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The Source of Magic in the Quantum World

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Abstract.

It has been frequently said that "Quantum Mechanics is Magic". The real fact is just the opposite: quantum mechanics is not magic, it is rather one of the best scientific theories in terms of the amplitude and exactness of its predictions. Quantum Mechanics surprises us as it does not satisfy some *a priori* principles usually considered to be necessary preconditions to build up physics (as Einstein dixit). As these principles are also the basis of some important philosophical theories of science, these philosophical theories cannot be well founded. After criticizing them, we offer the preliminary lines of a methodology of physics adapted to the formalism of quantum mechanics.

Keywords: Foundations of Quantum Theory; Frazer's System of Magic; *a priori* Principles, Entanglement; Consciousness; Participative Universe; Operative Methodology of Physics.

Resumen. *El origen de la magia en el mundo cuántico.*

Se ha dicho con frecuencia que "la mecánica cuántica es mágica". El hecho real es todo lo contrario: la mecánica cuántica no es magia, es más bien una de las mejores teorías científicas en términos de la amplitud y la precisión de sus predicciones. La mecánica cuántica nos sorprende, ya que no cumple algunos de los principios a priori que, por lo general, se consideran condiciones previas necesarias para construir la física (como Einstein sostenía). En la medida en que estos principios son también la base de algunas importantes teorías filosóficas de la ciencia, estas teorías no pueden estar bien fundadas. Después de una critica a estos, ofrecemos las líneas preliminares de una metodología de la física adaptada al formalismo de la mecánica cuántica.

Palabras clave: Fundamentos de la Teoría Cuántica, sistema de Frazer de la magia; principios a priori, el enredo, la conciencia; Universo Participativo; metodología operativa de la física.

1. Introduction.

In the initial stages of our present work we intended to argue against the relatively frequent use of the word magic when describing, explaining or writing about Quantum Physics. What called our attention was the incorrect and somewhat anachronic use of this term. From a rigorous anthropological point of view, which should be the context were the word magic can properly get its true meaning, magic is a stage in the evolution of human thought, prior to religion and science. And, although it could be said that science and magic share some common aspects and could even coexist within different groups in a concrete period of time, they are essentially different institutions created by the human beings. What is then the purpose of using this word in the context of one of the best theories of science? As the first few versions of this paper were drafted, we realized that the arguments put forward against the use of this word in quantum physics were leading us to conclusions which had by themselves interesting methodological consequences. They are now partially the gist of the paper and we will present them in its last few pages.

The word magic has three different entries. According to the first one, magic is "the pretended art of influencing the course of events by compelling the agency of spiritual beings or by bringing into operation some occult controlling principle of nature". The second is "a secret and over-mastering influence, resembling magic in its effects". The third is "the art of producing (by legerdemain, optical illusion, etc.) surprising phenomena resembling the results of magic" (*The Shorter Oxford Dictionary*, Vol. I, 1988, p. 1257). As the second and third entries include the very same word magic, the use of the term with those two acceptions necessarily requires some kind of previous knowledge of its meaning in the first one.

It is true that since its inception, Quantum Theory, perhaps the most effective physical theoretical structure build-up by human beings, has had a shaky philosophical foundations, giving way to many discussions between the founder fathers of the theory. They utilized sometimes words like paradox, puzzle, mystery, weirdness, spooky, etc, to manifest their surprise at some of the theory's predictions. However, the word magic that, as we shall see very soon may have some other implications, entered the scene only at a later stage in the development of the discussion in the Foundations of Quantum Physics. It was only in the eighties that the sentence: "quantum mechanics is magic" became famous. Daniel Greenberger introduced it in the discussion remarks at the Symposium on *Fundamental Questions in Quantum Mechanics* held at SUNY, Albany, in April 1984 (Greenberger, 1985). The sentence called the attention of the scholars working on the Foundations of Quantum Physics and it achieved some popularity one year later when David Mermin opened with it a nowadays classic paper on Foundations of Quantum Mechanics published in *Physics*

Today (Mermin, 1985). Maybe due to the success, D. Greenberger repeated the formula throughout the years. For example, in the preface of the book *Fundamental problems in Quantum Theory*, published to honour Professor J. A. Wheeler in 1995, he writes: "What makes quantum mechanics so much fun is that its results run so counter to one's classical intuitions, yet they are always predictable, even if unanticipated. That is why I like to say that quantum mechanics is magic, but it is not *black* magic" (his emphasis) (Greenberger, 1995) In the collection of statements gathered on the occasion of the meeting *Quantum Physics of Nature*, held in Vienna ten years later, Greenberger said again: "Quantum mechanics is magic! It is not black magic, but it is nonetheless magic!" (Arndt et al., 2005).

Using the word magic in its third meaning, we must agree with D. Greenberger. The results of experiments like the double slit experiment carried out at low intensity (Merli et al., 1976; Tonomura et al., 1989; Carnal and Milnek 1991; Arndt et al., 1999), the delayed choice experiment (Wheeler, 1983) and many other experiments performed in the last 35 years in Foundations and Quantum Information Processing (QIP) (Aspect et al., 1981; Rowe et al., 2001; Matsukevich et al., 2006) show that the behaviour of individual quantum systems is indeed amazing! [1]

If that were all, it would have been useless to pay any attention to the use of the word magic in the context of quantum physics[2]. Almost everybody is using it in the correct *third meaning*: surprising phenomena. However, this consideration does not close all the questions. Modern physics was born against common sense and it has always been amazing for both the lay man on the street and for those who had enough knowledge of it. What are the reasons behind stating that quantum mechanics is magic, while the same expression is not applied, for example, to relativity theory or to cosmology? Both introduce counterintuitive ideas and lead to some results that are unexpected and surprising. Why is quantum mechanics so different in this respect? Where does its strangeness reside? Why its results seem to be so paradoxical or extraordinary?

We think that if one considers the word magic from the point of view of its first basic meaning, not contemplated until now in what we have just said, we can obtain a non-anecdotal significance which exceeds the particular realm of physics. It has philosophical interest and could give us a clue about our previous queries. In this paper we address the question of what are the full implications of Greenberger's statement "quantum mechanics is magic", but when taking the word magic in its first foundational sense. We will try

1 Note that not all scholars would agree with the standard interpretation of these experiments. See for example E. Santos (2008). *arXiv: quant-ph/0801.1572*, and references therein.

2 History of Science shows that this word has been used many times also in the past and in the context of different scientific theories.

to show that the profound reason behind its use is that *quantum mechanics is a body of scientific knowledge different to all previous ones*. By this statement we mean that it does not require the introduction of various *a priori* principles regarding Nature that other bodies of knowledge implicitly introduce. This fact has some consequences. On the one hand, it makes more difficult to build up an image of the quantum world. And, on the other, it indicates that those principles cannot play the role of *necessary preconditions* to construct scientific theories, a methodological role that, for example, Einstein attributed to them. If this last point is right, the *philosophical theories* based on the consequences derived from those principles can be misleading, and a different approach would be necessary to understand the methodology of sciences, an approach that should incorporate the new ideas introduced by quantum theory. We will advance here the conjecture that this new "operative" methodology may have close connections and resemblances with the one used to survive, since the mists of time, by observer-participants (the human beings) when confronted both with uncertainty and with the resolution of that uncertainty.

The paper is organized with the following structure. In part two, and just for completeness, we give a brief approximation to the concept of magic in its anthropological sense as theorized by Frazer. Part three briefly addresses the question of the similarities between this system of magic and classical mechanics, with the foundations of all different sciences actually, modulo quantum theory. Part fourth intends to show how quantum entanglement implies a big break from the principles and foundations of both magic and other scientific theories. Part fifth contains the conclusion and some preliminary considerations about the methodology of sciences.

2. Magic in Frazer's sense.

For the purpose of this paper we will adopt the characterization of magic introduced by Sir James Frazer, one of the founders fathers of modern anthropology, in his seminal work *The Golden Bough* (Frazer 1993), a truly masterpiece of intellectual work. If his conception of magic is not accepted[3], then some of the arguments contained in this paper would be partially altered, but not its main conclusions.

In page 11, under the title *The Principles of Magic* Frazer says:

> "If we analyse the principles of thought on which magic is based they will probably be found to resolve themselves into two: first, that like produces like, or that an effect resembles its cause (Law of Similarity); and second, that things which have once been

3 Frazer's conception of magic has been strongly criticized by many anthropologists, like Malinowsky, Levi-Straus or M. Harris, to quote only a few. A serious discussion of this topic lies outside the purpose of this paper.

> in contact with each other continue to act on each other at a distance after the physical contact has been severed (Law of Contact or Contagion)".

Through the first principle a magician infers that she/he can produce any desired effect by imitating it; through the second, that whatever she/he does to a material object will affect the person with whom the object was once in contact. The first law produces 'Imitative Magic' and the second, produces 'Contagious Magic'.

"If my analysis of the magician's logic is correct, its two great principles turn out to be merely two different misapplications of the association of ideas. Imitative magic is founded on the association of ideas by similarity; contagious magic is founded on the association of ideas by contiguity […]. In practice the two branches are often combined […] and may conveniently be comprehended under the general name of Sympathetic Magic, since both assume that things act on each other at a distance through a secret sympathy, *the impulse being transmitted from one to the other by means of what we may conceive as a kind of invisible ether, not unlike that which is postulated by modern science for a precisely similar purpose, namely, to explain how things can physically affect each other through a space which appears to be empty*" (p. 12, emphasis ours).

Frazer observes that the magician "tacitly assumes that the laws of similarity and contact are of universal application and not limited to human actions (p.11) […] The magician does not doubt that the same causes will always produce the same effects, that the performance of the proper ceremony will inevitably be attended by the desired result […] yet his power […] is by no means arbitrary […]. He can wield it only so long as he strictly conforms to the rules of his art or to what may be called the laws of nature as conceived by him […] The succession of events is assumed to be perfectly regular and certain, being determined by immutable laws, the operation of which can be foreseen and calculated precisely; the elements of caprice, chance and accident are banished from the course of nature" (p. 49). The essential characterization of magic for our purpose is already contained in which we have just said. This is all we need.

If the previous analysis done by Frazer and our understanding of his ideas are correct, underlying the whole system of magic there is a kind of belief in the order and uniformity of nature. Magic assumes that in nature one event follows another necessarily. This is *causality* with *sufficient* reason, plus the continuous flow of time[4]. And although Frazer says nothing about it, we conjecture that his characterization is also based in some other implicit methodological principles that would permeate the whole system of magic. Let us introduce them. Those principles are: the *principle of realism*, the *individuation principle* and the *locality principle* (as we call it today). We use the term *realism* both in the broad sense that there exists a material reality, and in the restricted sense that the world is composed by objects that *have properties* with well defined values. The determination of a property, with a measurement for example, reveals that pre-existing value. The implicit

4 Sympathy is not causality. The idea of causality used in Frazer's magic is only apparent, not effective, as it is in sciences. This is one of the reasons why Frazer was criticized (and why magic was superseded; see below).

consideration of this principle is what gives sense to the two magic laws. Besides, it can also be easily perceived, without forcing Frazer's conception too much, that the *individuation* and *locality principles* are also working in the magician's approach. Let us explain these two principles a bit further using Einstein's words:

> If one asks what, irrespective of quantum mechanics, is characteristic of the world of ideas of physics, one is first of all struck by the following: the concepts of physics relate to a real outside world, that is, ideas are established relating to things such as bodies, fields, etc., which claim a "real existence" that is independent of the perceiving subject[5] [...].

Afterwards, in the same text, Einstein introduces the *individuation principle*[6] with the following words:

> "It is further characteristic of these physical objects that they are thoughtless arranged in a space-time continuum. An essential aspect of this arrangement of things in physics is that they may claim, at a certain time, to an existence independent of one another, provided these objects 'are situated in different parts of space'. Unless one makes this kind of assumption about the independence of the existence of objects which are far apart from one another in space [...] physical thinking in the familiar sense would not be possible [...]".

Einstein's paragraph finishes stating that:

> The following idea characterizes the relative independence of objects far apart in space (A and B): external influence on A has no direct influence on B; this is known as the "principle of locality" [...]. If this axiom were to be [...] abolished [...] the postulation of laws which can be checked empirically in the accepted sense, would become impossible (Einstein 1971).

In short: individuation is equivalent to separability and separability requires the non existence of actions-at-a distance. Consequently, individuation can be possible only if no actions-at-a distance exists.

These two principles are working in the magician approach because the magician maintains that once the objects have been in contact, they continue to act upon each other by sympathy at a distance after the physical contact has been severed. But, in order to have such a situation, we need that things exist separately and individually. Let us argue it in the negative sense: the second law of magic says that if two things had never been in contact,

5 This is the *principle of realism* in the broad sense. At the end of the paper we will qualify the meaning that "independent of the perceiving subject" may have.

6 Throughout this paper we will use the individuation principle as equivalent to the separability principle.

whatever is done to one would not affect the other whatsoever. That is, the two things must exist as separated and independent entities. Note that in Frazer's characterization, individuation is not lost through contact, or interaction, because once the contact has been severed, sympathy, "a kind of invisible ether", connects one with the other. In our opinion, this wording involving sympathy is implicitly using a kind of *locality principle:* things cannot be manipulated at a distance without the existence of any mediator. It may sound surprising speaking about magic, but based in our previous analysis we conclude that "spooky actions at a distance", to quote Einstein once more, are not possible in this system of rules.

The second law of magic says nothing about further and subsequent interactions. We conjecture also that implicit in magic's system is the idea that a new contact does neither severe the previous one, nor establish new relations between the second and third that have never been in *direct contact*. Entanglement swapping, for example, would be impossible within the system of magic.

To summarize: As characterized by our previous extension of Frazer theory, the system of magic seems to have four underlying principles and two laws. The principles are: the principle of realism (both in the broad and in the restricted senses); the causality principle; the individuation principle and the locality principle. The two laws are: the law of similarity and the law of contact.

3. Magic and the Foundations of Classical Physics.

As described in the previous paragraphs, magic appears to be a legitimate body of knowledge with close resemblances with sciences in general and with classical physics in particular. We refer now to physics in a broad sense and in the period elapsed between Copernicus and the beginning of the Twentieth Century. The foundations of these similarities are what we are going to elaborate now.

The first and most important resemblance is that both magic and classical physics believe in an established order in nature, determined by eternal and immutable laws that permit to foresee the course of events with certainty [7] and which allow us to act in accordance with these, as Laplace - in a well know sentence that we refrain from quote- superbly summarized. Therefore, the fundamental conception of magic is in this respect coincident with that of classical mechanics. The basic forces that govern the world are in both impersonal and unconscious, as opposed, for example, to religion, that conceives of them as personal and conscious. In Frazer's words:

7 To be rigorous: Thermodynamics and Statistical Mechanics would be partially at variance with this statement. We cannot enter in this discussion now.

"It is true that magic often deals with spirits, which are personal agents of the kind assumed by religion […] but it treats them exactly in the same fashion as it treats inanimate agents […]. Thus it assumes that all personal beings, whether humans or divine are in the last resort subject to those impersonal forces which control all things" (Frazer, 1993, p.52)[8].

The second important similarity between magic and classical physics is that both satisfy the principles of realism, determinism, continuous time flow, individuation and, with due qualification, locality. It is true that gravitation law in classical physics was non-local, and that through its influence, non-local actions reined in physics for almost two hundred years. Yet it is also true that since its introduction, even Newton perceived it as to be simply unintelligible, as a provisional expedient to be eliminated from physics (Janiak, 2004). As we have seen, one possible way of avoiding the action at a distance and restore locality is to go back to magic, leaving open the possibility that gravity is transmitted thanks to the presence of a kind of ether that penetrates and acts on all matter. It is well documented that Newton speculated about such ether as a medium for the gravitational interactions of material objects at least since 1679, as can be read in a letter written to Boyle (Janiak, 2006)[9]. Seen in this context, the ravings of Newton with alchemy and his search for the philosophers' stone to gain an understanding and power over nature in a historical moment in which the old medieval knowledge was becoming useless, seems to be understandable.

This second similarity can be easily perceived by looking at the following frame:

	Realism	Determinism	Individuation	Locality
Magic	yes	yes	yes	yes
Classical Physics	yes	yes	yes	yes (with qualification)

Frame 1. - Methodological principles working in magic and in classical physics. The yes/no inside the boxes are the answers to the question: Does this body of knowledge (magic/c. physics) satisfy the principle of…? Realism is intended in the restricted sense.

8 Later on Frazer goes as far as saying that "magic directly prepares the way for science. Alchemy leads up to Chemistry", p. 92.

9 Newton speculations about the characteristics that ether might have can be seen in query 21 of *Optics*. As a possible alternative to restore locality, Newton also considered God as intermediary of gravitational interactions.

As we see in frame 1, the same methodological principles underlie the two bodies of knowledge, magic and classical physics. However, classical physics is considered to be a genuine scientific theory, while magic is not. In our opinion, the true failure of magic to be a scientific body of knowledge does not lie either in its general assumption about the order and uniformity of nature or in the hypothesis that the events are determined by local law. These characteristic aspects are shared with classical physics. The flaw lies in the wrong nature of the particular laws that govern the events. That is, whereas the rules laid down by the different scientific theories are derived by an inextricable combination of hypothesis and experiment, from ideas and careful experimentation or observation of phenomena, from conjectures with predictive power and subsequent confirmations, the magician *translates directly to nature* the laws that he feels present in his head. For the magician, the origin and legitimacy of the laws resides in our heads, while for us the origin and legitimacy of scientific theories resides in nature itself (although through our interventions, see below).

Let us emphasize our point of view with a well known example. Aristotelian physics gave, for more than two thousand years, a perfect explanation of movements. This was due to his theory of natural places and violent movement. The specific laws of Aristotelian physics could be also classified themselves into two: first, that each object has a natural place in the universe to which it naturally returns if free to do so; and second, that any moving object that is not going to its natural place, must be moved by the force exercised by some other. Natural movement did not require any explanation, as this lies in the very nature of things. All the other movements, characterized by the fact that the objects had some speed, were violent, and speed requires the presence of a force necessarily performed by another body: nature abhors vacuum. Yet, Aristotle's physics is not considered to be a scientific body of knowledge as we understand it today. Modern physics was born in the dawn of the XVII century when Galileo was able to refute this particular Aristotelian theory about the movement, introducing new specific laws masterly developed years later by Newton. Galileo changed Aristotle's natural movement to the inertial one and Newton showed that the force caused a change in the velocity, as the two first Newton's laws state. However, as in the case of magic, Aristotelian physics satisfied both the belief in an order and uniformity of nature and the principles mentioned above in frame 1, locality included. The flaw was, once again, in some other place, to wit, in his two specific laws about the movement.

To summarize, although we cannot enter now into detail, since immemorial times the evolution of human thought seems to have past first from survival, so to speak, to magic. Then, from magic to religion. And, finally, from religion to sciences. The transition from survival to magic seems to be lost in the mist of times[10]. As far as the transition from

10 Our scientifically informed ignorance about ourselves and for this long period of

magic to religion, also partially lost and not touched upon until now in this paper, we could conjecture that it occurred as a consequence of two facts: on the one hand it became clear that the laws of magic lacked predictive power and, consequently, they didn't work properly. Presumably, it was the magician's elite whom became progressively conscious that they were not getting the results they were asking for[11]. And, on the other hand, the progressive discovery of the mind (Snell, 1982). The result seems to have been a very complex process by which the impersonal beings, subjects to the same laws than us, were substituted by some others that were able to violate these immutable laws. The following transition, from religion to science, closer to us, took place when we introduced a different kind of laws; we dispensed with these unsatisfactory gods and became alone in the universe.

Although we cannot properly justify it now, it is not too adventurous to conjecture that these three transitions have all the characteristics of a Darwinist process with evolutive advantages for mankind. No matter how, what is relevant for our analysis is that these transitions have happened handed down from the remote antiquity the principles quoted in frame 1, principles that until the beginning of the 20th century were never questioned.

4. Entanglement: a new tool for quantum theory.

We will try to show now how quantum mechanics produces a dramatic break with these principles for the first time in the history of human thought. To do it without using explicitly the quantum mechanical formalism, we will introduce a characteristic property of quantum systems know by the name of *entanglement*.

Entanglement is a formal concept deriving from two fundamental aspects of the quantum mechanical formalism. Namely, the superposition principle and the tensor product composition of the joint space state of two o more subsystems. It was, in some primary sense, introduced by EPR in 1935 in a today's very famous paper (Einstein et al., 1935). Since its inception until nowadays, entanglement has been considered to be "the essence" of quantum mechanics (Schrödinger, 1935). After a long ripening process characterized by the surprise that some predictions derived from it caused upon us (Gilder, 2008), it set off in the nineties as the basic resource for information processing, and today it has become the central tool in quantum information theory (QIT), a new and emergent field in quantum physics with an outstanding potential to change our societies of information in the XXII century. Given its technological applications, like cryptography and teleportation, in what follows we will adopt the position that entanglement is a

human evolution is legendary. The origins of language and of consciousness, for example, come easily to mind.

11 As we have already said, the main reason was that causality was only apparent, not effective.

wholly physical property: it simply happens. It exists as a new aspect of nature, of material reality. This is not an arbitrary choice: it is based on the result obtained in many different experiments (Aspect et al. 1981; Rowe et al. 2001; Matsukevich et al., 2006) carried out in the last 36 years that *converge* in this very same aspect. This is a good example of how material reality manifests itself in a far more complex way than it was previously thought, as it has always been the case in the history of physics. This renewable complexity of matter makes "ontological completeness" (Maudlin, 2007) to sound like an oxymoron.

On the other hand, entanglement is the technical explanation for quantum correlations. Although very well known today, let us explain this point a little further. There are correlations everywhere in the world: in classical physics, in our societies, in our personal relations, etc. So, what is the problem with quantum correlations? Are they different from all the others? A quick answer to this question is: yes, they are. Quantum correlations encoded in some entangled states are stronger than all the other (classical) ones and cannot be imitated by any classical correlation (Bell's theorem). At the philosophical level in which we are interested now, we could say that classical correlations can be explained on the basis of common causes (in the past) and/or hidden communication. Quantum correlations, cannot. They are *instantaneously established by the act of measurement*. Let us put an example to explain this last sentence. Imagine that two friends, Alice in London and Bob in Rome, are asked to produce one hundred times the "face side" (heads) or the "cross side" (tails) of a euro coin. This is a very simple experiment. What are the expected results? The results will be that Alice will get heads in –approximately- half of the cases (the same for Bob) and that in –again approximately- 25% of the cases both of them will get heads and in other 25%, tails. What would happen if they get *always*, in this and in many other experiments carried out equally, the same result (heads-heads or tails-tails)? Nobody would believe that this could happen by an implausible coincidence, by mere chance. Contrarily, and as an explanation of the persistent coincidences, we would seriously think that they have some device that allows both of them to get heads or tails at will, as well as any of these two possibilities:

1st. - they had previously agreed in the order in which they were going to produce the face side or the cross side (common cause in the past), or

2nd. - they have a special equipment (that we do not see) that tells one of them the result that is being produced by the other (hidden communication).

Any other alternative would be logically rejected, implying that these correlations could be reduced to the categories of cause and effect.

What about the quantum correlations? To make a long story short, in the particular case of the previous quoted experiments devised to verify the quantum correlations of maximally entangled pairs (Aspect et al., 1981), we would *always* get heads-heads or tails-tails. However,

1st. – It may sound surprising or even absurd for those that are not familiar with quantum mechanics, but the real fact is that "quantum coins" have neither heads, nor tails *until* they are observed, that is, registered or detected. This is again not an arbitrary decision. It has been empirically tested in many different and independent experiments carried out in the last one hundred years.

2nd. - No hidden communication exist (this possibility has been also excluded empirically and nowadays can be consider to be a well established experimental fact).

When considered jointly, these two characteristics imply that to get such correlations what *Alice does and obtains in London instantaneously*[12] has a consequence in Rome (it defines so to speak the corresponding value, face side or cross side, undefined until this very precise instant). On the other hand, and as Bell's theorem and related experiments prove, no common cause is possible: there are not local hidden variable theories able to reproduce all quantum correlations. Material reality is here manifesting quantum correlations without referents, without correlata (Mermin, 1998).

In conclusion, the heads/tails do not exist until detected and the result we get here has irretrievable instantaneous consequences there. What Alice does and obtains instantaneously establish the correlations, undefined until this very moment. Note that the correlations *are not new pre-established properties*, because the correlations revealed depend on and are created by Alice's *kind of measurement*.

To avoid such amazing conclusion, it has been occasionally mentioned that what Alice does in London has not instantaneous consequences in Rome, because it was impossible for Bob to find out what Alice has been doing. He will keep getting 50% heads and 50% tails, and from these results it is completely unfeasible for him to ascertain if she has taken measurements or not, and therefore the outcomes of those measurements. Non-local correlations are useless when it comes to send instantaneous messages! This is a very surprising result (in which the founder fathers probably never thought), and is absolutely correct. Quantum formalism *guarantees* that these correlations cannot be used to send messages at superluminal velocity (*no-signalling* condition). Signalling and non-local correlations seem to be different issues. Today the agreement regarding this matter has made this discussion to come to an end. However, let us be very clear in this precise point. The problem is that we are not trying to elucidate upon that question. What we would like to emphasize is that, if Alice and Bob arrange afterwards to meet half way -let us say Paris- with their respective result notes (heads, heads, tails, and so on), they will confirm that they had *always* obtained the same result. This is what quantum mechanics predicts, verified by the experiments on Bell's inequalities, teleportation and cryptography. Moreover, it is precisely this absolute coincidence what we are interested in now. As we have said, to be

12 It could be v >> c instead. We do not explore this possibility here.

able or not to be able to use correlations to send signals faster than the speed of light is *a different issue,* a very important one, but in our discussion is secondary. Let us emphasize it again: what we want to discuss is how is it possible that Alice and Bob can corroborate that they have obtained *the same result when right before the ending of each test the individual "quantum coins" did not even have a definite state!* [13]

Our answer to the difficulties sorted out in the previous pages created by quantum entanglement is that the methodological principles of realism, determinism, individuation and locality are not satisfied in quantum theory. Let us explain further how this crucial break is produced.

Realism, in *the restricted sense*, as it is usually understood in the context of Bell's inequalities, is violated by entanglement because the "quantum coins" do not have a pre-existing fixed value that we will obtain when measuring, but a range of probabilities. This is not a peculiarity of entanglement. In quantum theory there are not dispersion free states for all observables: non-commuting observables cannot have definite values simultaneously, as the uncertainty relations reflect. As a consequence, quantum systems, like our imaginary coins, have not in general properties with definite values: Einstein's elements of reality cannot exist[14]. Any consistent philosophical theory about reality must incorporate this new knowledge obtained by physics.

Determinism is violated by entanglement because neither Alice nor Bob can control their own individual results. Quantum theory is an essentially probabilistic theory, whatever essential might signify. Even though we had complete knowledge of the state of a quantum system, only conditional probabilities can be predicted in a concrete experiment. All this has been tested in experiments carried out with particles equally prepared entering the apparatus one by one. The individual results occur without deterministic law: different effects can follow exactly the same causes[15].

The *locality* principle is violated because any external influence on one of the two previously entangled particles that are far apart from each other, has a direct influence on the second. In other words: locality is violated because the results Alice gets in London have an irretrievable instantaneous consequence in Rome, even though she cannot use this

13 We emphasize this point. Even if the density matrix does not describes the "real" state of the system, but the information that the preparer has about its state, and therefore the collapse is just a mere change in the description, we still have the problem of understanding the strict correlation corroborated when they met in Paris.

14 It is possible to maintain some kind of realism introducing non-local properties, like en Bohm theory. This discussion lies beyond the purposes of this paper.

15 The clicks registered in a detector that controls a radioactive source are described by a truly random Poisson process. See also, in this respect, the pictures shown by Tonomura *et al.,* 1989.

influence to send signals at superluminal velocity. Nature is non-local and, once more, any consistent philosophical theory about reality must incorporate also this new knowledge obtained by physics.

Finally, the *individuation principle* is violated because the two previously entangled particles may not claim an existence independent from the other: they are no-separable.

The conclusion of our previous analysis should by now be manifest: Quantum Mechanics challenges our fundamental concepts about realism, cause and effect, individuation and locality. It strongly suggests that our present ways of thinking, partially based on them, are inadequate.

We summarize our previous discussion in the following frame:

	Realism (restricted sense)	**Determinism**	**Individuation** (separability)	**Locality**
Magic	yes	yes	yes	yes
Aristotelian physics	yes	yes	yes	yes
Classical physics	yes	yes	yes	yes (with qualification)
Relativity	yes	yes	yes	yes
Quantum theory	no	no	no	no

Frame 2. - Methodological principles working in the system of magic, Aristotle's physics, classical physics, relativity and quantum physics. The yes/no, etc. inside the boxes are the answers to the question: Does this body of knowledge (magic/ c. physics, etc.) satisfy the principle of…? Realism is again intended in the restricted sense.

5. Methodological considerations.

As can be seen in the previous frame, the break that quantum mechanics introduces in the basic underlying principles that have been working in the development of human thought since immemorial times, is absolute. Our thesis is that it is precisely the violation of these principles handed down from the remote antiquity and deeply engraved in our minds, what makes quantum mechanical phenomena so surprising that they seem to resemble the results of magic.

Quantum mechanics is an extremely well established and confirmed scientific theory, as its capacity to organize a vast field of phenomena demonstrates. But at the same time it seems to be a radically new sort of theory about nature. Based on which we have already said, if we introduce a quantitative distance measure between different bodies of knowledge (and this can be done in many different ways, one being, for example, the number of

violated principles), the distance between magic and quantum mechanics would result in being *the greatest* one. Any other scientific theory would be closer to magic than quantum theory. Hence, although the behaviour of quantum systems are "weird" from the point of view of theories that satisfy the above-mentioned fundamental principles, this reason of "distance" should invite us to refrain from using words like magic in the context of a scientific theory like quantum mechanics.

There is another interesting conclusion that could be drawn in relation with the scientific method if we contrast the mentioned similarity between magic and (classical) sciences with quantum theory. Let us anticipate that we do not pretend to have a closed and full-fledged philosophical theory in this respect, but only a few preliminary (perhaps naive) insights that we will put now forward as part of a research program to be developed in the future.

The idea is the following. Magic and "classical" scientific theories were based upon the belief of a certain preestablished order in nature. Since the dawn of mankind we have survived, presumably, taking advantage of that order, perceived as external and independent of our own activity. In both cases, the origin of the order was some immutable laws conferred by the Gods, God or the Big Bang at the beginning of time. God or the Big Bang, are conceived as external to us, detached passive observers that have nothing to do with the order that those everlasting laws produced in nature. Being they established from the beginning and forever, our role as outside observers could only be to *discover* them. From this point of view, the scientific method would consist in raising the veil of Maya and gradually uncovering the real essence of the phenomena, the "unalterable givens" (to use Einstein's words, see below). Although brief and schematic, this naive caricature is sufficient to show the attractiveness of the realist research programs, to the point that many physicists do indeed believe that the equations of physics are obeyed by material reality. However, if we look back to the history of sciences and we analyse any concrete case, it would be clear that these programs and the persuasive image of truth as mirroring (or, more cautiously, truth as correspondence) they propose, cannot be literally accurate. History of physics shows that with the unique exception of current laws and theories, all previous theories have been proved to be limited in one way or another, forcing us to change our theories and our descriptions. They have been surpassed by the new knowledge and the order introduced. As explanations of what really is going on behind the scenes, none of them have lasted forever, (although some *constants* could, but this is different question in which we cannot enter now).

This brief description of what has happened in the history of physics is incompatible with the idea of science as representation and of truth as correspondence. This methodology, shared by the majority of physicists still today, cannot incorporate the rupture of quantum mechanics with the aforementioned principles and cannot respond to the challenge put forward by the non-trivial change of theories, in particular the one produced by quantum

theory. It cannot give a satisfactory answer either to the question why things are not what they look like.

Quantum Mechanics strongly suggests that this way of looking at things is inadequate. It has, definitely, modified the role we play in such scenario. By putting us back in the frame as observer-participants, and restoring the essential role that we have always played in the achievement of the order introduced in material reality, quantum mechanics has opened a completely different methodological perspective that seems to be more adjusted to the facts than the "representative" one we have caricaturized and criticised. A conjecture of how natural laws and theories could be understood from this new perspective could be the following. Since the mists of time, humans have operated -first with their hands and then with their beliefs and technological devices-, with material reality, whatever this be. Undifferentiated material reality was then decomposed into pieces and composed once again differently from the inside, because we observers are self-organized matter. It was this interaction with our environment towards survival what, in the becoming of time and over millions of years, gave rise, from that undifferentiated material reality, to something that we now regard as "material objects". It was through this manipulation with material objects that some objective recursive relations were established. These relations were then used to build up new material objects and new relations, and so on. Undifferentiated material reality gave way to pieces of matter, "entities which simplify our account of the flux of existence" (Quine 1980) and, finally, to relations between these entities. Some of those relations were summarized in a certain algorithm and designated as a *natural law*. Note that from this operative mindset, the scientific laws appear as computational algorithms that allow us to condense and reproduce an enormous variety of relations between macroscopic devices. The principles of quantum mechanics fall naturally into this category. This everlasting process shaped not only the world with our experimental interventions in a malleable nature, introducing what could be understood as order within the material reality, but also our minds (Jaynes, 2000).

Magic and classical perspectives present the order as the consequence of some given immutable laws (to be discovered) that the material objects should satisfy, while the new quantum mechanical operative perspective, presents laws as the *consequence of the previous order* that we, as human observer-participants, have introduced. Therefore, the word "discovering", profusely used in physics, can only be properly applied to *our previous interventions,* being that the Atapuerca fossils, a pyramid in Egypt, relics of past splendour or a new property of prime numbers.

Naturally, there must be here an essential tension between two different aspects. On the one hand, laws and theories are consequences of the previous order we have managed to introduce in a concrete field of human activity. Yet, on the other, this ordering is not

arbitrary: it is independent of our individual will. Matter has legality[16], revealed by its resistance to our manipulations, by the fact that not everything works. This is the point at which this perspective retains a materialist and realist connection: the transformation of matter is de facto a proof of its existence. Although this approach has some constructivist characteristics, it is nevertheless realist (in the broad sense) and materialist because the objects and devices we manipulate show invariants, regularities that are not under our control. But this material legality manifests itself only through our interventions.

Although uncovered by quantum theory, this process is not a peculiarity of this theory. In fact, it may have been always the case, even if for a long time we have been able to remove our interventions. When that happened, the phenomena were explained "as if" we were detached observers of a reality that is just there, in front of us, and "as if" the principles in frame 2 were necessary preconditions to build up scientific theories. Einstein, in the sentences quoted at the beginning of this paper, says explicitly that the principles of realism (in both senses), individuation and locality are preconditions to construct sciences, physics in particular. However, as a matter of fact, quantum theory is a genuine scientific theory that does not satisfy any of them, except realism in the broad sense.

Let us remember that the realist point of view is not in itself a scientific theory, but a philosophical one build up on the basis of the aforementioned principles. And if the principles do not work in Quantum Mechanics, why should any philosophical theory build up upon them do? Historically, and until the XX century, the "old" approach has revealed itself as a useful and necessary step forward, where the detached reality played the role of a reference to help us to decrease the uncertainty of our relations with matter and, at a later stage, to construct sciences. But after the quantum revolution has taken place, we should not think any longer about scientific theories as if they had an independent existence of the process from which they were built up. Nowadays any theory is a device not only for understanding, but for allowing us to set up also new instruments through which we enlarge our capacity to intervene in the world and extend so the order previously produced. The origin of the same quantum theory was in the incomprehensible behaviour (in classical terms) of some macroscopic devices, like a macroscopic cavity and the radiation it had inside it. For at least the last one hundred years, the most important advances in physics have arisen "not through the study of phenomena as they occur in nature, but, rather, through the study of phenomena in man-made devices, in products of technology" (Pierce, 1980).

Although we cannot enter now in the detail, some may think that the challenge to the quantum operative perspective we have introduced is to understand the success of physics; to explain why some superseded theories are still partially useful and why we have so little

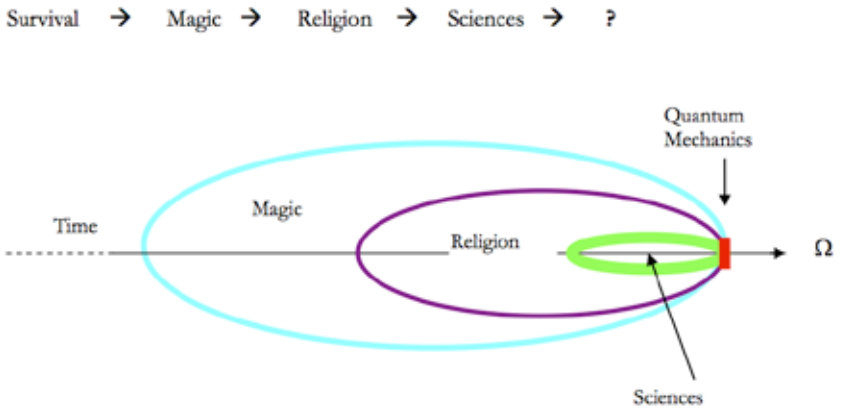
16 Legality cannot be understood here as a deterministic law, but as a manifestation of environment pressures.

control over which theories seem to be temporarily correct. It cannot be a real challenge for an approach that sees theories as relating different aspects of our experience, an approach in which the resistance that matter manifests when operating with it plays an essential role. We will develop these ideas in a separate paper.

It is not difficult to find in physics *partial anticipations* and precedents to this new methodological perspective. For example, Einstein seems to have been conscious of the relevance of the forgotten process that we have described in the last three pages: "concepts that have proven useful in ordering things easily achieve such authority over us that we forget their earthly origins and accept them as unalterable givens" (Einstein, 1916). And Niels Bohr repeatedly insisted: "from now on the purpose is not to disclose the real essence of the phenomena but only to track down, in so far as it is possible, relations between the manifold aspects of our experience" (Bohr, 1934). However, it was John Wheeler who once again was able to develop and state the idea more precisely by introducing the concept *participative*. What we have tried to show in the previous few pages is that the universe we live in has always been a participative universe.

> The task now is to move the imposing structure of sciences over onto the foundation of elementary acts of observer-participants…[that is] the one who operates an observing device and participates in the making of meaning… understanding by [meaning] the joint product of all the evidence that is available to those who communicate (Wheeler, 1996).

Let us close with a last remark and a quote, both speculative and both from Frazer. As we have outlined, the evolution of the human thought has been from survival to magic, from magic to religion and from religion to science. Nothing in the history of mankind suggests that we are at the end of the road. On the contrary, many highly non-trivial problems are still waiting to be solved, and their number increases with time. Only a few defenders of the "old" representative perspective, dream with a final theory. And, in the same way that three or four thousand years ago sciences as we conceive them today were unthinkable, it could result for us unthinkable to conceive the new structure of knowledge that could prevail, let us say, in two or three thousand years from now. In historical terms everything we have said suggests that we are in the path that the following scheme shows:



"The advance of knowledge is an infinite progression towards a goal that for ever recedes" (Frazer 1993, p 713). The interrogation (and the omega) in the figure could be or could be not only an empty symbol. We will never know. But our conjecture is that quantum mechanics has profound implications that we do not understand yet and that could finish by giving sense to these symbols.

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