generated would be nil even in billions of years of evolution (what about biological systems that we have seen to be exponentially more complex). In this sense we can understand what the effect of synchronicity is, which would be to determine choices that are not completely random, but with significantly higher probabilities towards the "intelligent" evolutionary purpose, using an adjective of anthropomorphic connotation. In fact, in all the experiments on the so-called Bell inequalities in quantum physics that highlight entanglement, we always have to do with probabilities that cannot be considered completely determined by chance as would be expected according to the local realism principle. Synchronicity could therefore take the place of the pseudo-scientific principle, called "anthropic principle". Such a term was coined in 1973 by Brandon Carter in his speech "Large Number Coincidences and the Anthropic Principle in Cosmology" during a symposium held in Krakow as part of the celebrations for the 500th anniversary of the birth of Copernicus. In fact I think it can be said very plausibly that the idea of the anthropic principle (although obviously not under this name) was actually introduced by Boltzmann about 100 years earlier, pointing out that it is only in an "atypical" region of the Universe that human life has been able to develop. The anthropic principle has been used to explain with ad hoc hypotheses the perceived meaning of a "guided" evolution for the exponentially improbable phenomenon that is the appearance of life on the earth (and in the universe in general). I think that it will soon be possible to formalize in rigorous terms through a more current conception of the scientific method the influence of quantum synchronicity on the evolutionary process, probably precisely with the advent and diffusion of quantum computers, which are the only tools to be able to study exponentially complex phenomena with some chance of success.

6. Harmony and Synchronicity

To me, synchronicity also plays a very important role in determining what we can call a feeling of "harmony", both in natural manifestations and in the artistic creation produced by man. I want to express my feeling in this regard, which is not rigorous but can be evocative for individual reflection. Let's start with a simple example. Suppose we listen to a symphony by Beethoven or Mozart, or a Bach sonata: I imagine that first of all we will notice a harmony linked to a local relationship of the notes, that is to say the neighboring notes form sequences that appear harmonic to us, pleasant to the listener. Following a more trained ear, a more global harmony will appear, in which even groups of more distant notes are harmoniously connected throughout the composition: we could identify for example the general tonality, the symmetries and appropriate symmetry breaking, for which the complex will appear more and more organic. Finally, we may perhaps notice single and apparently insignificant details, but which on the whole make the work a masterpiece of perfection, beyond the perfect structure of the mathematical relationships that express the various wavelengths of the notes. This "something unpredictable", this invisible thread that binds the whole work is inextricably linked to the genius of the artist, just as it is linked to the sensitivity of the execution, to the non-mechanical intelligence of those who perform the work at the moment. This invisible element, not detectable by measurements or arguments of any kind, is the "synchronicity" that makes a complex whole a unique and irreplaceable work of art. Not only this, the intuition of the irreplaceable majesty of the work also requires the listener's capacity for synchronicity, non-mechanical intelligence, in no way attributable to mathematical equations, and the mysterious empathy that is generated between author, performer and listener. This is why each performance is unique, and belongs to the magic of the moment and here lies the charm of live concerts. To put it again with a phrase of Prigogine: "Whatever we call reality, it is revealed to us only through the active construction in which we participate."

For me, Art is a work characterized by a great component of synchronicity, while mastery is mechanically perfect but has a low content of synchronicity. In the same way, intelligence for me is not a local but rather an organic phenomenon of synchronicity, where the entire universe participates, whose mechanical expression is manifested by harmonic local relations.

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