The Measurement Problem: Decoherence and Convivial Solipsism

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Abstract The problem of measurement is often considered an inconsistency inside the quantum formalism. Many attempts to solve (or to dissolve) it have been made since the inception of quantum mechanics. The form of these attempts depends on the philosophical position that their authors endorse. I will review some of them and analyze their relevance. The phenomenon of decoherence is often presented as a solution lying inside the pure quantum formalism and not demanding any particular philosophical assumption. Nevertheless, a widely debated question is to decide between two different interpretations. The first one is to consider that the decoherence process has the effect to actually project a superposed state into one of its classically interpretable component, hence doing the same job as the reduction postulate. For the second one, decoherence is only a way to show why no macroscopic superposed state can be observed, so explaining the classical appearance of the macroscopic world, while the quantum entanglement between the system, the apparatus and the environment never disappears. In this case, explaining why only one single definite outcome is observed remains to do. In this paper, I examine the arguments that have been given for and against both interpretations and defend a new position, the “Convivial Solipsism”, according to which the outcome that is observed is relative to the observer, different but in close parallel to the Everett’s interpretation and sharing also some similarities with Rovelli’s relational interpretation and Quantum Bayesianism. I also...
show how “Convivial Solipsism” can help getting a new standpoint about the EPR paradox providing a way out of the seemingly unavoidable non-locality of quantum mechanics.

**Keywords**  Measurement problem · Consciousness · Decoherence · Realism · Entanglement · Non-locality

### 1 Introduction

Quantum mechanics works extremely well to predict the results of measurement. No example of conflict between experiment and prediction has been found yet. So, if you are interested in predictions of experiments and only in predictions of experiments, you can stop here. But if you are wondering just a little bit more about the formalism that is used to make these predictions then you open the door to a series of questions that seem not easy at all to answer. For example, you could be interested in knowing whether quantum formalism is only a list of recipes, the terms it contains having no other meaning than the one directly linked to the results of experiments, or if these terms mean something more, being related in some way to the real world that we seem to live in. You could think that the formalism is nothing else but the simple reflection of your knowledge of the system. You could as well be interested in knowing whether it is possible to give a description of what happens “between” experiments or if this question is meaningless. Trying to answer to only one of these questions leads to examine a whole set of analogous questions that are intertwined into a complex network of relationship. One central question that is at the core of all the others is the measurement problem. Although I don’t share his realist point of view when Bell says [2]:

> “But it is interesting to speculate on the possibility that a future theory will not be intrinsically ambiguous and approximate. Such a theory could not be fundamentally about measurements for that would again imply incompleteness of the system and unanalyzed interventions from the outside. Rather it should again become possible to say of a system not that such and such may be observed but rather that such and such be so.”

because I think, on the contrary, that it is unavoidable that the concept of measurement be deeply rooted inside any quantum theory as its main object, I think that Bell is one of those who have described in the most accurate and explicit way the lacuna of the commonly agreed presentations of the quantum formalism [3]:

> “It remains that the theory is ambiguous in principle, about exactly when and exactly how the collapse occurs, about what is microscopic and what is macroscopic, what quantum and what classical. […] What exactly qualifies some physical systems to play the role of ‘measurer’? Was the wave function of the world waiting to jump for thousands of millions of year until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system … with a PhD?”

The measurement problem lies at the very heart of the conceptual problems of interpretation of quantum mechanics. Depending on the stance they adopt, physicists put up with the difficulty more or less easily. The problem is more acute for those
who endorse a realist position assuming that the wave function (or the state vector) represents the real state of the system than for those, as instrumentalists, who think that the formalism is but a tool allowing us to make predictions about future results of experiments. For physicists like John Bell, who want to maintain the view that physics must describe things as they really are, the problem is so serious that he says [3] he can’t be satisfied with standard quantum mechanics. In this case, quantum mechanics is not considered as complete and must be either completed by hidden variables or modified to welcome a dynamical process allowing for the state reduction. Another possibility is also to admit that the quantum formalism is not universal and that there are “entities” for which it is not applicable. On the contrary, for Bohr and the supporters of the so-called Copenhagen interpretation, quantum mechanics is complete and there is no problem if a correct epistemological distinction between the apparatus and the system is made.\(^1\) Nevertheless, whatever position is adopted, it is not so easy to completely get rid of the problem despite what some authors seem to have claimed.

In this paper, I first state the problem under its most usual form and then I show that many previously proposed solutions are not satisfying. I give a series of puzzling questions to which any serious interpretation should reply and I stress the fact that it is the case for no previous interpretation. I analyze then the decoherence program which has often been understood as providing a solution of the measurement problem using only the standard rules of quantum mechanics. I show that this is not the case. I conclude that, if we want to stay inside the standard quantum formalism it seems impossible to define what a measurement is without any reference to a conscious observer. I present then the “Convivial Solipsism” which acknowledges this fact and I explain how it solves the measurement problem. I also show how Convivial Solipsism can help understanding the EPR paradox in a new way, allowing quantum mechanics to be both complete and local. At last, I argue to say that Convivial Solipsism is giving a global coherent interpretation answering every question of the series of puzzles.

2 The Measurement Problem

2.1 Formulation of the Problem

As is well known, the measurement problem arises from the fact that quantum mechanics contains two postulates for computing the evolution of a system. The first one is the Schrödinger equation:

\[
\frac{i\hbar}{\hbar} \frac{d|\psi\rangle}{dt} = H |\psi\rangle
\]

which is supposed to be used for an isolated system when no measurement is performed on it. The second one is the reduction postulate which says that when a measurement of a certain observable \(P\) is made on a system which is initially in a state that is a superposition of eigenstates of \(P\), \(|\Psi\rangle = \sum c_i |\varphi_i\rangle\), then after the measurement, if the result is \(\lambda_k\), one eigenvalue of \(P\), the state \(|\Psi\rangle\) is projected onto the eigenvector \(|\varphi_k\rangle\) linked to this eigenvalue \(\sum c_i |\varphi_i\rangle \rightarrow |\varphi_k\rangle\) or onto the sub-space of the Hilbert space that is spanned by the eigenvectors linked to \(\lambda_k\), if \(\lambda_k\) is degenerated. These two computations do not lead to the same result. Following

\(^1\) Of course this is an oversimplified presentation of Bohr’s position which will be discussed in Sect. 3.2 with more details.
the notorious analysis given by von Neumann [4], a measurement is an interaction between a system \( S \) in a state \( |\Psi_S\rangle = \sum c_i |\phi_i\rangle \) and an apparatus \( A \) in the initial state \( |A_0\rangle \) through a hamiltonian \( H_{\text{int}} \) operating during a short time. Before they interact, the state of the system-apparatus is the tensorial product:

\[
|\Psi_{SA}\rangle = |\Psi_S\rangle \otimes |A_0\rangle = \sum c_i |\phi_i\rangle \otimes |A_0\rangle
\]  

(1)

After the interaction between the system and the apparatus, the Schrödinger equation which describes a linear and unitary process gives:

\[
|\Psi_{SA}\rangle = \sum c_i |\phi_i\rangle \otimes |A_0\rangle \rightarrow \sum c_i |\phi_i\rangle \otimes |A_i\rangle
\]  

(2)

Where \( |A_i\rangle \) is the state of the apparatus corresponding to the result \( \lambda_i \). Now if the value \( \lambda_k \) is found (let’s suppose that it is not degenerated), the reduction postulate gives:

\[
|\Psi_S\rangle = \sum c_i |\phi_i\rangle \rightarrow |\phi_k\rangle \text{and} |A_0\rangle \rightarrow |A_k\rangle
\]  

(3)

Equation (2) shows that after the interaction, the system and the apparatus are in an entangled state. In particular, this is to be interpreted as if the apparatus was in a state which is a superposition of states linked to different possible results of the measurement.\(^2\) Of course, no such macroscopic superposition has ever been observed. If we add another system (even a cat or a man) to the initial system and the apparatus, it becomes entangled as well with the first two. This is the core of the celebrated Schrödinger’s cat argument [5] and Wigner’s friend problem [6].

It could indeed be tempting to think that quantum mechanics is usable only for sets of systems and that an “easy” interpretation of superposed states is that they represent statistical descriptions of mixtures of systems each one in a definite state corresponding to a classical state. But it is easy to prove that such an interpretation is not valid: a superposed state is not interpretable as a classical description of the probabilistic ignorance about the real definite state in which the system is. Hence, if we consider that quantum mechanics is complete (i.e. it cannot be completed by hidden variables as we will see in Sect. 3.1.2, a quantum measurement cannot be considered as a process simply revealing a pre-existing value.

### 2.2 What is a Measurement?

The conclusion of Sect. 2.1 shows that the problem of the incompatibility between the two descriptions of a measurement cannot be solved easily. The Schrödinger equation describes a linear and unitary process while the reduction postulate is neither linear nor unitary. That means that there is a priori no way we can get a reduction of the state

\(^2\) Actually, the apparatus being in an entangled state with the system has no state by itself strictly speaking since through this entanglement only the system \( S + A \) has a state. So, it is only a convenient way to speak to say that it is in a superposition of \( |A_i\rangle \) The correct formalism in this case is the density matrix that we will describe in the following.
through the Schrödinger equation. That would not be a problem if it was possible to give a clear and not ambiguous definition of what a measurement is. In this case, we would have two well separated situations, a first one when no measurement is made on the system and a second one when a measurement is made. In the first case, we should apply the Schrödinger equation and in the second one, the reduction postulate.

Is it possible to define clearly what a measurement is? What many physicists are looking for is a definition that could be regarded as “strongly objective” in the meaning that d’Espagnat gave to this term [7] (i.e. without any mention to a human observer). Widely accepted by a large majority of physicists who want to believe that it solves all problems, the Copenhagen interpretation, mainly proposed by Bohr, says that a measurement is an interaction between the system and a macroscopic classical apparatus. Is this interpretation strongly objective? In the following, we are going to see that, despite the appearance, it is not the case. We will also present and analyze several other interpretations that have been proposed to solve the measurement problem and will show that they fail.

3 Many Interpretations

Faced to what seems a real inconsistency inside the quantum formalism, physicists have proposed many solutions largely depending on their initial philosophical inclination. A very rough description of the different families of positions is the following:

– A first one is the family of instrumentalist positions which consider that quantum mechanics is nothing but a tool to predict the results of the experiments done by the physicists. Bohr’s position and the Copenhagen interpretation are instrumentalist as we will see. Belonging to the same family, the pragmatist interpretation tries to stick to the practice of the physicists and often takes as basic given facts some features (for example, the unicity of the result of a measurement) that other interpretations want to explain [9–11]. Some pragmatist positions (for example Healey [12]) are nevertheless not instrumentalist but partially realist.

– A second one is the realism (to be more precise, the association of the metaphysical realism, the epistemic realism and the scientific realism) which considers that there is an external reality which exists independently of any observer (metaphysical realism), that this reality is roughly similar to the way it appears to us, that it would be unchanged even if there were no human beings, that it is possible to describe and to understand it (epistemic realism) and that the scientific formalism aims at describing the world as it really is (scientific realism). This was the natural position of the majority of scientists during the nineteenth century and it is in this framework that the standard initial formulation of quantum mechanics was done by Dirac and von Neumann. This was the position of Einstein, Schrödinger, Bell, de Broglie and Bohm.

– A third one is the idealism which gives the primacy to the spirit and considers that what we perceive is nothing but a creation of our mind. Many different sorts of idealism exist depending on the degree to which they accept or refuse the concept.

3 See for example [8] for a typical exposition of this quest.
of reality. The most extreme kind of idealism is the solipsism which denies that there exist something else than one’s own personal mind (as we will see, Convivial Solipsism is not that extreme and allows for the existence of other minds and of something external to the mind). More prudently, the idealism can limit itself to affirm that the only reality we have access to is our perceptions and that postulating every other kind of reality is at best risky. Kant’s transcendental idealism does not deny that there is a reality, the “thing in itself”, but states that there is an unbridgeable gap between the phenomena that we perceive and the noumena that are unknowable.

It is of course out of question to present all the interpretations that have been put forward to try solving the measurement problem. But even for the most recent ones that I want to compare with Convivial Solipsism, I have not enough place here to analyze them in details. This will be done in a forthcoming work. So in this paper, I will just briefly mention for each one the reasons why I find it not satisfying. First I will present solutions that imply modifying the quantum formalism and then I will stay for the remaining part of the paper inside the standard quantum mechanics.

3.1 Modifying Quantum Mechanics

3.1.1 Welcoming Hidden Variables

For several decades, a proof given by von Neumann in 1932 [4] was accepted as showing that hidden variables were impossible. It is now well known that von Neumann’s proof relies on an assumption that is much too demanding. Bell [14] constructed a very simple hidden variables model for one spin 1/2 fully satisfying a more reasonable set of assumptions for a hidden variables theory. According to the Bell, Kochen, Specker theorem a hidden variables theory in agreement with quantum mechanics cannot be noncontextual. We also know that another Bell theorem proves that any theory reproducing the results of quantum mechanics must be non-local. Hence, a successful hidden variables theory must be contextual and non-local. The most famous example of such a theory is the Bohm theory [16,17] in which the measurement problem does not exist.

3.1.2 Modifying Schrödinger Equation

The Schrödinger equation being linear and describing a deterministic and unitary evolution cannot give a probabilistic reduction of the state vector. Hence it is natural to try modifying the Schrödinger equation in a way that allows getting a reduction when a measurement is done but preserving of course the current predictions when

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4 See Mermin [13] for a discussion of it and for a very simple proof of the Bell, Kochen, Specker theorem.

5 The usual presentation of contextuality is given through the observables of a spin 1 particle. The observable \( S^2 \) which is the sum of the square of the components of the spin along any three orthogonal directions is equal to 2. Since the unsquared components have eigenvalues equal to \(-1, 0 \) or \(1\), that implies that one must be equal to 0. It is then possible to show that it is impossible to assign a value to one spin component without deciding which the orthogonal directions are [15].
no measurement is made. The most famous attempt in this direction has been done by Ghirardi, Rimini and Weber (GRW theory) [18] who add stochastic and nonlinear terms in the Schrödinger equation. The wave function is subjected at random times to a spontaneous localization in space and the frequency of this localization increases with the number of constituents of the system. When the parameters of this process are well tuned, this allows macroscopic systems to be well localized without changing the usual quantum predictions for micro systems. Actually this is not exactly true since GRW theory makes some predictions that disagree with the predictions of quantum mechanics even though only in a presently non-testable manner [19].

3.1.3 Are These Modifications Acceptable?

We cannot discuss here in details if the modifications of quantum mechanics through GRW theory or Bohm theory are acceptable or not and what is the price to pay for switching from the standard quantum theory to these other theories. Let’s just say first that building relativistic versions of these theories is difficult even if recent developments seem to indicate that it is possible in both cases. Moreover each one of these theories suffers from some unsatisfactory points. GRW theory explains the reduction through a mechanism that seems truly ad hoc. Bohm theory was initially intended to restore the intuitive representation of the particles and their trajectories whereas quantum mechanics forbids to speak about them. But it appears that the picture that is given by the theory is far from allowing to come back to a simple realism similar to the one we can assume in classical physics. The question of deciding if either of these theories should be accepted is left open. In the following of this paper, I will assume that we fully accept the standard quantum formalism as a framework for the discussion.

3.2 Bohr’s Position and the Copenhagen Interpretation

The Copenhagen interpretation is mainly due to Bohr [9] with major contributions from Heisenberg [10] and Born. Before the article [11] of Einstein, Podolski, Rosen in 1935 [25] (hereafter EPR paper), Bohr’s view was that observing a quantum object involves an uncontrollable physical interaction with a classical measuring device that affects both

6 See [20] for Bohm theory and [21,22] for GRW theory.
7 See [23] for an open discussion between several physicists on the reasons to accept or to reject Bohm theory.
8 Of course, this choice is not neutral for the philosophical discussion and we have to make clear that the conclusions that we will get could be mitigated in the case where either of these theories is proved to escape all the objections that today prevent from considering that it is the “best” theory according to its empirical predictions, to its fruitfulness and to its adequacy with our preexisting philosophical requirements (which is probably the most problematic aspect).
9 See [24] for an extended description of Bohr’s position.
10 Actually, Bohr and Heisenberg were not in total agreement. Heisenberg’s position was considered as too subjective by Bohr.
11 See Sect. 4 for a presentation of the EPR Paradox.
systems. A pictorial representation of this idea was given by Heisenberg in a thought experiment called Heisenberg’s microscope [26]. After the EPR paper, Bohr’s position evolved into a more radical departure from the vision that microscopic systems were classical objects possessing definite properties. He started to say that a measurement is an interaction between the system and a macroscopic classical apparatus and that the property that is measured belongs not to the system itself but to the whole composed of the system plus the apparatus. He even went so far as saying that the very meaning of a property depends on the experimental set up that is used and that speaking about a property of a system without making reference to the apparatus that is used for measuring this property is meaningless. Since a physicist using a macroscopic apparatus for measuring a physical property on a system perfectly knows what he is doing, there is no ambiguity and the reduction postulate must be applied. This mature version of Bohr’s ideas is often considered to eliminate all the problems of interpretation of quantum mechanics. Even if this point of view is perfectly working in practice from an instrumentalist standpoint, it leaves open the question of knowing what a macroscopic apparatus is. Another difficulty with this view is that quantum mechanics is assumed to be universally valid and should be applied to any physical system, whether microscopic or macroscopic. But actually a more careful analysis of Bohr’s position shows nevertheless that what he had in mind was not that the classical behavior of the apparatus was directly linked to its macroscopic aspect but that it was linked to the use that the observer wanted to make of it. Bohr had in mind pragmatic reasons. If the apparatus is used to make an observation on another system, it has a classical behavior [7,24,27]. But if the observer wants to make a measurement on the apparatus through another apparatus, it has a quantum behavior. So, it is clear that the role of a human observer in the definition of the measurement process cannot be avoided and that this definition can hardly be considered as “strongly objective” in the sense that we mentioned in Sect. 2.2.

3.3 Interpretation Involving the Consciousness of the Observer

Faced to the difficulty to avoid mentioning consciousness during the measurement process, some authors considered that even if the quantum formalism has a physical universal validity, the consciousness of the observer lies outside of its scope. As von Neumann says [4]:

“Experience only asserts something like: an observer has made a certain (subjective) perception, but never such as: a certain physical quantity has a certain value.”

“It is inherently entirely correct that the measurement or the related process of the subjective perception is a new entity relative to the physical environment and is not reducible to the latter.”

“But in any case, no matter how far we calculate, […], at some time we must say: and this is perceived by the observer. That is, we must always divide the world into two parts, the one being the observed system, the other the observer.”

Wigner adds [28]:

“When is the measurement completed? We will see that […] the measurement is completed only when we have observed its outcome.”
More precisely, according to their view, a measurement is made only when the consciousness of an observer has an interaction with a system. This interaction between the system and the consciousness of the observer has the physical effect to change the state of the system and to project it according to the reduction postulate. This is the position stated by Wigner [29] and by London and Bauer [30]. As we will see, these authors got a correct intuition about the fact that consciousness cannot be eliminated from the measurement process and that it is impossible to give a strongly objective definition of what a measurement is in quantum mechanics. But from this correct premise they draw a wrong conclusion. Assuming that, although lying outside of the field of the physical entities obeying quantum mechanics, consciousness has nevertheless a physical action on them is altogether shocking and incoherent. In Convivial Solipsism, consciousness plays also an essential role but does not interact with systems in a physical sense.

3.4 Interpretations Considering the Vector States as Relative

I present in the following three interpretations that share the feature that vector states are no more absolute but relative. Of course, the way they are relative and what they are relative to differ from one interpretation to the other. But this is as well an important feature of Convivial Solipsism and I need to clarify the similarities and differences between the way this relativity is used in these interpretations and in Convivial Solipsism.

3.4.1 Everett’s Interpretation

Everett was worried by the measurement problem [31] that he was seeing as a fundamental inconsistency of the standard collapse formulation of the quantum mechanics given by von Neumann. He noticed that in the Copenhagen interpretation of the standard theory, the observer must be treated as an external system and that this prevents the universe to be described as a whole. He proposed [32,33] a relative-state formulation of pure wave mechanics without reduction. In his interpretation, there is no collapse and the universal wave function (observers included) evolves uniquely under the Schrödinger equation. Actually, there are several ways to understand Everett’s interpretation and I will present here only Everett’s own one and the one given by Graham and De Witt [36] usually called the “many-worlds interpretation” that is the way the majority of physicists understand Everett’s interpretation even though it was not supported by Everett. Everett was interested in giving a coherent explanation of the Wigner’s friend problem [6].

Let’s for example, consider the measurement by a friend of mine F of a system S with an apparatus A. Assume that S is a spin half particle in a superposed state along Oz.

$$|\Psi_S⟩ = \alpha |+⟩_z + \beta |−⟩_z$$

(4)

12 In particular there is the so called “many-minds” version [34,35] that I will not analyze here.
A is a Stern and Gerlach apparatus with a magnetic field oriented along Oz and F performs a measurement of the spin of S using A. After the interaction between my friend, the apparatus and the system, the Schrödinger equation gives the final entangled state\(^\text{13}\) for the whole (system + apparatus + friend):

\[
|Ψ_{SAF}\rangle = \alpha |+\rangle_z |↑⟩ |F_+⟩ + \beta |−\rangle_z |↓⟩ |F_−⟩
\]

Where \(|↑⟩\) and \(|↓⟩\) are the states of the apparatus with impact “up” and “down” and \(|F_+⟩\) and \(|F_−⟩\) are the states of consciousness of my friend having seen a result “up” or “down”.

If I include myself in the global state I get:

\[
|Ψ_{SAFO}\rangle = \alpha |+⟩_z |↑⟩ |F_+⟩ |⊗⟩ + \beta |−⟩_z |↓⟩ |F_−⟩ |⊗⟩
\]

Where \(|⊗⟩\) and \(|⊗⟩\) are my personal state after having asked to my friend what she has seen and having received the answer “up” or “down”. Usually, the reduction postulates is used to insure that I will end either in the state \(|⊗⟩\) or in the state \(|⊗⟩\). But if there is no collapse as Everett assumes, it is necessary to explain why I end in a definite state and not in a superposition. For Everett, observers are automatically functioning machines possessing recording devices (memory). The result of a measurement made by an observer is the state of her memory. Everett then makes a crucial distinction between absolute and relative states. For him, subsystems do not possess states that are independent of the states of the remainder of the system. So \(|Ψ_{SAFO}\rangle\) can be considered as absolute because it concerns the whole system, while \(|⊗⟩\) and \(|⊗⟩\) are relative because they concern only a part of the system.

"Let one regard an observer as a subsystem of the composite system: observer + object-system. It is then an inescapable consequence that after the interaction has taken place there will not, generally, exist a single observer state. There will, however, be a superposition of the composite system states, each element of which contains a definite observer state and a definite relative object-system state. Furthermore, as we shall see, each of these relative object system states will be, approximately, the eigenstates of the observation corresponding to the value obtained by the observer which is described by the same element of the superposition. Thus, each element of the resulting superposition describes an observer who perceived a definite and generally different result, and to whom it appears that the object-system state has been transformed into the corresponding eigenstate." [37].

So each relative memory state describes a relative observer with a determinate measurement. \(|⊗⟩\) and \(|⊗⟩\) are then relative memory states of my consciousness having recorded different results. Everett insists on the fact that this in full agreement with our experience because no observer can be aware of the branching when it occurs. Now, an important and often forgotten point of his position is that Everett considers that all elements of a superposition must be regarded as simultaneously existing. That means that it would always be possible in principle to put other branches in evidence through

\(^\text{13}\) In the following, we will often omit the symbol \(⊗\) for the tensorial product.
a measurement that would show interferences between them since the universal state vector remains superposed.

The main difference with the “many-worlds” interpretation of Graham and De Witt [34] is that for them, when a measurement is made, the world splits into several causally isolated worlds and each possible outcome of this measurement appears in some of these worlds in a proportion given by the quantum probability of that outcome. What is interesting is that it would be possible in principle to make a crucial experiment to decide between the two versions through an attempt to detect some interferences between branches, predicted by the first version and forbidden by the second one.

Actually Vaidman [38,39] defends a “many worlds” interpretation which is very close to the initial Everett position. The main difference is that in Everett’s picture, worlds are relative to us and independent of our concepts while Vaidman prefers to define the concept of world relative to our concepts and independent from us, especially for helping discussion about times without observers (far past and far future).

However, all these versions face two problems. The first one is the problem of the preferred basis (see below Sect. 6.3). But that could be solved by adding decoherence to it as we will see later. The second one is recovering the quantum statistics and Born rule in a sequence of measurement records. Attempts for that have been proposed but no general agreement has been reached.14 Moreover it is not very satisfying to deal with so many conscious minds for the same observer, which is the case in all versions.

3.4.2 The Relational Interpretation

The relational interpretation is due to Rovelli who denies that the state of a system is observer-independent and says that a system has a state only relative to some other system [42–44]. Rovelli often calls the other system an “observer” but he stresses that it need be neither human, conscious, nor macroscopic but can be any quantum system: an electron can play the role of an observer relative to another electron. But Rovelli does not explain what a measurement and an observation are. It seems as if he postulated that any interaction between two physical systems (usually described as an entanglement between the two systems) has the consequence that from the point of view of the first one, the state of the second one is reduced (and vice versa). That comes from the fact that he seems to confuse two things: (a) that, following the interaction between S and O, there is a correlation between the state of S and the state of O (if S is in the state $|1\rangle$ then O is in the state $|O_1\rangle$ and if S is in the state $|2\rangle$ then O is in the state $|O_2\rangle$), and (b) that a measurement has been made (which means that S and O are in one unique definite eigenstate):

“The fact that the pointer variable in O has information about S (has measured q) is expressed by the existence of a correlation between the q variable of S and the pointer variable of O. The existence of this correlation is a measurable property of the S-O state” [42].

But this correlation reflects merely the entanglement between the two systems while a measurement implies a reduction to only one of the two possibilities: either $|O_1\rangle|1\rangle$

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14 See for example Wallace [40] who claims having proved the Born rule in this context and Kent [41] who denies that it is the case.
or $|O_2⟩|2⟩$. Assimilating a correlation to a measurement seems difficult to accept. And if it is not the case, one does not see why every interaction between two systems (even microscopic ones) should result in a measurement selecting one of the possible values. So his solution to the measurement problem is not acceptable.

3.4.3 The Quantum Bayesianism: QBism

QBism is mainly supported by Caves, Fuchs, Schack and Mermin [45–48]. QBists think that the primitive concept of experience is the central subject of science. The word “experience” must be understood here as “personal experience”, meaning for each agent what the world has induced in her throughout the course of her life. It is partly an instrumentalist position since, for QBists, quantum mechanics is but a tool allowing any agent to compute her probabilistic expectations for her future experience from the knowledge of the results of her past experience. QBists adopt the subjective interpretation of probability according to which probabilities are representing the degree of belief of an agent and, hence, are particular to that agent. QBism shares with the relational interpretation and Convivial Solipsism the feature that the entities of the formalism (wave functions, probabilities) are relative (to a particular agent for QBism, to a particular physical system for the relational interpretation, to a particular conscious observer for Convivial Solipsism). QBists refuse the idea that the quantum state of a system is an objective property of that system. It is only a tool for assigning a subjective probability to the agent’s future experience. So quantum mechanics does not directly say something about the “external world”. A measurement (in the usual sense) is just a special case of what QBism calls experience and that is any action done by any agent on her external world. A measurement does not reveal a pre-existing state of affairs but creates a result for the agent. The way QBists solve the measurement problem is very simple: they assume that the direct internal awareness of her private experience is the only phenomenon accessible to an agent which she does not model with quantum mechanics and that the agent’s awareness is the result of the experiment. Hence, there is no more ambiguity about when using the reduction postulate which does not say anything about the “real state” of the system that is measured but is nothing else than the updating of the agent’s state assignment on the basis of her experience. In particular, there is no measurement when there is no agent: a Stern and Gerlach apparatus cannot measure by itself the spin of a particle. That is a very important point and we will see that Convivial Solipsism assumes something very similar.

Convivial Solipsism shares some features with QBism, the most important one being the fundamental role that the observer plays in the measurement process and the relinquishment of any absolute description of the world. Now QBism is fuzzy on many aspects and leaves open many important questions whose answers would be necessary if one wants to get a detailed precise picture of what is going on. The first

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15 Rovelli claims nevertheless that the assumption that an observer is merely a physical system having got information (i.e. correlation) on another system lies at the heart of the relational interpretation [23].

16 The subjective interpretation of probability has been mainly developed by de Finetti and Savage. It amounts to say that probabilities are related to an epistemic (hence personal and subjective) uncertainty and represent the degree of belief of an agent for the happening of an event.
one is to clarify what it is that makes “something” an agent. According to QBists, an agent must have experience. Does that mean that an agent must be conscious? That is something that they are reluctant to accept. Nevertheless, they admit that experience and consciousness are difficult to disentangle.\(^\text{17}\) The second one is: how is it possible for an agent to create a result? Where this result does come from? Is it something that can be described by the quantum formalism? QBism seems to take the fact that the agent gets a unique (and classical) result as a basic given fact and does not make any attempt to give an explanation of it. Moreover QBists claim to have no need of decoherence [46]. How is it then possible to understand the fact that no macroscopic superposition is observable?

These points should be made clear in order to be able to get a global coherent picture of the way QBism tries to solve the problems. All the above questions can find some kind of answer if decoherence and consciousness are taken into consideration as is the case in Convivial Solipsism.

4 EPR Paradox and Bell’s Inequalities

It is well known that the initial Einstein, Podolski, Rosen paper [25] was aimed at proving that quantum mechanics is not complete. As Fine puts it [49]:

“In summary, the argument of EPR shows that if interacting systems satisfy separability and locality, then the description of systems provided by state vectors is not complete. This conclusion rests on a common interpretive principle, state vector reduction, and on the Criterion of Reality.”

In Bohm’s formulation [50] of the EPR paradox, a spin zero particle decays with spin conservation into two spin \(1/2\) particles \(U\) and \(V\) in the singlet state which can be written as:

\[
|\psi\rangle = \frac{1}{\sqrt{2}} \left[ |+\rangle_U |-\rangle_V - |-=\rangle_U |+\rangle_V \right]
\]

This state is invariant by rotation so the total spin of the two particles along any axis must be zero. Hence, if a measurement by Alice of the spin of the particle \(U\) along one arbitrary axis \(R\) is “+” then a measurement by Bob of the spin of the particle \(V\) along the same axis will have to give “−”. The important point is that it is not possible to assume the fact that “things are done” when the two particles separate. The spin of \(U\) is determined only after Alice’s measurement on \(U\) and hence, the value of the spin of \(V\) along the same axis is also only determined when the measurement on \(U\) is done, whatever the distance between \(U\) and \(V\) be. So Alice’s measurement of the spin of \(U\) along an axis \(R\) providing the result “+” has the effect of projecting the singlet state vector of the pair into a new state, tensorial product of two pure states corresponding to a definite value of the spin along this axis:

\[
|\psi\rangle = \frac{1}{\sqrt{2}} \left[ |+\rangle_U |-\rangle_V - |-=\rangle_U |+\rangle_V \right] \xrightarrow{\text{becomes}} |+\rangle_R |-\rangle_R
\]

\(^{17}\) Private communication.
V state vector becomes $|−⟩^V_R$ immediately after Alice’s measurement on U having given the result “+”. Hence, this measurement has three effects. It determines the value of the spin of U along the axis R, it separates U and V allowing each of them to possess its own state (which is not the case before because they are entangled) and it determines the value of the spin of V along the axis R. This measurement seems then to have an instantaneous influence at a distance on the state of V.

This conclusion is embarrassing especially for realists who assume that the state vector is representing a real state of the system, since a change in the state vector is, for them, a change in the real state of the system. Hence it seems that locality is violated in some respects even if no mechanical disturbance is involved and even if it can be shown that is not possible to transmit any information through this process.

The EPR argument was only a thought experiment until Bell came and showed [51] that, under a given set of assumptions, certain of the correlations that can be measured between the two systems in an EPR experiment must obey some inequalities that quantum theory violates. That means that quantum theory is inconsistent with the assumptions used to derive the inequalities. Briefly stated, quantum mechanics is incompatible with either realism or locality (or both). Many different variant of Bell’s inequality have been derived. The most usual form tested in experiments is the Bell–Clauser–Horne–Shimony–Holt (BCHSH) inequality [53] and it concerns the polarization of photons. As is well known, it is now widely agreed, after Aspect’s experiments, that the inequalities are violated and that the result given by quantum mechanics is the correct one [54,55]. The usual conclusion is that no theory can respect both realism and locality. That’s true also for any hidden variables theory that must be non-local.

If we summarize, EPR argument shows that either quantum mechanics is not complete or it is not local. Bell’s inequality shows that no local hidden variables theory is acceptable. Hence, non-locality seems unavoidable since either quantum mechanics is complete and hence is not local or it is not complete and should be completed by a non-local hidden variables theory. We will nevertheless see (Sect. 7.4) that Convivial Solipsism allows quantum mechanics to be complete and local even if it is at the price of reinterpreting the formalism in a rather radical way.

5 Summary of the Puzzling Questions

At this stage, many questions are puzzling:

– What is a measurement and when must we use the Schrödinger equation or the reduction postulate for describing the evolution of systems?
– When and why only one of the many possible results of measuring an observable is selected?
– If the measurement does not reveal a preexisting value, how is it possible that this value be created during the measurement?

\[18\] For a very simple proof which is useful for understanding what Bell’s inequalities mean without being involved into useless technical stuff, see Maccone [52].
– Does this value so created belong to the system itself, does it belong to the system and the apparatus, does it concern the external reality and if so, is this reality the same for all observers, or is the value something that concerns merely the observer?
– If even macroscopic systems can become entangled, why don’t we observe macroscopic superpositions?
– How do we know which observable is measured when we use an apparatus? (That is the preferred basis problem, see Sect. 6.3).
– How must we understand the non-locality shown by Bell’s inequalities and is there any instantaneous action at a distance?

Some of the interpretations we have seen above give different answers to some of these questions. But none gives answers to all these questions in a coherent way. We are going to see that decoherence allows to answer the fifth and the sixth questions. Convivial Solipsism (which welcomes the decoherence mechanism) is an attempt to answer all the others and to get a coherent general image.

6 The Decoherence Mechanism

This mechanism finds its origin in a remark from Zeh [56] that no system is really totally isolated. Hence it is necessary to take the environment into account. Then Zurek [57,58] did the final move. The decoherence theory is nothing else than the description of the way to take the interaction between the system, the apparatus and the environment into account inside the quantum formalism. I shall first briefly describe the technical framework (the density matrix formalism) in which the decoherence theory is usually stated. Then I will explain how decoherence works and what it achieves (mainly selecting the preferred basis and explaining why macroscopic superpositions are never seen). I will refute then the realist interpretation of decoherence that pretends that decoherence solve the measurement problem.

6.1 The Density Matrix Formalism

I assume the reader to be familiar with the density matrix formalism. For the sake of simplicity, we will consider a two dimensional Hilbert space 19 with a basis \( |\varphi_1\rangle, |\varphi_2\rangle \). Let \( |\Psi_S\rangle = \alpha |\varphi_1\rangle + \beta |\varphi_2\rangle \) then the density matrix in this basis is:

\[
\rho_S = |\Psi_S\rangle \langle \Psi_S| = \begin{pmatrix} |\alpha|^2 & \alpha \beta^* \\ \alpha^* \beta & |\beta|^2 \end{pmatrix}
\] (9)

If we consider now a statistical mixture E of N systems in the state \( |\varphi_1\rangle \) with probability \( p_1 \) and in the state \( |\varphi_2\rangle \) with probability \( p_2=1-p_1 \), the density matrix is diagonal:

\[19\] Of course, all that will be said here for a two-dimensional Hilbert state is applicable for any other dimensional Hilbert space.
Let’s now consider an ensemble $E$ of $N$ identical systems $S$ each composed of two entangled subsystem $U$ and $V$ in the state $|\Psi_S\rangle = \sum c_{ij} |u_i\rangle |v_j\rangle$. We have $\rho_E = |\Psi_S\rangle \langle \Psi_S|$. Assume now that we are interested only in the ensemble $E_U$ of the subsystems $U$. It is well known that $U$ and $V$ being entangled it is not possible to assign a state vector to $U$ alone. Only the composed system $S$ has a state vector. Now the quantum formalism allows to compute for this ensemble $E_U$ a density matrix from which it is possible to compute the mean value of any observable $A$ and the frequency with which the measurement of $A$ will give each one of its eigenvalues provided that $A$ is acting only in the subspace linked to $U$. The ensemble $E_U$, though without state vector can be described by a density matrix. This density matrix is got by the partial trace of the global density matrix $\rho_E$. This is a general procedure. When one is interested only in a subsystem of a composed global system, when one decides to restrict the measurements to observables that are related only to this subsystem, the density matrix that one must use is the partial trace of the global one. This plays a major role in the decoherence mechanism. One very important conceptual point about this mathematical operation of partial trace has been shown by d’Espagnat [59]. Let’s consider for example the density matrix of an ensemble $E$ composed of $N$ systems $S$ of two spin $1/2$ particles in the singlet state:

$$|\psi\rangle_E = \frac{1}{\sqrt{2}} \left[ |+\rangle_U |\Psi_z\rangle - |\Psi_z\rangle |+\rangle_U \right]$$

(11)

and $\rho_E = |\psi\rangle_E \langle \psi_E|$. The density matrix of the ensemble $E_U$ composed only of the $U$ particles is got form the partial trace of $\rho_E$:

$$\rho_{E_U} = \frac{1}{\sqrt{2}} \left[ |+\rangle_z \langle +|_z + |\Psi_z\rangle \langle \Psi_z| \right]$$

(12)

It has the same form as the density matrix of a mixture of particles $U$ having a spin “+” along $Oz$ for half of them and a spin “−” for the other half. But it would be wrong to consider that it is actually the density matrix of a proper mixture of that kind. Indeed, assuming so (and the same for the $V$ particles) would mean that the ensemble $E$ is composed of a mixture composed for one half, of pairs of one particle $U$ having a spin “+” along $Oz$ and one particle $V$ having a spin “−” along $Oz$ and for the other half of pairs of one particle $U$ having a spin “−” along $Oz$ and one particle $V$ having a spin “+” along $Oz$ (the other combinations are impossible in the singlet state). But such a mixture, let’s call it $E'$, has a density matrix $\rho'_E$ that is different from $\rho_E$ and which would lead to predictions relative to the correlations of measurement of spin along other directions than $Oz$ that would be different from the predictions made from $\rho_E$. For example a measurement of the spin of $U$ and $V$ along $Ox$, would get a probability 0 from $\rho_E$ for finding both spin equal to “+” while this probability would be $1/4$ from $\rho'_E$. This shows that even though the density matrix of a subsystem obtained as the partial trace of the density matrix of a global system has the same form than the density...
matrix of a proper mixture of systems being each in one well defined eigenstate, it is impossible to consider that this density matrix represent a proper mixture. D’Espagnat has called this type of mixture an improper mixture (it is made of systems all in the same state). This point will be important for analyzing what decoherence really achieves because that is precisely because of the illegitimate assimilation of improper mixtures to proper ones that some authors claimed that decoherence solved the measurement problem.

Another important point to notice is that no individual system can have a diagonal density matrix with more than one non null element. Indeed, an individual system is necessarily in a pure state. Now, if this state is $|\Psi_S\rangle = \alpha |\varphi_1\rangle + \beta |\varphi_2\rangle$ in the basis $(|\varphi_1\rangle, |\varphi_2\rangle)$ then the density matrix in this basis is:

$$\rho_S = \begin{pmatrix}
|\alpha|^2 & \alpha \beta^* \\
\alpha^* \beta & |\beta|^2
\end{pmatrix}$$ (13)

Whereas if the state of the system is only one of the vector of the basis (for example $|\varphi_1\rangle$) then the density matrix is:

$$\rho_S = \begin{pmatrix}
1 & 0 \\
0 & 0
\end{pmatrix}$$ (14)

One can see that in neither case the density matrix can be:

$$\rho_S = \begin{pmatrix}
|\alpha|^2 & 0 \\
0 & |\beta|^2
\end{pmatrix}$$ (15)

with $\alpha$ and $\beta$ both not null. So, such a diagonal density matrix, when attached to an individual system, has no physical meaning. It is just a tool for computing probabilities. This will be important in the following to show that the decoherence process applied to an individual system is not sufficient to explain the reduction of the state vector even if it leads to a diagonal density matrix.

### 6.2 The Role of the Environment

Following Zeh’s remark, Zurek [57, 58] proposed the following mechanism to explain the reduction. Let’s take the environment into account in the measurement process and consider a big system composed of the initial measured system plus the apparatus plus the environment.

$$\rho_{SAE} = |\Psi_{SAE}\rangle \langle \Psi_{SAE}|$$ (16)

After the interaction, according to the Schrödinger equation:

$$\Psi_{SAE} = \sum c_i |\varphi_i\rangle |A_0\rangle |E_0\rangle \rightarrow \sum c_i |\varphi_i\rangle |A_i\rangle |E_i\rangle$$ (17)
As previously, we can assume a two dimensional space without loss of generality (and let $c_{1,2} = \alpha, \beta$). In the basis $\{|\varphi_1\rangle |A_1\rangle |E_1\rangle, |\varphi_2\rangle |A_2\rangle |E_2\rangle\}$ we have, similarly to equation (13):

$$\rho_{SAE} = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}$$  \hspace{1cm} (18)

Apparently nothing has been gained! In the basis of the Hilbert space which is the tensorial product of the Hilbert space of the system plus the apparatus plus the environment, the density matrix has exactly the same form as before. But the key point comes from the remark that we cannot perform measurements on all the degrees of freedom of the environment because that would require apparatuses that are totally out of reach. As we have seen, the quantum formalism prescribes in this case that the density matrix of the sub system $S+A$ formed by the initial system and the apparatus is given by the partial trace on the degrees of freedom of the environment of $\rho_{SAE}$ which can be computed as:

$$Tr_E \rho_{SAE} = \rho_{SA} = \begin{pmatrix} |\alpha|^2 & Z\alpha\beta^* \\ Z\alpha^*\beta & |\beta|^2 \end{pmatrix}$$  \hspace{1cm} (19)

where it is possible to show that in general the coefficient $Z(t)$ decreases towards 0 very rapidly. So:

$$\rho_{SA}(t) = \begin{pmatrix} |\alpha|^2 & Z(t)\alpha\beta^* \\ Z(t)\alpha^*\beta & |\beta|^2 \end{pmatrix} \rightarrow \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$  \hspace{1cm} (20)

This density matrix looks like the density matrix of the equation (10) that describes a statistical mixture and no more a pure superposed state. So it seems that each system belonging to the set of systems described by $\rho_{SA}(t)$ has now a definite state corresponding to one of the eigenvectors of the observable that has been measured. This is the reason why many authors (including Zurek in his first papers) thought that the decoherence process allows to explain in an objective way the reduction of the state vector. We analyze in Sect. 6.4 the reasons why this is not correct.

### 6.3 The Preferred Basis

Let’s take the example of a spin 1/2 particle and a Stern and Gerlach apparatus whose magnetic field is oriented along Oz and hence measuring the spin along Oz. The preferred basis is: $\{ |+\rangle_z |\uparrow \rangle, |-\rangle_z |\downarrow \rangle \}$ where $|+\rangle_z$ (resp. $|-\rangle_z$) is the eigenvector of the observable spin along Oz with the eigenvalue $+1/2$ (resp. $-1/2$) and $|\uparrow \rangle$ (resp. $|\downarrow \rangle$) is the state of the apparatus in which the particle has an impact at the top (resp. at the bottom) of the screen. In this basis, the measurement process is described as follows:

The initial state of the particle is $|\Psi_S\rangle = c_+ |+\rangle_z + c_- |-\rangle_z$. The Schrödinger equation gives:
\[ |\Psi_{SA}\rangle = (c_+|+\rangle_z + c_-|-\rangle_z)|A_0\rangle \rightarrow c_+|+\rangle_z |\uparrow\rangle + c_-|-\rangle_z |\downarrow\rangle \]  

(21)

Hence we have a measurement of spin “+” along Oz if we observe an impact at the top of the screen, described by the state \(|\uparrow\rangle\) and “−” if we observe an impact at the bottom of the screen, described by the state \(|\downarrow\rangle\). But assume for example that \(c_+ = -c_- = \frac{1}{\sqrt{2}}\). Then \(|\Psi_S\rangle\) is invariant under rotations and can also be written in the basis using the eigenstates of the spin along Ox:

\[ |\Psi_S\rangle = \frac{1}{\sqrt{2}}|\pm\rangle_x = \frac{1}{\sqrt{2}}|\uparrow\rangle_x - \frac{1}{\sqrt{2}}|\downarrow\rangle_x \]  

(22)

In this case, \(|\Psi_{SA}\rangle\) can be written:

\[ |\Psi_{SA}\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle_x |\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle_x |\downarrow\rangle \]  

(23)

where \(|\uparrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle\) and \(|\downarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle\).

The states \(|\uparrow\rangle\) and \(|\downarrow\rangle\) of the apparatus correspond to superposed impacts on the screen. Of course such states are never observed but nothing in the formalism says that they must be eliminated. Equation (23) is a perfectly legitimate way to write \(|\Psi_{SA}\rangle\) and can be interpreted as leading to a measurement of spin “+” along Ox if we observe a superposed impact \(|\uparrow\rangle\) and “−” if we observe a superposed impact \(|\downarrow\rangle\). What is the reason why the correct description is the one done in the preferred basis? In other terms, why is it impossible to measure the spin along Ox with a Stern and Gerlach apparatus whose magnetic field is oriented along Oz? The quantum formalism has nothing to say about this question.

The decoherence theory explains that the reduced density matrix ends up being diagonal in the basis of eigenvectors of an observable of the apparatus that commutes with the Hamiltonian of interaction between the apparatus and the environment. The observable pointer position is such an observable with eigenvectors \(|\uparrow\rangle\) and \(|\downarrow\rangle\), and the commutation means that it will be a constant of motion of the interaction Hamiltonian so that the interaction with environment will leave it unperturbed. Decoherence hence provides a natural explanation for the selection of the preferred basis.

### 6.4 The Realist Interpretation of Decoherence

This is the position of those [60,61] who want to see decoherence as solving the measurement problem. It consists in considering that:

- first, the transition to the diagonal form given in equation (20) corresponds to an objective process.
- second, this diagonal form must be interpreted as a proper mixture of systems each one being in a definite state of the basis in which the density matrix is diagonal. Hence, the squares of the diagonal coefficients are exactly like classical probabilities.

This interpretation relies on several wrong assumptions [7,27,62–64]. First, the reason why the partial trace leading to the diagonal form can be done is entirely due to the
fact that it is acknowledged that no measurement of the environment is possible for the observer. That means that the final diagonal form of the density matrix is the form it takes for an observer with limited means of measurement. Hence, it is not an objective (without any mention of observer) form. Second, the small non diagonal terms that have been considered as null \( (Z(t) \to 0) \) are actually not rigorously null and can even become again big after a (very) long time. So the diagonal matrix is a perfectly acceptable tool for computing probabilities but it is illegitimate to use it for drawing any conceptual conclusions as if it was objective.

Moreover, regarding this diagonal matrix, it is illegitimate to consider that it is associated with a proper mixture of systems each of them being in a definite state of the basis in which it is diagonal. As we have seen above, it is associated with an improper mixture composed of systems that are all identical. As Bell emphasized [3], the correct interpretation should be that each system is in a state where all the possibilities are simultaneously present. This is the celebrated “and / or” difficulty. Hence it is not correct to interpret the decoherence process as leading to a set of systems each having a definite state in a proportion given by the diagonal coefficients of the matrix.

This is even clearer if we consider the case of an individual system. We noticed that no individual system can have a diagonal density matrix with more than one element not null. So the diagonal density matrix got after the partial trace for an individual system must be understood as a mere tool for computing probabilities of results in case of a measurement but it is illegitimate to use it to infer something on the real state of the system. Moreover, decoherence cannot allow to get rid of the reduction postulate as it is clear from the consideration of a repeated measurement on the same individual system. For all these reasons, the realist interpretation of decoherence is not acceptable and must be replaced by a more modest interpretation that I explain below.

6.5 What Decoherence Brings and Does Not Bring

Solving the measurement problem would mean that, independently of any observer, decoherence has the effect to project the initially superposed state onto one definite state of the basis. We have seen that it is not the case. What is justified to say is that the diagonal form of the density operator can be used to compute the probability of each result in case a measurement with limited means is performed. The reduction postulate says that the probability of finding a specific result is given by the corresponding diagonal element. Now this assumes that it is known what a measurement is whereas nowhere inside the formalism of decoherence this is specified. Decoherence has nothing to say about the reason why a superposed state gives only one result among the many possible ones when a measurement is done. Hence the problem of knowing what a measurement is and when it occurs remains a mystery. The hope to get rid of any mention of observer in the formulation of quantum mechanics is still not fulfilled at all.

So, decoherence explains why we (human observers) cannot observe any macroscopic superposition and why what we see is conform to the classical description of
the world. But after decoherence and before measurement, the underlying reality (if there is any) remains in a superposed and entangled state. It remains to define what a measurement is and to analyze if the reduction postulate is nothing but a convenient and practical way to describe the observations or do correspond to a real physical process.

7 Convivial Solipsism

Of course, the vast majority of physicists considers that the measurement problem should be solved without reference to any observer. But a careful analysis of all the attempts in this direction shows that no interpretation of the non-modified quantum mechanics has been successful yet in giving a convincing solution. If a satisfying strongly objective interpretation is given in the future (however unlikely as it may be) then it will fulfill the hope of these physicists but in the meanwhile it is useful to explore the possibility that including the observer in the measurement process could lead to a coherent solution. That is exactly what Convivial Solipsism is; an attempt to provide a coherent solution at the price of including consciousness. This attempt is not new. Many great physicists insisted on the important role that consciousness plays. We have quoted von Neumann [4] and Wigner [28] but even Planck said [65]:

“I regard consciousness as fundamental. I regard matter as derivative from consciousness. We cannot get behind consciousness. Everything that we talk about, everything that we regard as existing, postulates consciousness.”

Actually it is easy to see that the measurement problem arises in a realist context where one thinks that the state vector is representing the real physical state of the system independently of any observer and hence, such that it is the same for all observers. The astonishment that the two postulates of evolution give different results is natural as soon as it is considered that the two ways of describing the measurement are equally possible and that the two different final state vectors concern the physical state of the system that should be the same in both cases. But if the state vector is considered as relative to each observer and if it is clear that the reduction postulate must be used only when this very observer becomes aware of one result, there is no more problem as we are going to show. As Bitbol says [66]:

“The measurement problem boils down to finding a way to articulate the indefinite chain of relational statements of the quantum theory to the absolute statements that are used in the experimental work. An articulation of this kind can easily be found, provided one realizes that the latter absolute statements are in fact indexical; provided one realizes that these statements are only absolute relative to us […]. At this point one is bound to realize the ineliminability of situatedness from the apparent neutral descriptions of quantum mechanics.”

Convivial Solipsism\(^\text{21}\) draws all the consequences of these ideas in a neokantian perspective and rests on two main assumptions completed by the use of decoherence.

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20 I am indebted to Chris Fuchs for this quotation from Planck inside a newspaper.

21 Convivial Solipsism is a widely modified and extended version of a model initially proposed by d’Espagnat [7,59]. I have first stated it in a 2000 book [67].
7.1 Two Assumptions: The Hanging-Up Mechanism and the Relativity of States

Acknowledging the seeming impossibility to get rid of the concept of observer in the measurement problem, the first assumption states that a measurement is but the awareness of a result by a conscious observer. This cancels the ambiguity about when to use the Schrödinger equation and when to use the reduction postulate. At first sight, that looks like the old proposal of London and Bauer and Wigner. But there is a big difference with their position. They thought that the reduction that occurs during a measurement was a physical process through a real action of the mind on the system. Convivial Solipsism defends a much less shocking position. Let’s remind that at the end of the process of decoherence the reduced density matrix is diagonal in the preferred basis. We insisted on the fact that it does not mean that the measurement problem is solved since this diagonal density matrix is not the density matrix of a proper mixture of systems each one in one state of the preferred basis. The systems remain in a superposed and entangled state and the reduced density matrix is only a tool giving the probabilities for observations. No other physical meaning should be attributed to the reduced density matrix. The diagonal form shows that no interference between the states of the preferred basis is observable. It remains to explain why only one of the different possible outcomes is observed (the famous Bell’s problem “and/or”) and this is precisely what the hanging-up mechanism does. The hanging up mechanism selects one result among the possible ones. That is very similar to the reduction postulate but the difference is that this selection concerns only the consciousness of the observer and does not affect the system itself. The reduction is then a way to describe what appears to the observer and does not concern the “reality” which remains superposed. The reduction is not a physical process but merely the fact that when a conscious mind makes an observation, what it can see is only one of the results described by the diagonal density matrix. So the system remains in an entangled state with the apparatus and the environment but the observer’s mind can only be aware of one result that is selected at random following the Born rule among the possible ones.

Let’s compare with what happens in the initial Everett’s interpretation. There is no reduction (the physical world remains in a superposed state) but the memory of the observer is different according to the branches corresponding to possible results. If $|O_0\rangle$ is the initial state of the observer and $|O_i\rangle$ the $i^{th}$ state of the observer’s memory:

$$
\Psi_{SAEO} = \sum c_i |\psi_i\rangle |A_0\rangle |E_0\rangle |O_0\rangle \rightarrow \sum c_i |\psi_i\rangle |A_i\rangle |E_i\rangle |O_i\rangle
$$

For Everett, each $|O_i\rangle$ corresponds to an experience of the observer having the feeling (or the memory) to have observed the result $|A_i\rangle$.

In Convivial Solipsism, contrarily to what happens in Everett’s interpretation where the observer has as many relative states in which he is aware of one definite result as there are possible results, we assume that the observer is aware of only one result which is selected at random. Of course, the hanging-up mechanism has exactly the same status (it must be postulated and one cannot do without it) and a role similar (but slightly weaker as we will see in Sect. 7.3) than the reduction postulate. But the conditions of its usage are explicitly given, there is no more ambiguity about when
to use it, its meaning is now clear and we are going to give below a pictorial way of understanding it. So, the first assumption is:

“Hanging-up mechanism: A measurement is the awareness of a result by a conscious observer whose consciousness selects at random (according to the Born rule) one branch of the entangled state vector written in the preferred basis and hangs-up to it. Once the consciousness is hung-up to one branch, it will hang-up only to branches that are daughters of this branch for all the following observations.”

Of course that is totally unfaithful to the spirit of Everett who wanted to eliminate the reduction postulate. But it is greatly more economic regarding the number of conscious states of one observer and as soon as we are able to give, first a rule stating when it must be used and second a reason why this hanging-up mechanism occurs, the repugnant aspect\(^{22}\) of the reduction postulate becomes more acceptable. So let’s give a very simplified image. A pictorial way to understand it is to think that among the many possibilities of the superposed states of the brain (however chosen only among those belonging to the preferred basis), only one of them is accessible to the consciousness very similarly to what could happen if, watching to a multi colored picture through one pair of colored glasses, the observer would see the picture colored with the unique same color than the glasses. The physical brain of the observer is in an entangled state but the consciousness of the observer, because of internal filters (in a Kantian spirit) that play the same role than the colored glasses, is able to hang-up to only one of the components of the entangled state. Moreover, imagine that the observer draws one colored pair of glasses at random from an urn full of pairs of glasses of different colors, the color she would think the picture is would be predictable only in a probabilistic way. The branch that is selected is chosen at random following the probabilistic law given by the coefficient \(c_i\) and so the Born rule is respected. So, even if the wave function is never reduced, as in Everett’s interpretation, a great advantage of Convivial Solipsism is that it is not subject to the same problem for recovering the Born rule.

The last part of the hanging-up mechanism guarantees that repeating the same measurement will give again the same result. Consider a spin \(1/2\) particle in a superposed state along \(Oz\).

\[
|\Psi_S\rangle = \alpha |+\rangle_z + \beta |-\rangle_z
\]

(25)

After the interaction with the apparatus and taking the environment into account the global state is:

\[
|\Psi_{SAE}\rangle = \alpha |+\rangle_z |\uparrow\rangle_E + \beta |-\rangle_z |\downarrow\rangle_E
\]

(26)

If we include the state of the observer we get:

\[
|\Psi_{SAEO}\rangle = \alpha |+\rangle_z |\uparrow\rangle_E \tau \rangle |E_+\rangle |\varnothing\rangle + \beta |-\rangle_z |\downarrow\rangle_E |E_-\rangle |\varnothing\rangle
\]

(27)

\(^{22}\) According to some letters, Everett considered Bohr’s approach as “somewhat repugnant” [68].
Beware here to make a difference between the physical brain of the observer and her consciousness. $|\Theta\rangle$ and $|\Theta\rangle$ are physical states of the observer's brain. Now, the hanging-up mechanism says that the consciousness of the observer chooses one branch at random. Let's denote by $\Theta$ the fact to be aware of having seen “+” (resp. by $\Theta$ of having seen “−”). After the hanging-up mechanism, either $\Theta$ or $\Theta$. We must be very clear not to confuse $|\Theta\rangle$ with $\Theta$ and $|\Theta\rangle$ with $\Theta$. $|\Theta\rangle$ and $|\Theta\rangle$ are kets describing the physical states of the observer's brain that enter into the entangled universal state vector. $\Theta$ and $\Theta$ are not state vectors and cannot enter into any linear combination with state vectors. That is the reason why they are not written as kets. They are just representing non physical states of awareness. So, even if the universal entangled wave function is not reduced and remains as written in equation (27), for all subsequent measurements, everything happens for the observer as if the wave function was reduced either to $|\Theta\rangle$ or $|\Theta\rangle$ if her state of awareness is $\Theta$ or $\Theta$ if her state of awareness is $\Theta$. This insures that repeating the same measurement will give the same result.

Now, assume that the observer has seen the result “+”, so her state of awareness is $\Theta$. What happens if she measures an observable which does not commute with the spin along Oz, for example the spin along Ox? Let’s denote with index 1 what is related to the results of the first measurement along Oz and with index 2 what is related to the second measurement along Ox. So her state of awareness after the first measurement is denoted $\Theta_1$. After the second measurement, the final entangled state will be:

$$|\Psi_{SAEO}\rangle = \frac{a}{\sqrt{2}} |\Theta\rangle_1 \left[ |+\rangle_x |\Upsilon\rangle_1 |E_+\rangle_1 |\Theta\rangle_2 + |-\rangle_x |\Upsilon\rangle_1 |E_+\rangle_1 |\Theta\rangle_2 - |+\rangle_x |\Upsilon\rangle_1 |E_+\rangle_1 |\Theta\rangle_2 \right]$$

The hanging-up mechanism says that since we have $\Theta_1$ after the first measurement, the selection for the second measurement must be done among the states of the branch that is correlated $|\Theta\rangle_1$. The only term to consider is then:

$$|+\rangle_x |\Upsilon\rangle_1 |E_+\rangle_1 |\Theta\rangle_2 + |-\rangle_x |\Upsilon\rangle_1 |E_+\rangle_1 |\Theta\rangle_2$$

So her final state of awareness will be either $\Theta_1\Theta_2$ corresponding to a spin “+” along Ox or $\Theta_1\Theta_2$ corresponding to a spin “−” along Ox (each one with a probability 1/2) which is conform to the usual prediction stating that if one performs a measurement of spin along Ox on a particle in a state “+” of spin along Oz, the possible results are “+” and “−” with probability 1/2.

Nevertheless, the physical state of the observer’s brain continues to be superposed and entangled as described in equation (28) with the rest of the universe) even if the observer cannot be conscious of what happens in the other branches (but see Sect. 7.3).
The second assumption is:

"Relativity of states: Any state vector is relative to a given observer and cannot be considered as absolute."

There is no absolute state vector. This is reminiscent of the relational interpretation and QBism.

7.2 Answers to Questions Raised by the Two Assumptions

1. A first question is whether there can be any conflict between different observers hung-up to different branches. The answer is no for, as d’Espagnat [59] puts it:

"Any transfer of information from B to A—for example, any answer made by B to a question asked by A—unavoidably proceeds through physical means. Therefore it necessary takes the form of a measurement made by A on B. And we know that under these conditions A necessarily gets a response (answer) that agrees with his own perception."

For any observer, everything outside her own private consciousness has to be treated as a quantum system obeying quantum mechanics. This is true of course of electrons but also of macroscopic objects and even of other conscious observers. This is quite similar to what happens in the relational interpretation and in QBism. Hence, when an observer, say Alice, speaks with another one, Bob, it is as if Alice was doing a measurement on Bob. Let’s take an example and keep in mind that the state vectors are relative to observers: the measurement of the spin along Oz of an electron in an initial superposed state of spin. Suppose Bob has performed such a measurement on this electron. From Bob’s point of view, a measurement has been made so he knows the value of the spin along Oz of this electron. According to the hanging-up mechanism Bob’s consciousness is hung-up to one of the two possible branches linked with the results “up” or “down”. But from Alice’s point of view, Bob is entangled with the electron, as described by the Schrödinger equation. Now Alice can perform the same measurement on the electron and Alice’s consciousness will be hung-up as well to one of the two branches and will see one value. The crucial point is that this branch includes the state of Bob that is linked to the very same value. So when Alice, hung-up to that branch, speaks with Bob to know what Bob saw, she performs a measurement on Bob and, accordingly to the hanging-up mechanism, she cannot hear Bob saying anything else than the value that she has got herself. Alice will never hear Bob saying that he saw “up” when she saw “down”. No conflict is possible and the intersubjectivity is preserved.

Now, a natural question arises: Is it possible that Bob saw “up” and Alice “down” even if Alice will never know? Actually, this question can only been asked from a meta point of view allowing to speak simultaneously of what Bob and Alice saw. This meta point of view (third person point of view) is like God view, an absolute view assuming that it is meaningful to speak as a meta-observer using absolute independent states. But as Bitbol [69] correctly notices, there is no meta-observer able to witness neutrally what the other observers “really” see, so there is no way to compare what they have seen in the absolute. Bitbol’s remark has been made for the relational interpretation but it applies as well to Convivial Solipsism. This point has also been clearly developed by
Van Fraassen [70] and Brown [71]. Juxtaposing different points of view is not allowed because there is no absolute state.

2. A second (more philosophical) question is: what is the meaning of continuing speaking of the universe if the universe is no more an absolute reality existing outside independently of any observer but is relative to each observer? This question of ontology would indeed be embarrassing if Convivial Solipsism assumed that nothing else than the mind exists and that the universe is totally created by the consciousness of each observer. That would amount to coming back to a pure idealist position which is not what Convivial Solipsism maintains. Convivial Solipsism is situated in a neo-Kantian framework and assumes that there is “something” else than consciousness, something that (according to the famous Wittgenstein’s sentence) it is not appropriate to talk of. This is close to what Kant calls “thing in itself” or “noumenal world”. Consciousness and this “something” give rise to what each observer thinks it is her reality, following Putnam’s famous statement “the mind and the world jointly make up the mind and the world”. So perception is not a passive affair: perceiving is not simply witnessing what is in front of us but is creating (independently for each us) what we perceive through a co-construction from the world and the mind. The hanging-up mechanism takes part in this co-construction and helps (very partially) understanding it through the selection it does. But a detailed description of what happens in the whole process of perception is indeed out of reach. In this respect, Convivial Solipsism is close to QBism since it considers also that an observation does not reveal a preexisting state of affair but is a creation for an individual observer. But where QBism is dumb about how this creation can happen, Convivial Solipsism explains that each conscious observer builds her own world of which she is aware by selecting one possible results through the hanging-up mechanism from her universal entangled state vector of which she cannot be aware.

That is a sort of solipsism because the consciousness of each observer is located inside its own branch of its own relative universal state vector independently of the others. But that is not a true solipsism as it welcomes both others minds and an external stuff that is independent of the mind and shared with all the other minds even if nothing can be said about it. It is rather an extension of Kant transcendental idealism. Now, it is convivial since no conflict is possible: the hanging-up mechanism for each observer prevents any possibility to notice a divergence between the perceptions of two different observers.

There is another striking consequence which is a strange answer to the famous phrase of Einstein: God does not play dice. Einstein was right, God does not play dice but each of us does! This is so because the random aspect of the quantum predictions comes, not from the fact that the physical systems change at random (the dynamic

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23 I will let here the concept of consciousness unanalyzed and take it as a basic given fact. Even if a proper characterization of consciousness is still an open subject in cognitive sciences, it is not the place here to dive into these problems.

24 Actually the ontology of Convivial Solipsism and the co-construction of the mind and the world are slightly more sophisticated and will be described in more details in a forthcoming more philosophically inclined paper. A sketch of it has been given in my book [67]. The simplified version given here is however faithful enough in the context of this paper to not alter the fundamental underlying idea.
of the Universe, even if relative, is fully deterministic) but from the random way our consciousness chooses the branch to which it hangs-up!

7.3 The Hanging-Up Mechanism Reformulated and the Contextuality of Quantum Mechanics

Now there is a subtlety that I have passed over in the way I presented the hanging-up mechanism above. The correct way to understand the hanging-up mechanism is a little bit more complex than equation (27) could let think, if both decoherence and the relativity of states are taken into account. Let’s start again from equation (26): \( |\Psi_{SAE} \rangle = \alpha |+_z \rangle |\uparrow \rangle |E_+ \rangle + \beta |-_z \rangle |\downarrow \rangle |E_- \rangle \). This state is the relative (to the observer) state of entanglement between the system, the apparatus and the environment after the interaction between them, written in the preferred basis selected through the Hamiltonian of interaction between the apparatus and the environment. By using the hanging-up mechanism directly applied to equation (27): \( |\Psi_{SAEO} \rangle = \alpha |+_z \rangle |\uparrow \rangle |\bigotimes \rangle + \beta |-_z \rangle |\downarrow \rangle |\bigotimes \rangle \), and concluding directly that either \( \tilde{\omega} \) or \( \tilde{\omega} \), we have bypassed the decoherence process. We have used the hanging-up mechanism exactly like the reduction postulate was used in the measurement theory before decoherence. It is as if we had started from \( |\Psi_{SA} \rangle = \alpha |+_z \rangle |\uparrow \rangle + \beta |-_z \rangle |\downarrow \rangle \) and get the entangled state with the observer \( |\Psi_{SAO} \rangle = \alpha |+_z \rangle |\bigotimes \rangle + \beta |-_z \rangle |\bigotimes \rangle \) to conclude that the consciousness of the observer hangs-up to one of the branch and becomes either \( \tilde{\omega} \) or \( \tilde{\omega} \). No use of the environment has really been made in this presentation. The fact that we got a correct conclusion is only the reflection of the fact that in general, the reduction postulate can be considered as a shortcut to the decoherence processes, giving correct results provided the state vector is written in the preferred basis considered as already known (which is the case for empirical reasons when we use an apparatus built for measuring a specific observable). Now this is not strictly correct and in particular this has a consequence that we want to avoid: it cancels any possibility to observe later (even in principle) the interferences coming from the fact that the universal state vector remains superposed. This is precisely what led to discard the many-worlds interpretation for the benefit of the initial Everett’s version.

The correct way to describe the hanging-up mechanism is the following. We start from equation (26) which is the state vector that the observer can assign to the universe after the interaction. Then a choice has to be made about what kind of future measurements will not be performed. This choice can come either from physical limits (compulsory for the observer, such for example the physical impossibility to use an apparatus bigger that the universe) or from a deliberate choice of the observer. Then, a partial trace of the density matrix \( \rho_{SAE} = |\Psi_{SAE} \rangle \langle \Psi_{SAE} | \) on the degree of liberty that will not be observed must be done to get a reduced density matrix which describes the (still entangled) universe that is accessible to observation. This is at this step that the usual decoherence process gives a diagonal density matrix when all the degrees of freedom of the environment are neglected. Now the hanging-up mechanism says that the consciousness of the observer hangs-up to one of the states of the preferred basis.
In the example we used, under the assumption that we do not observe the environment, that leads to exactly the same result than the simplified presentation. Now, if we change what it is possible to observe in principle, we will trace off differently and will get a different reduced density matrix. The consciousness of the observer will then still hang-up to one of the states of the preferred basis but the new density matrix will not mandatorily be diagonal and some interferences could be put in evidence (at least in principle). That means that all the components of the universal entangled state vector are remaining present (as it is the case in the initial version of Everett’s interpretation) and that what it is possible to put in evidence (interferences or not) depends on what is considered as unobservable for the observer. In the vast majority of cases, this second formulation of the hanging-up mechanism is equivalent to the first one. Nevertheless, the second formulation has the advantage to avoiding cutting branches as if once an observation has been made by an observer, the world relative to this observer was no more in a superposed entangled state.25

Bohr’s claim according to which the value of an observable belongs not to the system but to the whole composed of the system plus the apparatus becomes now easy to understand and even obvious.26 Through the hanging-up mechanism the value that is measured is not something objective attached to the system but is only the result of the fact that the consciousness of the observer hangs-up to one of the possible branches of the entangled state vector written in the preferred basis which, in turn, can be defined only when the apparatus and its interaction with the environment have been chosen. Therefore the very concept of an objective value attached only to a system independently of any apparatus is meaningless. It is even clearer if we remember how this value is obtained. What decoherence and the hanging-up mechanism say is that the observer’s consciousness can only be aware of one of the branches written in the preferred basis. But actually, what the observer’s consciousness is aware of is only the macroscopic state of the apparatus because this is what she sees during a measurement (the microscopic system is of course not directly observable). Hence, the value attributed to the observable of the system is only a deduction made by the observer according to the following reasoning: (a) I see this macroscopic state of the apparatus, (b) this state of the apparatus is correlated to this eigenstate of the microsystem, (c) hence, the microsystem is in this eigenstate, (d) so the observable has the eigenvalue associated to this eigenstate. This reasoning is possible only if the observer has gone through all the process of decoherence and hanging-up which is not possible without an apparatus. From the point of view of Convivial Solipsism, Bohr’s claim should even be extended to: the value of an observable belongs not to the system but to the whole composed of the system plus the apparatus plus the observer.

25 See Lockwood [36] or Vaidman [72] for gedanken experiments allowing to distinguish between theories with collapse and without.

26 Of course, I do not pretend that Bohr had Convivial Solipsism in mind when he said that. His claim was a useful assumption helping him to fight against the EPR argument. Convivial Solipsism allows to understand why Bohr was right although he probably would not have liked it!
7.4 EPR and Non Locality

As Fine says [49]:

“Of course it may also be possible to break the EPR argument for the dilemma plausibly by questioning some of its other assumptions […]. That might free up the remaining option, to regard the theory as both local and complete. Perhaps a well-developed version of the Everett Interpretation would come to occupy this branch of the interpretive tree.”

Convivial Solipsism could be regarded as this kind of version of Everett’s interpretation even though the hanging-up mechanism needs to be added. As explained in Sect. 4, the EPR paradox comes from the assumption that when Alice and Bob do their measurement, each one on one particle, the result of their measurement is assumed to be valid instantaneously for any other observer. In case of an initial singlet state, when Alice finds the value “up” on the first particle, it is assumed that this value is “down” for the second particle immediately for herself and for Bob. The consequence is that it seems that at the very moment when Alice does her measurement, everything is determined both for herself and Bob. Indeed when she asks Bob, later, which value he found on his particle, she will hear “down” and this is true even if Bob’s measurement and Alice’s measurement are space-like separated. So it seems that the very fact that Alice found “up”, determined instantaneously the value “down” for Bob’s particle (and vice versa, which is even more paradoxical, since if the two measurements are space-like separated, no one can be said to be before the other in an absolute way).

But to be more precise, the reasoning goes like that: when Alice asks Bob which result he got and hears “down”, she deduces in retrospect that the value has been “down” as soon as Bob did his measurement. If their measurements are space-like separated this implies a spooky instantaneous action at a distance. This conclusion relies on the assumption that state vectors are representing objective physical descriptions of systems and that they are changed by measurements. But this is not true anymore in Convivial Solipsism. Indeed, it is only when Alice asks Bob (in the future of her measurement) which value he found that she performs a measurement on Bob and learns what result he got on his particle. According to the hanging-up mechanism, she will necessarily hear “down” because she is hung-up to the branch which is linked to this result in agreement with her own measurement on the first particle. Similarly if she performs a measurement on Bob’s particle, she will find the same “down” value.

But, and that is the important point, in Convivial Solipsism that does not mean that the second particle “was already before” in the state “down”. Indeed, the hanging-up mechanism is nothing else than the fact that Alice’s consciousness hangs-up to the branch corresponding to the value “up” for her particle and “down” for Bob’s particle, while the state vectors of the systems remain unchanged. These posterior measurements done by Alice (on Bob and his particle) are of course time-like separated with Alice’s first measurement and moreover, they do not affect physically the state of Bob’s particle. There is no more “spooky instantaneous action at a distance”.

Rovelli’s relational interpretation gives a similar explanation. The solution for QBists is even simpler. They reject the fact that a probability 1 assignment needs to be backed by an objective fact [48]. Hence, the famous reasoning made by EPR relative to this “element of reality” which can be predicted with probability 1 does
not follow anymore. I am not convinced by this argument because I think that their position about probability 1 raises philosophical problems that should be addressed more carefully. But since state vectors are relative to each agent, the explanation I give above works also for QBism.

8 In Summary

Convivial Solipsism gives satisfying answers to all the questions raised in Sect. 6. Of course, the picture it offers can seem a little weird since it means abandoning the idea of an absolute external reality which is the same for everybody. It forbids also considering as meaningful usual sentences that compare the private experience of observers. But abandoning simultaneity was already something shocking for many scientists at the beginning of the twentieth century even though we are all accustomed to it now.

It is now possible to understand the appeal of many interpretations that have been previously proposed even if no one succeeded in providing a coherent global answer to all the questions. This appeal comes from the fact that they all share a part of the whole story:

– The Copenhagen interpretation correctly stressed the fundamental role of the experiment and the contextual aspect of the measurement but failed to identify clearly the role of the observer.
– Wigner, London and Bauer correctly noticed that it is impossible to give a coherent interpretation of quantum mechanics without consciousness. But they wanted it to play a role that was not coherent.
– Everett in the initial version is close to a coherent picture but, even if it would be unfair to blame him for that, his interpretation needs to be complemented by decoherence. Moreover, the unclear aspect of this huge multiplication of states of consciousness of the observer and the difficulty to give any meaning to probabilities and to recover the Born rule are not satisfying.
– The relational interpretation shares with QBism and Convivial Solipsism the concept of relative states. But the way it deals with measurement is unacceptable.
– QBism, conceived as an instrumentalist interpretation has the merit to clearly state when the reduction postulate must be used. But, it raises many questions left unanswered and without any mention to decoherence, it is unable to explain the classical appearance of the world.

Convivial Solipsism allows answering coherently the main questions that have been raised at the beginning of this paper. Of course, we must recognize that the image it gives is very unfamiliar. But, isn’t it the case that quantum mechanics has already accustomed us to very strange things?

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