The Montevideo interpretation of quantum mechanics: frequently asked questions

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Abstract

In a series of recent papers we have introduced a new interpretation of quantum mechanics, which for brevity we will call the Montevideo interpretation. In it, the quantum to classical transition is achieved via a phenomenon called "undecidability" which stems from environmental decoherence supplemented with a fundamental mechanism of loss of coherence due to gravity. Due to the fact that the interpretation grew from several results that are dispersed in the literature, we put together this straightforward-to-read article addressing some of the main points that may confuse readers.

In a series of recent papers we have introduced a new interpretation of quantum mechanics, which for brevity we will call the Montevideo interpretation. The most complete description published up to date is the essay [1]. Here we clarify some points about the interpretation in the form of a set of questions and answers.

- **Briefly, what is the Montevideo interpretation of quantum mechanics?**

  This interpretation explains the emergence of the classical world via decoherence through the interaction with the environment plus loss of coherence of the quantum theory when studied with real clocks and measuring rods (a pedagogical discussion of why there is loss of coherence when one considers real rods and clocks is in [2]). The combined effect of both losses of coherence implies that all information about quantum coherence in the system plus apparatus plus environment becomes inaccessible.

  After a while, there is no experimental arrangement that is able to decide if the evolution of the state of the complete quantum system was unitary or suffered a collapse. Whenever such situation of *undecidability* is reached, the interpretation assumes that an event (measurement) takes place [1].

- **Is the interpretation realist?**

  This interpretation is realist in the sense that it attempts to yield a description of reality based on available physical theories. We assume that physical reality is constituted by two fundamental elements: the states and the events. The latter include observable events, (the observable phenomena). From the latter we define the physical properties of the system, which are all quantitative expressions of phenomena. The states characterize the disposition of the system to produce events with certain probabilities. We admit that certain elements of reality are undecidable, that is, the laws of physics may not describe reality completely (see below).

- **What is this loss of coherence due to real clocks and rods?**

  Ordinary quantum theory evolves unitarily in terms of a time parameter t. Such parameter is assumed to be a completely classical variable, which we know with arbitrary accuracy. In reality, no variable in nature is purely classical, so when we use a real clock, we are not measuring t but a new variable T. Even if one chooses a very classical clock, trying to correlate T with t as well as possible, such a variable has some level of quantum fluctuations and other inaccuracies. Our inability to measure time accurately implies that pure states evolve into mixed states, the superposition being that "a state at time T" really corresponds, due to the clock's inaccuracies, to a probabilistic distribution of several possible values of t upon evolution. The spread of the distribution grows as the system evolves. Similar effects arise in quantum field theories when one measures the spatial coordinates. A pedagogical introduction can be seen in [2].

- **Couldn't one eliminate the effects by using better clocks?**

  At some point one will encounter fundamental limitations to the accuracy of a clock, so the effect will always be there. Some authors have argued that the fundamental limits are surprisingly large (in Planck units), by noting that every measurement requires the expenditure of energy and if you expend too much energy trying to be accurate your clock becomes a black hole. This is the rough argument, there are variations on it in the literature and they all seem to come to remarkably similar limits [3]. This particular limit states that the inaccuracy of a clock that measures a time T is given by $\delta T \sim T_{\rm Planck}^{2/3} T^{1/3}$, where $T_{\rm Planck} \sim 10^{-44}s$. One sees that for laboratory typical times of a few hours, $\delta T \sim 10^{16} T_{\rm Planck} \sim 10^{-28}s$.

- **But aren't those fundamental limits quite questioned in the literature?**

  Indeed (see [4]). We have, however, carried out detailed calculations [5] with much more conservative estimates on the clock inaccuracies, for instance that the fluctuations in the clock grow with any power of the time measured —even close to zero—. We find that the effects we are discussing are still present even for systems having a number of degrees of freedom several orders of magnitude smaller than what would consider "the classical world".

- **Does one need to involve quantum gravity for all this?**

  Not really. It is true that in quantum gravity the theory is generally covariant and one naturally accepts that there is no absolute time t (the so-called "problem of time" [6]). A favored solution to this problem is to build the theory relationally by choosing a clock from among the physical variables [7] (for readers with more interest in how the fundamental decoherence relates to the problem of time in quantum gravity, see the next to last question). Gravity also plays a role in setting a fundamental limit to how accurate a clock can be. Up to now detailed models of this from quantum gravity are lacking, the bounds placed are phenomenological semi-classical estimates. That in part justifies why they are criticized in the literature.

- **But ultimately, you are just talking about loss of coherence. In addition to the degrees of freedom environment you now just added the degrees of freedom of the clock. How could that change things so much?**

  What makes things different is that a clock is a very special set of degrees of freedom (in practice it is also a quite large set of degrees of freedom, at least if one wants it to remain accurate for a while). These degrees of freedom are being used to establish a property of the rest of the system. This is very different from the degrees of freedom of the environment. A clock is also special in that it is supposed to stay accurate during the lifetime of the experiment one studies (and better yet, beyond). Real clocks set limits on what is experimentally accessible, in particular from a pure state after it has evolved for a certain amount of time.

- **One of the objections to environmental decoherence is that the evolution of the "system plus measuring device plus environment" viewed as a closed system is unitary and one could recover quantum coherence eventually, by waiting a long time**

  The loss of coherence due to the loss of the clocks' accuracy is such that it gets worse the long one waits. So waiting longer does not help. In fact it guarantees that the "revivals" of coherence several authors have studied for closed macroscopic systems are killed off by the loss of coherence due to the clock. A concrete calculation was worked out in [5, 8].

- **d'Espagnat [9] has argued in models like Zurek's [10] that one could in principle measure global observables of the system that would indicate if collapse has occurred, even without the need of observing "revivals". Can't the observables be used to decide if the system collapsed or not?**

  It is obviously difficult to attempt to give a general answer to such a question since global observables require including quantum measurements of properties of the environment, which are in practice virtually impossible to carry out. We have tried to model the situation in a modification of Zurek's example where one has some control of the environment. This allows a chance at least in principle of measuring the global observable proposed by d'Espagnat. We have found that fundamental limitations of quantum mechanics and the use of real clocks disallow its measurement [5]. Notice that, at least in this example, these limitations are not practical in nature, but fundamental, resulting from applying the laws of quantum mechanics.

- **But there are other problems with the solution to the measurement problem by decoherence. What about the and/or problem as Bell [11] called it, or "the problem of outcomes"?**.

  The "problem of outcomes" is that although decoherence may have taken place, taking the system plus measurement apparatus to a state in which their density matrix is quasi-diagonal, the system remains in a superposition of states, each of them associated with different macroscopic behaviors. States corresponding to the diagonal of the density matrix, coexist with each other. How does one go from this situation to the classical world, where one of those alternatives and one only is realized? How does one go from a situation where one has alternatives "A *and* B" to "A *or* B"? In our approach we argue that there exist situations where the decoherence due to the environment and the use of real rods and clocks implies that "A and B" provided by a unitary evolution and the "A *or* B" result we would attribute to a reduction, are indistinguishable. When one reaches this state of *undecidability*, an event has taken place, without affecting any experimental outcome.

- **What happens to the quantum state, does it collapse or not?**

  Since we claim an event (measurement) has happened when one cannot decide if the state has collapsed or has evolved unitarily, one clearly cannot decide if it collapsed or not. We have proposed that a point of view is that both alternatives be accepted as possible for the system. Entering the realm of philosophy, this means we are taking a "regularist" point of view. In philosophy there are different attitudes that have been taken towards the physical laws of nature (see for instance [12]). One of them is the "regularity theory", many times attributed to Hume [13]; in it, the laws of physics are statements about uniformities or regularities of the world and therefore are just "convenient descriptions" of the world. Ernest Nagel in *The Structure of Science* [14] describes this position in the following terms: *"...according to Hume [physical laws consist] in certain habits of expectation that have been developed as a consequence of the uniform but de facto conjunctions of [properties]."* The laws of physics are dictated by our experience of a preexisting world and are a representation of our ability to describe the world but they do not exhaust the content of the physical world. A second point of view sometimes taken is the "necessitarian theory" [12], which states that laws of nature are "principles" which govern the natural phenomena, that is, the world "necessarily obeys" the laws of nature. The laws are the cornerstone of the physical world and nothing exists without a law. The presence of the undecidability we point out suggests strongly that the "regularity theory" point of view is more satisfactory since the laws do not dictate entirely the behavior of nature. Notice that the freedom of the system to collapse or not is not governed by any probabilistic rule. This introduces a notion of free will into our description of nature [1].

- **Does your point of view argue against the many-worlds interpretation?**

  Not necessarily. The many-worlds interpretation is compatible with what we are claiming. However, it becomes less compelling. The many-worlds interpretation was introduced in part to address the "and/or problem" by assigning different worlds to different alternatives. Since we are given a criterion for the passage from and to or, the other alternatives (and other worlds) are therefore not really necessary. That does not mean that they are precluded by our point of view.

- **Does your point of view argue against the "modal" interpretations?**

  Well, let's see. Dieks [15] lists the following set of properties as shared by all modal interpretations:

  ◇ The interpretation is based on the standard formalism of quantum mechanics. [OK, plus quantum gravity].

  ◇ The interpretation is realist, that is, it aims at describing how reality would be if quantum mechanics were true. [OK].

  ◇ Quantum mechanics is a fundamental theory, which must describe not only elementary particles but also macroscopic objects. [OK].

◇ Quantum mechanics describes single systems: the quantum state refers to a single system, not to an ensemble of systems. [OK].

◇ The quantum state of the system (pure state or mixture) describes the possible properties of the system and their corresponding probabilities, and not the actual properties. The relationship between the quantum state and the actual properties of the system is probabilistic. [OK].

◇ Systems possess actual properties at all times, whether or not a measurement is performed on them. [NO, actual properties only appear when the system becomes undecidable].

◇ A quantum measurement is an ordinary physical interaction. There is no collapse: the quantum state always evolves unitarily according to the Schroedinger equation. [NO, this cannot be decided]

◇ The Schroedinger equation gives the time evolution of probabilities, not of actual properties. [OK].

As we see, there are a lot of points in common, but not all properties of a "modal" interpretation are satisfied by ours. In modal interpretations a central problem is the determination of when events occur. There have been many proposals for such a point and there has not emerged a unanimous consensus on this (see [16] and references therein)

- **A friend of mine works in string theory and claims the theory is unitary and your effect therefore is wrong.**

  String theory has been studied in many situations and in all cases where it makes sense to talk about an evolution as a function of a parameter, such evolution is unitary. In these situations however, we are just like in ordinary quantum mechanics, when formulated in terms of a classical parameter t (ok, the story is slightly more complicated since we are talking about a field theory but we mentioned the effect is present there too, supplemented with additional spatial decoherence effects). Our point is that such classical parameters are not accessible in reality. So if one were to formulate string theory in terms of a real clock T one would have the same types of effects we discuss here. Ask your friend if she believes that string theory solves the "problem of time" of quantum gravity. The reply will likely be that the problem persists, it is just that string theorists tend to concentrate on other issues and situations, where the problem of time is not relevant.

- **This loss of coherence of yours could be made arbitrarily large by choosing a very inaccurate clock. Has this been observed experimentally?**

  Actually yes, although no experimentalist has deliberately used a bad clock to observe the loss of coherence, certain correlations in experiments involving Rabi oscillations can be interpreted as using some of the atoms as "bad clocks" and indeed one sees loss of coherence like the one we mention [17].

- **Will the fundamental loss of coherence arise naturally in a technical treatment of the problem of time in quantum gravity, or is it a choice?**

  It does. In general relativity there is no notion of absolute time. In fact, there is no absolute notion. All physical predictions have to be formulated as relations between physical quantities. This has been recognized since the early days of general relativity through Einstein's "hole argument" [18]. In particular the notion of time has to emerge "relationally". One possible way of attacking this was introduced by Page and Wootters [19]. In their proposal one takes any physical quantity one is interested in studying and chooses another physical variable that will act as "clock". One then studies how the first variable "evolves as a function of the second one". In this view, time does not play any preferred role among other physical variables. This is in contrast to ordinary quantum mechanics where one has to unnaturally assume that time is supposed to be the only variable in the universe not subject to quantum fluctuations. In spite of the simplicity and naturalness of this proposal to tackle the problem of time in quantum gravity, technical problems arise. The problems are related with what one considers to be physical quantities in a theory like general relativity. Usual things that one may consider physical quantities, like "the scalar curvature of space-time at a given point" are not well defined objects in general relativity. The problem is what is "a given point"? Points in space have to be defined physically in general relativity. One can characterize a point as a "place where something physical happens" (for instance, a set of physical fields takes certain values). Then one could ask "how much is the curvature at that point". The end result is indeed physical. But it is again a relation between the values of curvatures and fields. Such relation is given and immutable. How could one construct a clock out of something immutable? It appears that the only things that are physical are immutable relations and the only things that evolve are the members of the relations, like the curvatures and fields. In technical terms, what one can consider as physical observable in general relativity is a quantity that is left invariant under the symmetries of the theory, or in the canonical language, that commutes with the constraints. Since one of the constraints is the Hamiltonian, physical quantities do not evolve. Therefore they cannot work as clocks. This created problems [6] for the Page–Wootters proposal. A way out was sought by trying to establish relations not between physical quantities but between mathematical quantities one uses to describe the theory that are not directly measurable (like for instance, the components of the metric at a point). Far from helping, this led to significant technical problems since one ends formulating the theory in terms of unobservable quantities. Ultimately it was shown in model systems that the proposal cannot be used to compute elementary things, for instance quantum probabilities of transition [6].

The observation we have recently made [7] is that the Page–Wootters construction can be rescued by using Rovelli's proposal of "evolving constants of the motion" [20], a concept that can be traced back to DeWitt, Bergmann and Einstein himself. This idea is to introduce genuinely observable physical quantities, i.e. relations between magnitudes as we highlighted above, but that depend on a continuous parameter. If one imagines evolution as changes in such a parameter, one can actually construct the relational description of Page and Wootters and show that it actually leads to the correct quantum probabilities of transition, at least in model systems [7]. The beauty of the complete construction is that the continuous parameter in the evolving constants completely drops out at the end of the day and the formulation remains entirely written in terms of truly observable physical quantities, even in the extreme situations that can develop in physics when quantum gravity effects become important. The calculation of the propagator with this construction, at least in model systems, yields the usual propagator at leading order, but one has corrections to it due to the mechanisms of loss of coherence that we are referring to in this paper.

- **What is a good reference for all this?**

We have an Fqxi essay where these ideas are presented for non-experts [1]. A pedagogical detailed discussion of the fundamental loss of coherence is in [2]. Papers discussing specifically issues of the problem of measurement in quantum mechanics are [8] and [5].

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