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Objectivity in Perspective: Relationism in the Interpretation of Quantum Mechanics

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Abstract Pekka Lahti is a prominent exponent of the renaissance of foundational studies in quantum mechanics that has taken place during the last few decades. Among other things, he and coworkers have drawn renewed attention to, and have analyzed with fresh mathematical rigor, the threat of inconsistency at the basis of quantum theory: ordinary measurement interactions, described within the mathematical formalism by Schrödinger-type equations of motion, seem to be unable to lead to the occurrence of definite measurement outcomes, whereas the same formalism is interpreted in terms of probabilities of precisely such definite outcomes. Of course, it is essential here to be explicit about how definite measurement results (or definite properties in general) should be represented in the formalism. To this end Lahti et al. have introduced their *objectification requirement* that says that a system can be taken to possess a definite property if it is *certain* (in the sense of probability 1) that this property will be found upon measurement. As they have gone on to demonstrate, this requirement entails that in general definite outcomes cannot arise in unitary measuring processes.

In this paper we investigate whether it is possible to escape from this deadlock. As we shall argue, there is a way out in which the objectification requirement is fully maintained. The key idea is to adapt the notion of objectivity itself, by introducing *relational* or *perspectival* properties. It seems that such a "relational perspective" offers prospects of overcoming some of the long-standing problems in the interpretation of quantum mechanics.

Keywords Objectification · Perspectivalism · Relational quantum mechanics · Locality · Realism

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1 Objectification

The last couple of decades have seen a renewed interest in foundational problems in quantum mechanics; indeed, important parts of present-day cutting edge research in physics owe their existence to this renaissance of foundational studies. The brunt of the revival may be situated in the 1980s and was stimulated by a number of important and timely conferences. Foremost among these were the Joensuu meetings on the Foundations of Modern Physics [1–3] organized by Pekka Lahti. They, together with the impressive monograph *The Quantum Theory of Measurement* by Busch, Lahti and Mittelstaedt [4] defined the field and its problems to a considerable extent and set the agenda for further research.

In *The Quantum Theory of Measurement* the authors review the measurement problem, and the interpretation of quantum mechanics in general, on a new level of logical and mathematical rigor. A central theme of their book is the problem of "objectification": how does quantum theory deal with definite, objective, physical states of affairs in the face of the ubiquity, on the theoretical level, of entangled states of the Schrödinger cat type? On the basis of experience we require that successful measurements lead to definite results, so that after the measurement a "pointer observable" belonging to the measuring device possesses one unique and objective value. Is the occurrence of such definite results compatible with the fact that the state of object plus device after the measurement is generally entangled? In order to answer this question we obviously need to know how definite properties are to be represented in the formalism. Here Busch, Lahti and Mittelstaedt propose their *objectification requirement*: a property of a system is definite and objective if and only if the system's quantum state is a mixture, *in the ignorance sense*, of eigenstates of the observable corresponding to the property in question [4, p. 21]. In such a mixture, in which the presence of different pure states as components reflects our lack of knowledge about which one of these states actually obtains, there can evidently never be any effect of interference between the components.

Now consider a measurement with an arbitrary initial object state. As already noted, after such an interaction (described by unitary evolution) the final state of the apparatus and the object will be entangled, which expresses the correlation brought about between object and apparatus. Now, as Busch, Lahti and Mittelstaedt argue, if there exists a specific pointer observable of the apparatus such that no interference whatsoever can ever be found between different pointer eigenstates, this pointer observable must be *classical*, i.e. it must commute with all other apparatus observables. But then an inconsistency arises [4, pp. 85–86]: If the pointer observable is classical, it will also commute with the Hamiltonian generating the interaction, so that it cannot change during this interaction. In other words, such a classical "pointer observable" will not be able to correlate to any property of the object system; it cannot be a pointer observable at all!

This no-go result reinforces the general result that mixed states derived from entangled states by the technique of partial tracing (so-called *improper mixtures*) are different from ignorance mixtures over pure states (*proper mixtures*). One could attempt to argue nevertheless for an observational equivalence of entangled states and such proper mixtures. This strategy would have to be based on the existence of superselection rules expressing classicality, but then the just-mentioned no-go result implies a conflict with the core idea of measurement, namely the possibility of establishing correlations between a measuring device and an object.

It therefore follows that unitary measurement dynamics cannot lead to objective pointer properties if this means that the final state must be a mixture in the sense of the objectification requirement (or a state equivalent to such a mixture). As Busch, Lahti and Mittelstaedt discuss [4, Chap. IV], one may respond to this situation in a variety of ways. One may decide to opt for a hidden variable model, so that definiteness of properties of physical systems is built in from the very start; this of course means renouncing the idea that quantum mechanics may be a fundamental and complete theory. Alternatively, one may assume that the Schrödinger dynamics should be modified, for example by assuming the occurrence of collapses in addition to the unitary evolution. Collapses destroy the coherence between the terms in a superposition, so this option implies empirical differences, in principle, with unitary quantum mechanics—a rather unpromising prospect in view of the ever-increasing empirical evidence in favor of the existence of even macroscopic entanglement (see, e.g., [5] and the references contained therein to a sample of recent experimental work).

A third way to go is to see whether it is possible to stay completely within the formalism of unitary quantum mechanics and nevertheless accommodate definite measurement results (and definite properties in general). From the foregoing it is clear that this strategy can only work if the objectification requirement in the exact form mentioned above is dropped. It is this response to the objectification problem that we shall now explore in some more detail. As we shall argue, the objectification requirement can consistently be maintained; but the price to pay is that the definite properties satisfying this requirement must be assumed to have a *relational* character.

2 A Different Type of Objectivity

The core of the objectification requirement is the idea that a system can be concluded to possesses a certain property if a yes-no measurement of that property leads to a positive answer with certainty, i.e. with probability 1 [4, p. 21]. Of course, we are speaking of ideal measurements here, non-intrusive and not subject to inaccuracy. It is also assumed that all possible properties correspond to quantum mechanical observables. With these provisos the idea behind the objectification requirement appears eminently reasonable. It might perhaps be objected that there is an operationalist flavor to it; but this would be off target, since there is no demand here that the measurements in question are feasible in actual practice—the requirement is about what the formalism predicts for the expectation values of theoretically defined observables. Moreover, the requirement is a *criterion* for testing the presence of objective properties rather than a verificationist *definition* of properties.

Another type of doubt might arise as follows. Consider the following completely classical situation. I know that a die will be cast in another room, and I also know that my friend, who is in that room and who is a perfect observer, will be watching the outcome closely. After some time I shall be sure that the experiment is over and that my friend will have observed a definite result. Still, I possess no certainty about the outcome: if I know that the die is fair I can express this knowledge by assigning a probability of $1/6$ to all possible situations (consisting of a particular outcome plus my friend having noted that outcome). So it seems that probability 1 and objectivity of possessed properties do not necessarily go hand in hand.

This argument does not yield an objection to the objectification requirement, however—at least not in the context of classical physics. It is precisely because of this type of situation that the requirement was formulated in terms of *ignorance mixtures*. Indeed, because I stand outside the room in which the experiment takes place, I happen to be blocked from direct access to observables pertaining to what is going on inside, so that I remain ignorant about the actual situation. My probability assignments of $1/6$ represent this ignorance. But there exist other observables than the ones I have direct access to that do lead to a definite result with probability 1, given the condition of the die after the roll. These are precisely the observables that my friend, inside the room, is measuring. According to classical physics nothing will change in the state of the room or the die when I make my way in cautiously enough and take cognizance of the outcome—it is only my knowledge that then changes. In other words, the objectification requirement does not need to refer only to the information that is actually available to the outside observer—one may also appeal to knowledge the observer could obtain without disturbing the system.

Within the framework of classical physical ideas the conclusion that both for me and my friend the same properties of the die are definite is consequently perfectly reasonable. Still, this conclusion depends on assumptions that cannot pretend to be valid *a priori*, but depend on the applicable physics. Even if it is granted that if I enter the room and look at the die I shall find a definite outcome, and that my friend will tell me that this outcome was there all along, this does not compel me logically to accept that this property is also objective for me now, standing outside and not performing any measurement. At least by way of a thought experiment I could contemplate the conceptual possibility that *for me* the situation in the room is really undecided, objectively "hovering between" the different outcomes; or as being in a state that should not be described in terms of outcomes at all. Admittedly this suggestion seems rather weird, in particular when we take into account the situation of my friend who is inside the room. It should be acknowledged that my friend at a certain point in time becomes aware of a definite outcome, and is not undecidedly hovering between possibilities at all. Is this not a direct refutation of the hypothesis according to which things in the room are undecided?

No such refutation results if we complicate our thought experiment further. Assume, at this point just for argument's sake, that we are going to describe the situation in and outside the room not with the usual physical properties that characterize objects as they are in themselves, but rather in terms of *relational* properties. That is, instead of saying that the die has landed on a particular face *tout court*, we are thinking of the possibility that this is the case *with respect to* my friend who has watched the roll of the die. And instead of simply saying that the room and its contents do not possess a property corresponding to a definite outcome, we are now going to say that this is so with respect to me as outside observer who has not interacted with what is inside. With this relativization manoeuvre logical contradiction can be avoided: "there is a definite outcome" could be true for the inside observer, "there is no definite outcome" could be true for the outside observer, whereas a contradiction would require both the presence and absence of definiteness for *one and the same* observer. In this scenario I as an outside observer could admit that *for my friend* the roll of the die has ended in some definite outcome, while at the same time maintaining that *for me* the state of die plus friend is completely different, not describable as an ignorance mixture of definite outcomes at all. The objectification that has taken place for my friend is in this case not represented by an ignorance mixture over states with respect to me, but by an ignorance mixture of the *states for my friend* that I consider possible (of course, since I am shut off from the experiment, I do not know what my friend has seen).

In the context of classical physics this proposal would boil down to accepting the objectification requirement in an implausibly strong form, namely that if I cannot *actually* make a prediction with probability 1 about the presence of a property, this property is not there. We have already pointed out that this version of the requirement is unduly strict, and the formulation of the requirement in [4] indeed allowed that such an impossibility of actually making certain predictions could be due to mere ignorance, i.e. an ontologically insignificant lack of knowledge about the real situation.

Going this way in the case of our example would lead to a much more complicated description than the usual one. Although it is true that such a perspectival description could be consistently maintained even within the context of classical physics, there is no physical reason to actually do so—as already emphasized, classical physical theory says that it makes no difference for the room if I enter and make (perfectly gentle, ideal) observations. The description available to my friend can therefore be considered valid for me too. It would complicate matters enormously if all physical laws in such cases had to be reformulated in terms of relational properties, without there being any compensation in the way of better or more predictions. The only motivation to engage in such a move would be philosophical, for example a desire to indulge in skeptical or verificationist predilections.

This is not to say that relational properties have no place at all in classical physics. The obvious counterexample are the length and time determinations of special relativity, which vary with the inertial frame of reference from which they are made. In fact, awareness that these and similar instances of relational properties already occur in classical physics may help to make our later introduction of perspectivalism in quantum theory more palatable. Still, there is a difference between these well-known cases of perspectivalism and the one considered in our discussion of the gambling experiment. In the latter case the perspective decided whether or not the die had landed on a definite face *at all*; whereas the different descriptions given from different frames in special relativity pertain to different numerical values characterizing a situation that is definite as judged from all frames. In the case of the Lorentz contraction, for example, all observers agree that a moving rod possesses a definite length; but they differ on the *value* to be ascribed to this length. Likewise, in relativity observers may disagree about the sizes of the faces of our die and its distance to other objects, but not about whether the faces have sizes at all or about whether the die has landed—or will land—on a definite face at all. The perspectivalism considered above, in the discussion of what is going on inside the room, is therefore really thoroughgoing, of a more dramatic kind than classical perspectivalism. No wonder that the philosophical and epistemological motivations that we mentioned do not suffice to justify the introduction of this kind of perspectivalism in classical physical theory.

But in quantum mechanics the situation becomes different. Think back of the von Neumann measurement scheme, applied to a situation like the above die experiment. The quantum equations of motion tell us that after the conclusion of the measurement interaction the state of my friend plus die will be given by a linear superposition of terms each of which will be a product of a die state with a definite face-up and a friend state representing awareness of that same definite face. Also experience seems to support the ascription of this superposed state: as we have pointed out before, experiments on so-called Schrödinger cat states definitely indicate that superpositions are needed to do justice to the experimental facts [5]. Accordingly, if I, standing outside the room, wish to make predictions about the results of measurements on the room I had better use the full superposition. In particular, if I am going to measure the projection operator $|\Psi\rangle\langle\Psi|$ (where $|\Psi\rangle$ stands for the superposed state of the room and its contents), the formalism tells me that I shall find the result "1" with certainty. The objectification requirement thus leads me to consider the corresponding physical property as objectively belonging to the room. Now, experience also tells me that during the experiment my friend becomes aware of exactly one result; for him the process certainly ends with a definite die property. Furthermore, my friend can predict with certainty, after having noted the face the die has landed on, what subsequent looks at the die will show. Therefore, application of the objectification requirement in his case will lead to the attribution of a definite-face state to the die. I, on the other hand, can only derive a mixed state for the die from my superposition for the total room, and well-known arguments forbid me to think that this mixture is an ontologically insignificant ignorance mixture (indeed, if the die actually were in one of the component states of the mixture, the total system would have to be a mixture as well, which conflicts with the assumption that the total state is a superposition).

In other words, quantum mechanics makes it physically plausible to ascribe more than one state to the same physical system. The contradiction that looms can be avoided if we drop the implicit assumption that only *one* state can belong to any object; in other words, if we decide to assign relational or perspectival states, i.e. states of a physical system A *from the perspective* of a physical system B. This manoeuvre creates room for the possibility that the state and physical properties of a system A are different from different perspectives. Consequently, a reconciliation between the unitary evolution that takes place during a quantum measurement and the occurrence of definite outcomes is perhaps no longer out of the question: the properties associated with the superposition and the definite outcomes, respectively, could relate to two different perspectives.

The significant difference between the classical and the quantum cases is that in the latter there are *physical*, *empirical* reasons for investigating the viability of working with relational properties of this drastic kind. By contrast, in the classical case physics favors the simpler picture of monadic (i.e. non-relational) states and properties.

3 A Quantum Scheme for Attributing Perspectival States

The foregoing sections offered a motivation for introducing perspectival states, but this should evidently be supplemented by a more precise account that makes it clear what these new states are and in what way they relate to the standard formalism of quantum mechanics. As it turns out, proposals are already available in the literature; in particular, a recent relational version of the modal interpretation [6] captures the above intuitions very well. There are also other—though similar—proposals in the literature [7–10], see also [11, 12], with which we should compare. But let us first reformulate the ideas from [6] for our present purposes.

Our point of departure is the standard Hilbert space formalism of quantum mechanics with only unitary time evolution (as governed by equations of motion of the Schrödinger-type). We assume the universal validity of quantum mechanics, so there is no division of the world in a classical and a quantum part. Within this framework it is not problematic, in principle, to speak about the quantum state of the whole universe; we assume this state to be a pure vector state $|\Psi\rangle$.

Our task is now to assign states to smaller systems S, components of the whole universe U. These states will in general be density operators, i.e., positive semi-definite and unit-trace Hermitian operators acting on the Hilbert space of S: ρ^S_R. The upper and lower indices attached to ρ anticipate that in our approach the state of a physical system S needs the specification of another system, the "reference system" R, with respect to which the state is defined: ρ^S_R is the state of S with respect to R. As explained in the previous section, we wish to create room for the possibility that one and the same system, at one and the same instant of time, has different states with respect to different reference systems.

An important special case is the one in which R coincides with S: the state of S with respect to itself. This state we define as one of the projectors occurring in the spectral decomposition of the reduced density operator of S in the standard formalism, i.e. the density operator that is obtained for S by partial tracing from $|\Psi\rangle\langle\Psi|$. In other words, ρ^S_S follows from $|\Psi\rangle\langle\Psi|$ by "tracing out" over all degrees of freedom not pertaining to S. If there is no degeneracy, this state will be a one-dimensional projector

$$\rho^S_S = |\psi_S\rangle\langle\psi_S|, \tag{1}$$

or equivalently a vector state $|\psi_S\rangle$. In accordance with the ideas of modal interpretations [13–17], we posit that *which* projector from the spectral decomposition of S's reduced density operator is ρ^S_S is not fixed by quantum mechanics; the theory only specifies probabilities (namely, the usual Born probabilities) for the various possibilities. Also in accordance with modal ideas is that we assume this state ρ^S_S, the "state of S with respect to itself", to codify the physical properties S actually has (i.e. the quantities that possess definite values): all operators of which $|\psi_S\rangle$ is an eigenvector have the corresponding definite value or, put differently, the observable $|\psi_S\rangle\langle\psi_S| = \rho^S_S$ possesses the definite value 1. These properties, since they are derived from the state of *S with respect to itself*, are interpreted as properties possessed by S "on its own", without reference to anything external.

So far, there is nothing explicitly relational or perspectival going on; $|\psi_S\rangle$ is just the "physical state" assigned to S in earlier versions of the modal interpretation of quantum mechanics [14]. The relational aspect enters when we consider states ρ_R^S for arbitrary S and R.

We are interested in situations in which there is a reference system, R, outside S, such that $A \equiv U \setminus R$ contains S. By virtue of the Schmidt decomposition of $|\Psi\rangle\langle\Psi|$ (the state of the universe), there is a unique state ρ_A^A that is coupled to ρ_R^R (in the sense of being perfectly correlated to it via $|\Psi\rangle$'s Schmidt decomposition). Again in accordance with earlier modal ideas, we posit that this correlated state ρ_A^A is A's state with respect to itself *given* R's state ρ_R^R. Now, since system S is contained in A (remember: $A = U \setminus R$), the state ρ_R^S can be defined as the density operator that follows from this ρ_A^A by taking the partial trace over the degrees of freedom in A that do not pertain to S:

$$\rho_R^S = \mathrm{Tr}_{A \setminus S}\rho_A^A. \tag{2}$$

Any relational state of a system with respect to another system, outside of it, can be determined by means of (2).

So for an arbitrary system S contained in the universe U, ρ_S^S is one of the projectors occurring in the spectral resolution of $\mathrm{Tr}_{U\setminus S}|\Psi\rangle\langle\Psi|$. If there is no degeneracy among the eigenvalues of this density operator these projectors are one-dimensional and the state can be represented by a vector $|\psi_S\rangle$, see (1). In the case of degeneracy this generalizes: now, the state of the system with respect to itself becomes a multi-dimensional projector [17]. For simplicity we shall in the following focus on the non-degenerate case. One-to-one coupled with ρ_S^S, via the correlation represented in the Schmidt decomposition, is a state ρ_R^R of the rest of the universe U. The state attribution rule of the foregoing paragraph says that the relational state of a component C of S, with respect to R, ρ_R^C, is found from ρ_S^S by tracing out the degrees of freedom not belonging to C.

The state $|\Psi\rangle$ evolves unitarily in time. Because there is no collapse of the wave function in our approach, this unitary evolution of $|\Psi\rangle$ is the main dynamical principle of the theory. Furthermore, we assume that the state assigned to a *closed* system S undergoes a unitary time evolution

$$i\hbar\frac{\partial}{\partial t}\rho_S^S = \left[H_S, \rho_S^S\right]. \tag{3}$$

For more about the dynamics, (joint) probabilities and other details, see [6, 17]. Here we intend to focus on the relational aspects of the just-introduced scheme of state attribution. These can be illustrated by looking at how this scheme works for the case of the gambling experiment from the previous section.

4 The Quantum World of Perspectives

The essential points are not affected if we simplify by taking the universe U to consist of only three systems: I (or a measuring device, initially not partaking in the interaction), the die, and "my friend" (a measuring device recording the outcome of the die roll), denoted by I, D and F, respectively. Let us take the initial state $|\Psi\rangle$ as a product state: $|\Psi\rangle = |I_0\rangle \otimes |D_0\rangle \otimes |F_0\rangle$, with $|D_0\rangle = \sum c_i|D_i\rangle$, where the states $|D_i\rangle$ are eigenstates of the observable corresponding to "face i coming up". Using the familiar von Neumann measurement scheme we can represent the first stage of the experiment (in which the die is rolled and my friend looks at the outcome) as follows:

$$|I_0\rangle \otimes |D_0\rangle \otimes |F_0\rangle \longrightarrow |I_0\rangle \otimes \sum c_i |D_i\rangle \otimes |F_i\rangle. \tag{4}$$

This may be followed by a second stage, in which I receive information about the outcome. In the same von Neumann style (which is obviously highly idealized and simplistic; but we are here interested in general characteristics of the situation) this is represented as:

$$|I_0\rangle \otimes \sum c_i |D_i\rangle \otimes |F_i\rangle \longrightarrow \sum c_i |I_i\rangle \otimes |D_i\rangle \otimes |F_i\rangle; \tag{5}$$

with obvious notation both in (4) and (5)—the states with different values of i are mutually orthogonal.

We can now apply the rules of the previous section to the states occurring in (4) and (5) in order to determine what the properties of the various component systems are. Looking at the final state in (4), we see that F by itself has registered a definite result i and also that D by itself has landed with a definite face up (possibility $i = k$ being realized with probability $|c_k|^2$). The state of I is, as expected, as it was before the experiment started, since I has not been involved in the process. The state of D plus F *for* I is given by $\sum c_i |D_i\rangle \otimes |F_i\rangle$, from which it follows that the state of F *for* I is the improper mixture $\sum |c_i|^2 |F_i\rangle\langle F_i|$; and analogously for the state of D with respect to I. So clearly, the states of D and F vary depending on the reference system with respect to which they are defined: they are different when taken with respect to the systems themselves from when taken with respect to I. The result reproduces what was discussed in the previous section: after the die has been cast there is a clear-cut outcome of the experiment *for my friend*, whereas *for me* the situation is still objectively undecided. The latter statement should not be interpreted in the sense that I do not know what the outcome has been, but rather as expressing that with respect to me the die *does not possess* a well-defined position showing a definite face. Indeed, with respect to me $\sum |c_i|^2 |D_i\rangle\langle D_i|$ is the state of the die. Taking our clue from the "objectification requirement" in answering the question to which definite physical property this state corresponds (in other words, looking for a projector P such that $\mathrm{Tr}\rho P = \sum |c_i|^2 \langle D_i|P|D_i\rangle = 1$), we readily find that the projector $\sum |D_i\rangle\langle D_i|$ is definite but that the individual projectors $|D_i\rangle$ are not.

But this becomes different when I enter into interaction with either the die, my friend, or both. During this new interaction the total state changes, with the right-hand side of (5) as the final result. At the end of this process I will have recorded a definite result: my state with respect to myself has become one of the states $|I_i\rangle$. With respect to me, the state of my friend plus the die will now be given by the corresponding $|D_i\rangle \otimes |F_i\rangle$, from which it follows that with respect to me the die has acquired a definite face-up position.

The state attribution scheme under discussion thus yields the type of relational states that a philosophical skeptic or verificationist would perhaps already be inclined to assign even in the context of classical physics. But again, the salient point is that in the context of quantum theory this way of attributing states has empirical consequences and corresponding empirical support: we may take it as supported by experiment that measurements performed by I on the composite D plus F system, after the die has been cast but before any further interaction with I has taken place (so that the state is given by (4)), can generally be successfully described only if the entangled state $\sum c_i|D_i\rangle \otimes |F_i\rangle$ is used instead of one of the "definite result states" $|D_i\rangle \otimes |F_i\rangle$.

We thus find that a relational description of the world, in the sense that the state and physical properties of any physical system depend on a reference system with respect to which they are defined, is implicitly present in the formalism of quantum mechanics. There is certainly some affinity here with the many-worlds or relative-state interpretation of quantum mechanics. One important point of difference is that we have not been assuming that *all* possible outcomes of experiments are equally realized; we have taken the modal point of view that only one result becomes actual and that quantum theory only contains probabilistic information about which result that will be. In this and other respects our proposals are akin to those made by Rovelli [7–9]. However, before going into a comparison with his "relational quantum mechanics", let us look at some more characteristics of the relational perspective developed above.

5 Holism, Locality and EPR

One of central themes in discussions about the interpretation of quantum mechanics is that of holism: it seems generally accepted today that quantum mechanics contains holistic features. Various types of holism have been distinguished in the literature, but the most important one relates directly to the existence of entangled states. Indeed, in a state like $\sum c_i|D_i\rangle \otimes |F_i\rangle$ the whole system, comprising D and F, physical properties appear to be instantiated that cannot be understood as being "built up" from properties of the individual component systems. A paradigmatic example is that of definite and fixed correlations between component systems, represented by well-defined fixed values of global quantities, in spite of the fact that the component systems do not possess fixed values for the correlated quantities. In the notorious case of the singlet spin state there is a perfect anti-correlation between the spins, following from the fact that the total spin has the definite value 0, whereas there are no definite individual spin values. In situations in which the component systems can be thought of as being at a large spatial distance from each other, this holistic feature manifests itself in the guise of non-locality.

We can use the results of the previous section to discuss this issue for the case of our gambling experiment. After the initial stage of the experiment the combined system of D and F is for I in an entangled pure state, whereas the states, again for I, of the component systems are improper mixtures. The associated physical properties are represented by the projector on the entangled state in the case of the total system, and by the rather uninformative projectors of the form $\sum |D_i\rangle\langle D_i|$ in the case of the component states. So from the perspective of I the total system indeed has properties that cannot be understood as constructed from the properties of the components: a manifestation of holism. From the point of view of F, however, there is nothing holistic: the die has landed on a definite side, this has been recorded by F, and the total system is characterized by the conjunction of these properties. So whether or not a system displays holistic features becomes itself a perspectival matter in this approach.

An important question is whether the holism that is present gives rise to non-locality in cases in which the component systems are spatially separated. In one sense of the question the answer is evident: if the properties of a spatially extended system do not supervene on the properties of the individual localized parts, there is non-locality in exactly this meaning of the term. But we are more interested in another question, namely whether in EPR-like situations it can be said that there are instantaneous—or faster-than-light—influences going from one part of the total system to another. It is this meaning of non-locality that is usually discussed in the context of debates concerning the implications of violations of Bell inequalities.

The essential features of the EPR case are already present in our gambling thought experiment. After the rolling of the die the state of D plus F is entangled, with the consequence that for I there is no definite face that has come up. However, if I looks at the die (and thus enters in interaction with it) the die will acquire such a definite face-up state for I, as is clear from (5). This offers no problem for locality, of course: the interaction between I and D can be assumed to be purely local. However, as a result of this same interaction the state of F for I also changes—namely into a state telling us that F had already observed the same outcome as I is observing now. This change of F's state with respect to I takes place without any causal contact between I and F. Appearances therefore are that there is some strange influence on F arising from the interaction between I and D; it is exactly this effect that translates into a non-local influence in the case of spatially separated systems.

But a more careful consideration of the relational character of the states takes away the impression of mystery here. It is true that there is no physical interaction between I and F, and that in this sense I's observation of D cannot have an effect on F's state. However, I's *own* state is modified during the (purely local) interaction with D, and since we are considering the state of F *with respect to* I, it need not cause bewilderment that this relational state also becomes different from what it was. As a result of I's looking at the die, I's state by itself becomes aligned with D's state by itself (cf. (5)); it is therefore no wonder that F's state with respect to I becomes the same as it already was with respect to D. We do not need to invoke any non-local influences here: the changes in the various states can be understood on the basis of the combination of local physical interactions and the relational character of the states.

This line of reasoning carries over directly to the case of the EPR experiment—see [6]. Einstein, Podolsky and Rosen famously proposed that *if, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity* [18]. We can accept this criterion within our relational framework—in its essence, it is the objectification requirement discussed before—but here its application does not lead to the conclusion that *for* I the properties of F were already before the experiment what they are after I's interaction with D. The crux of the matter is that in spite of the absence of physical disturbances going from I to F, there *does* exist an influence of the observation of D. This influence comes about via the relational, perspectival, character of the state we are considering: it is a state of *F with respect to I*, which makes the local change in I relevant. The premiss that this relational state of F is not "in any way disturbed" during the experiment is thus not fulfilled.

More in general, the perspectival character of the states is responsible for the failure of counterfactual reasoning in the way we are used to it: from the fact that no physical disturbance has affected an object, it cannot always be concluded that the object state is the same as it would have been if no interactions at all had been present. One should also look at the reference system, with respect to which the state is defined, and see whether anything has changed *there* that is relevant.

These considerations show the extent to which the very concept of reality is modified in this perspectival approach to the interpretation of quantum mechanics. However, to a point the quantum formalism itself hides these relational features from view. Indeed, when different observers compare their findings, they will agree on what they have seen, as is illustrated by the agreement between I and F about the outcome of rolling the die. This is a general feature of the formalism [6]. Furthermore, there are the omnipresent effects of decoherence that will blur the observability of entanglement. Yet, in principle the existence of superpositions (as in the case of the state of D and F before I has taken a look at the D) can be found out experimentally, even in the macroscopic domain. In fact, the violation of Bell inequalities can be interpreted as empirical support for the thesis that the traditional notion of reality (monadic properties combined with locality) is inappropriate.

Let us for clarity's sake look explicitly at the EPR case of distant correlated particles. We find that the state of the second particle that becomes known after a measurement on the first particle is the state of this second particle from the perspective of the measuring device that has interacted with particle 1. However, it cannot be concluded that this state was already present before the measurement, because the state of the measuring device with respect to itself changes during the measurement. If one writes down the states explicitly, applying the given rules to the situations before and after the measurement, one easily establishes that the relational state of particle 2 with respect to the measuring device at the position of particle 1 indeed changes as a result of the measurement, in spite of the fact that there was no mechanical disturbance propagating between 1 and 2. It is important to note that, by contrast, the state of particle 2 *with respect to itself* does not change—this is a direct consequence of the no-signalling theorem.

The modification of the reality concept that is inherent in the introduction of relational (perspectival) states thus appears to make the introduction of 'quantum nonlocality' unnecessary. The change in the relational state of particle 2 can be understood as a consequence of the local change in the reference system, brought about by the measurement interaction. One could express it like this: the local measurement interaction is responsible for the creation of a new perspective (namely the perspective connected with the new state of the measuring device), and from this new perspective even far-away systems look differently.

6 A Brief Survey of Relational Ideas

The idea that quantum theory points into the direction of perspectivalism is certainly not new. Some of the basic thoughts can already be recognized in Bohr's writings, in particular in his complementarity doctrine. Bohr emphasized that quantum objects cannot be characterized by a fixed set of physical magnitudes that are definite-valued at all times; instead, which properties can be attributed to quantum objects depends on the experimental set-up of which the object is a part. According to Bohr this experimental context should not be interpreted in terms of the presence of conscious observers; it is rather the presence of a measuring device measuring an observable A that makes it possible to speak about an object in terms of A-values. So it is the nature of the physical interaction between the object and the system with which it is in interaction and with which it establishes correlations that determines the validity of property ascriptions—for example, whether momentum or position values can be properly ascribed.[1] There is clearly a similarity here to some of the features of the approach explained in the foregoing sections here. However, one should be very careful in attributing to Bohr (or any other author) ideas that are not formulated explicitly by himself; and although it seems plausible to interpret Bohr's statements in terms of relational property ascriptions, he has never mentioned the possibility of different property ascriptions to one system depending on the perspective that is taken.

Kochen in [10] has proposed an interpretation of quantum mechanics that he dubs the "witnessing" interpretation, which strongly suggests that it is about properties of systems as "witnessed" or viewed from other systems—this seems an example of the explicit introduction of perspectival properties. However, in Kochen's only published paper on the subject there is only a discussion of a physical system consisting of two components, in which case the Schmidt decomposition of the total state (cf. Sect. 3 above) is used to assign properties to these components. This makes the witnessing interpretation identical, for this particular case, to a version of the modal interpretation [13, 14, 16]. Since there is neither mention of other systems in Kochen's proposal nor discussion of its supposedly perspectival nature, it is difficult to be certain about what the meaning and the relevance of the "witnessing relation" is.

This is very different in the work of Rovelli and coworkers, who propose an explicit *Relational Quantum Mechanics* (RQM) and emphasize the possibility of different descriptions of a physical system depending on the perspective [7–9, 20]. The spirit of RQM, in particular the central idea that quantum systems have states and properties that are defined relatively to reference systems, is very similar to what was discussed in the foregoing sections. It appears that there are also a number of differences, although it remains to be seen how important these are.

[1] Bohr stressed that measuring devices are macroscopic, and this has sometimes created the misunderstanding that Bohr thought that these devices were themselves not subject to quantum mechanics. Bohr has mentioned in several places, however, that these macroscopic objects should be treated by quantum mechanics if we want to make predictions about measurements performed *on them*—see, e.g., [19]. The invocation of the macroscopicity of the devices serves the purpose of making contact with experience and ordinary language, by referring to situations in which the concepts of classical physics, like position and momentum, are applicable.

In Relational Quantum Mechanics the concept of measurement interactions, and definite outcomes of measurements, is primary; the state $|\psi\rangle$ is introduced as a derivative quantity, a bookkeeping device that takes into account the information about previous interactions with a system S that has been stored in a system A and can be used for making predictions. As Smerlak and Rovelli write [9]: "The state ψ that we associate with a system S is therefore, first of all, just a coding of the outcome of these previous interactions with S. Since these are actual only with respect to A, the state ψ is only relative to A: ψ is the coding of the information that A has about S. Because of this irreducible epistemic character, ψ is but a relative state, which cannot be taken to be an objective property of the single system S, independent from A. Every state of quantum theory is a relative state". Smerlak and Rovelli append a footnote to this, saying "From this perspective, probability needs clearly to be interpreted subjectively". The basic idea of perspectivalism in RQM seems thus to be motivated by epistemological or operationalistic considerations (there are indeed references to operational definitions and operationally justified procedures elsewhere in the same paper). But it would be a mistake to read too much into this, since the papers [7–9] make it also clear that "measurements" are here meant not in the sense of human acts, but rather as physical interactions that give rise to correlations between physical systems. Moreover, all physical systems are treated as quantum systems: quantum theory is taken to be universally applicable, both to microscopic and macroscopic systems. In these latter points there is complete agreement with our proposals from the foregoing sections. However, the first point—the primary role played by "measurement results" and the derivative role of ψ—gives rise to differences with modal approaches.

Since the occurrence of definite events (as registered by some physical system) is taken as primary in RQM, and since the bookkeeping device ψ has to be *updated* every time such an event occurs, ψ changes discontinuously with every new event. As the authors of [9] say, "the state ψ is a tool that can be used by A to predict future outcomes of interactions between S and A. In general these predictions depend on the time t at which the interaction will take place. In the Schrödinger picture this time dependence is coded into a time evolution of the state ψ itself. In this picture, there are therefore two distinct manners in which ψ can evolve: (i) in a discrete way, when S and A interact, in order for the information to be adjusted, and (ii) in a continuous way, to reflect the time dependence of the probabilistic relation between past and future events". By contrast, according to modal interpretational ideas unitary evolution is the main dynamical principle, also when systems interact. Whether or not definite events occur, and what their characteristics are, is in the modal interpretation (which was on the background of our perspectival proposals in the foregoing) derived from the form of Ψ—instead of the other way around as in RQM. It may be true, however, that on the level of the physical properties that become realized over time (which process is treated in general as stochastic in the modal interpretation) continuity cannot always be guaranteed even in the modal scheme. The extent and the significance of the differences here therefore remain a question for further investigation.

In RQM *all* states are relative to some *other* system, there is no mention of states of systems with respect to themselves. *A fortiori*, RQM does not operate with the notion of a state of the whole universe U. Nevertheless, it seems that in cases like the gambling experiment from Sect. 2, RQM leads to the same relational state attributions as derived in Sect. 3: the "information" mentioned in RQM is both in RQM and in the modal scheme represented by the correlations between the systems, as encoded in the entangled states. It is less clear whether the state assignments agree in cases in which there is space-like separation between systems S and A, and in which no information about S has arrived at A from the past. It seems that in such cases RQM says that *it makes no sense* to speak of the state of B with respect to A: A cannot "know" anything about B [9]. In our proposal, in which we started from the assumption that there exists a well-defined state of the total universe Ψ, such a state of S with respect to A *is* well-defined. More generally, it appears that RQM defines less properties and states than are assigned in our proposal: according to RQM the attribution of a state of S relative to A becomes *meaningless* as soon as no actual information transfer has taken place in any way between S and A.

Obviously, there is a lot more to say about this and other topics (like the way EPR is dealt with in the different approaches). But for the purpose of this paper it is enough to conclude that the idea of perspectival properties makes it possible to give a new twist to many an old debate in the foundations and interpretation of quantum mechanics, and that a new field of detailed questions is opened up by this development.

7 Conclusion

Interpreting quantum mechanics via perspectival (relational) properties seems a promising way to go. One important result is that the relational perspective sheds new light on the long-standing locality debate: within a relational framework locality in quantum mechanics does not need to be jettisoned. The price to pay is that the nature of reality becomes different from what we were used to: all properties need a perspective for their definition. This is admittedly strange and far-fetched if judged from a classical point of view. But it is not a gratuitous philosophical suggestion: the very structure of the quantum formalism points in this direction. If reality is conceived of in this perspectival way, local realism seems to become a live option again.

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