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Quantum States, Reality, and Knowledge

—Revisiting the Dispute between Metaphysics and Epistemology in Light of the PBR Theorem

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Abstract

The debate concerning the interpretation of quantum mechanics does not merely concern how to understand a successful mathematical formalism and once more raises an old question: does scientific knowledge pertain to a reality that exists independently of the observer, or does it simply organize experience, predict the outcomes of experiments, and record information? This article focuses on the ontological status of the quantum state. It first distinguishes the traditional epistemological notions of truth, belief, and justification from the metaphysical, semantic, and epistemic commitments of scientific realism, and then examines the shift in research paradigms from classical to quantum mechanics. It subsequently reconstructs the Pusey-Barrett-Rudolph (PBR) theorem and makes clear its philosophical implications. Within the framework of ontological models and on the assumption of preparation independence, the ontic-state distributions associated with different pure quantum states cannot overlap. Yet this result does not demonstrate that the quantum state is a complete physical ontology nor does it prove that the wave function is an absolute, intrinsic entity that is concretely located in spacetime. On this basis, the paper advances a view called moderate relational realism. Interactions, correlations, and quantum events are real in a way that is independent of the mind; the systems remain as relata; and the quantum state is regarded as an objective representation of the preparation history, of the relations between systems, and of the physical dispositions which these relations preserve. This position accepts the restriction that the PBR theorem places on ψ-epistemic ontological models while at the same time rejecting the inference from ψ-onticity to the reification of the wave function. When addressing the objections relating to relations without relata, the objectivity of relative facts, and interpretive underdetermination, the paper states that quantum mechanics has not overcome scientific realism; on the contrary, it has moved realism away from a full commitment, an object-centered ontology, and absolute rep-

resentation towards selectivity, relationality, and fallible perspectival objectivity.

Keywords

Scientific Realism, Quantum State, PBR Theorem, Relational Quantum Mechanics, Structural Realism, Epistemology

1. Introduction

Quantum mechanics has shown an exceptional accuracy when it comes to predicting the results of experiments, but this empirical success has not led to a single, unified picture of the world. The same formalism can be understood by Bohmian mechanics in terms of particle positions and a nonlocal guiding law, by the Everett interpretation in terms of a universal wave function and its branches, or by objective-collapse theories in terms of genuinely stochastic dynamical processes. Relational quantum mechanics, on the other hand, denies the notion that a quantum state is an absolute state belonging to an isolated system; it considers the values of physical quantities to be facts that become actualized through interactions with another system [1]-[4]. Although these interpretations agree very closely in their empirical predictions, they provide different answers to the question, "What is there in the world?" The interpretation of quantum mechanics is thus both a metaphysical and an epistemological issue. Metaphysics concerns itself with the question of whether quantum states, particles, relations, and events are real; epistemology deals with how far the theoretical success justifies belief in such unobservable entities.

This paper focuses on the ontological status of the quantum state and poses the following question: since quantum mechanics compels us to give up the classical notions of determinacy, noncontextuality, and separability, can we still believe that scientific theories show us a world which exists independently of the mind? If we can, then what should our realist commitments be attached to? The question cannot be settled by a simple choice between "the wave function is real" and "the wave function is not real". At least three claims, becoming stronger as we go, must be distinguished. The first of these is that a quantum state cannot simply reflect an agent's lack of knowledge about an underlying invariant reality. The second is that a quantum state corresponds to an objective difference in physical reality. The third is that the wave function itself is the complete, absolute, and intrinsic state of a system. Under certain assumptions, the PBR theorem [5] shows an important link between the first two claims, but it does not automatically imply the third. One should not move too quickly from "PBR supports ψ-ontic models" to "the quantum state is a physical property of the system"; it is exactly this kind of inference that needs to be made clear.

The various ways of addressing the problem can be divided into four main cat-

egories. Naive scientific realism holds that the key entities and structures of mature theories are roughly true. Constructive empiricism insists only on empirical adequacy and therefore suspends belief regarding unobservable ontology. Ontic structural realism ranks relations or structure above objects. Relational quantum mechanics attaches states and physical values to the interactions between concrete systems. The present paper advocates a view which it refers to as "moderate relational realism". This term does not refer to a currently existing school of thought; rather, it combines two different lines of thinking: the moderate structural realist position which asserts that relations and relata occupy the same ontological level [6], and the relational quantum mechanical position which holds that a quantum state is not an absolute property of an isolated system [4] [7].

It can be put down in four points. The first is that there is a physical world which exists irrespective of human belief or experience. The second is that the basic facts of the world include interactions, correlational structures, and events between systems and that they cannot all be reduced to the intrinsic properties of isolated objects. The third is that physical systems are not abolished by their relations; they are concrete relata which can take part in relations and are identified by their relational profiles. The fourth is that the quantum state has an objective ontological status, but this status applies first to the physical state of affairs that exists between a preparation apparatus and a system, rather than to a wave-function entity owned by the system independently of any relation.

The argument is developed in the following way. In Section 2 the traditional three conditions of knowledge are set out, the three commitments of scientific realism are distinguished from them, and the no-miracles argument, the pessimistic meta-induction, and structural realism are reviewed. Section 3 compares the concept of state in classical and quantum mechanics and maintains that Bell's theorem and the Kochen-Specker theorem place constraints on classical-style realism rather than on realism in general. In Section 4 the PBR theorem is reconstructed, its contribution, assumptions and limitations are examined, and four levels are identified: system, relation, quantum state, and particle. Section 5 presents the case for a moderate form of relational realism. Section 6 looks at the main objections. Finally, Section 7 outlines the wider direction of the metaphysical and epistemological debate concerning quantum mechanics.

2. Literature Review

2.1. The Three Conditions of Knowledge and Their Minimum Ontological Commitment

The systematic examination of the connection between knowledge and reality is usually attributed to Plato's dialogue *Theaetetus* [8]. Although the dialogue does not finally accept the later definition of "justified true belief", its treatment of true judgment, true account, and knowledge is a key historical source for the three-part analysis. In modern analytic epistemology, propositional knowledge is typically expressed by three conditions: that the proposition p is true; that the subject

S believes p; and that S is justified in believing p. Gettier [9] demonstrated that these conditions are not enough to establish knowledge, since a person might come to a justified true belief through epistemic luck. The present paper does not aim at solving the Gettier problem; instead, it uses the three-part analysis as a conceptual framework in which the belief condition specifies the cognitive subject, the justification condition refers to the evidence and the inference, and the truth condition means that a belief must depend not only on how the subject regards matters but also on how the world actually is.

The truth condition therefore has a certain minimal requirement with regard to ontology. In order for the statement 'the electron has spin' to count as knowledge, it must not only be accepted by the scientific community and supported by experiment; it must, in the right sense, correspond to a real physical situation. Nevertheless, the truth condition by itself does not commit us to realism about all the entities introduced by a theory. A theory might be empirically successful even if it describes a phenomenon by means of idealisations, approximations, or several equivalent models, and a well-justified theory may at a later stage be revised. What the epistemological truth condition shows is merely that knowledge cannot be completely independent of the way the world actually is; it does not tell us how electrons, wave functions, or Everettian branches exist.

We must therefore keep the two tripartite schemes separate. The traditional conditions of knowledge are truth, belief, and justification, while the three dimensions of scientific realism are metaphysical, semantic, and epistemic commitment. The first of these deals with the conditions under which a single proposition is known; the second specifies how scientific theories and their unobservable content should be understood. Yet their relationship is important because if the truth values of scientific theories are determined by an independent world and the theoretical language is interpreted literally, then the epistemic evaluation of theoretical success will necessarily have ontological implications.

2.2. The Three Commitments of Scientific Realism and Those Who Criticise It

Scientific realism usually includes three commitments. In a metaphysical sense, it asserts that scientific investigation deals with a world which exists independently of the mind. Regarding semantics, it takes theoretical terms like "electron", "field", "gene", and "quantum state" to be literal, and therefore statements containing them have truth conditions rather than serving merely as rules for calculation. On an epistemological level, it states that well-developed, successful, and non-ad hoc theories can give us knowledge, or at least approximately true beliefs, concerning both observable and unobservable parts of the world [10] [11]. Each of these commitments can be questioned in turn. Idealism rejects or diminishes the idea of mind-independence; instrumentalism weakens the referential function of theoretical language; and constructive empiricism allows for a literal interpretation but argues that all one needs to believe in order to accept a theory is its empirical

adequacy, not the reality of its unobservable entities [12]. The quantum debate is thus not a simple choice between accepting or rejecting a single realist claim; it instead reallocates the strength of these three separate commitments.

The standard case in favour of scientific realism is the no-miracles argument. According to Putnam [13], if well-developed scientific theories did not reflect at least some of the real features of the world, their continued, accurate, and widespread ability to make predictions and to enable intervention would be almost miraculous. The fact that different instruments, theoretical approaches, and causal interventions independently detect and manipulate an entity increases the strength of this conclusion. Where various instruments, theoretical paths, and causal interventions all lead to the same unobservable object, it becomes all the more difficult to treat that object as merely a product of one particular method [14]. Furthermore, inference to the best explanation states that if an unobservable mechanism is able to account for a wide variety of phenomena in a unified manner, then the explanatory success of the theory provides only limited but real grounds for believing in it.

The objections of the antirealist are just as serious. First, the same evidence can be used to support theories that are ontologically incompatible, while criteria like simplicity, unification, and explanatory power, which might decide between them, rely on background assumptions. Second, Laudan's [15] pessimistic meta-induction shows that theories such as phlogiston, caloric, and ether were at one time successful but have since been given up together with their key entities. If past success does not ensure reference or truth, current success cannot be directly turned into ontological credit. Third, if 'approximate truth' is not backed by a clear standard of comparison, it might amount to no more than a kind of retrospective fix for realism. Quantum mechanics also increases the problem of underdetermination in that Bohmian mechanics, the Everett interpretation, and standard quantum mechanics share a wide range of empirical consequences but provide incompatible ontological accounts.

A more defensible approach is not to defend each and every part of every successful theory, but rather to embrace a fallibilist and selective realism. The realist commitment should be focused on the elements which are genuinely essential for making new predictions, for achieving stable interventions, and for maintaining continuity throughout theoretical change. Worrall's [16] epistemic structural realism is an example of this kind of approach; from Fresnel to Maxwell the ether mechanism was given up while important mathematical relations were kept; scientific progress can thus be seen as mainly accumulating knowledge about structure. Ladyman [17], and later French and Ladyman [18], developed this view further into ontic structural realism: structure is not only what we know most reliably but, in some sense, ontologically more basic than individual objects.

2.3. The Coming Together of Structural Realism and Quantum Mechanics

There is a strong reason provided by quantum mechanics for adopting ontic struc-

tural realism: identical quantum particles do not have intrinsic "labels" upon which classical individuality could be based, and an entangled state cannot be completely reconstructed from the pure states that each of the individual systems has alone together with an external relation between them. As a result, the identity and properties of quantum objects seem to depend largely on global correlations, symmetry, and their position within a structure. Moreover, Bell's theorem [19] and the Kochen-Specker theorem [20] both demand that any account of the phenomena which is to be in agreement with empirical results must give up certain assumptions regarding locality or noncontextuality. Taken together, these findings undermine the classical view in which individual entities that are self-sufficient come first and the relations are then added.

However, radical ontic structural realism has to deal with the question of what instantiates the structure; if there are only abstract relations and no concrete relata, then it becomes difficult to account for the difference between a mathematical structure and the physical world. Esfeld [21] claims that, in general, structural realism will not be able to provide an adequate physical ontology unless it is combined with a concrete interpretation of quantum theory. Moderate structural realism therefore holds that relations do require relata, but that relata do not need to have an essence made up of properties that are entirely independent of all the relations. Objects and relations can occupy the same ontological level [6]. This view remains compatible with quantum nonseparability while avoiding the problem of 'relations without relata' turning into pure abstraction. It also offers the immediate metaphysical foundation for the moderate relational realism which is defended below.

3. From Classical States to Quantum States

3.1. Ontology and Knowledge in Classical Mechanics

In the ideal depiction of classical mechanics, the full state of a system at a given time t is given by a point $\lambda = (q_1, \cdots, q_n, p_1, \cdots, p_n)$ in the phase space Γ. If a Hamiltonian H is given, then the state evolves in accordance with deterministic equations:

$$\frac{\mathrm{d}q_i}{\mathrm{d}t} = \frac{\partial H}{\partial p_i}, \quad \frac{\mathrm{d}p_i}{\mathrm{d}t} = -\frac{\partial H}{\partial q_i}.$$

Physical quantities are functions defined on phase space, and it is assumed that the system has definite values even if these values are not actually measured. A probability distribution $\rho(\lambda)$ usually expresses the observer's lack of knowledge regarding which definite state the system really is in, not an actual absence of a state in the world. The difference between an "ontic state" and a "state of knowledge" is therefore fairly clear: λ refers to the world whereas ρ refers to the observer's ignorance about λ. A composite system can generally be formed from the states of its constituent subsystems together with the spatiotemporal relations between them. Classical theories are not all local—Newtonian gravity for example

involves action at a distance. The essential classical metaphysical set of assumptions is instead the combination of definite values, noncontextuality, separability, and probabilities interpreted as ignorance of a complete state.

It is natural, when looking at this picture, to regard measurement as revealing a value that already existed. An instrument might affect the object under measurement, but in principle the effect can be told apart from the object's original properties. The epistemological task is to approach the phase-space point which was already determined through more and more accurate observations, while the ontology does not depend on the observational context. Quantum mechanics is philosophically disruptive not only because it introduces probability but also because this simple division of labour between ontology and knowledge cannot be left unchanged.

3.2. The Classical Package and Quantum-Theoretical Limitations

A pure quantum state is represented by a ray $|\psi$ in Hilbert space, while a general state is represented by a density operator ρ. For a measurement $M = \{E_k\}$, the Born rule states that:

$$P(k|\psi, M) = \psi|E_k|\psi.$$

Quantum probabilities, in contrast to classical probabilities, cannot all be understood as arising from ignorance about a set of pre-existing values that are independent of measurement unless additional structure is introduced, a structure that has to be severely constrained. Noncommuting observables do not allow for a single classical assignment of simultaneous values, and entanglement produces correlations in composite systems that cannot be accounted for by specifying the individual states of the constituent parts.

In 1935 the EPR argument presented this dilemma as one concerning completeness. Einstein, Podolsky and Rosen stated that if it is possible to predict the value of a physical quantity with certainty without disturbing the system, then there is a reason to regard this as an element of reality. The correlations in entangled states appeared to indicate that the wave function did not include all such elements and that therefore the quantum description was incomplete [22]. Bohr's [23] reply stressed that the conditions which define a quantum phenomenon cannot be separated from the entire experimental setup. The EPR criterion of reality imposed on quantum phenomena a classical and context-independent notion of properties. The fundamental question is already apparent at this stage: is the quantum state merely incomplete knowledge, or is it a physical description that cannot be separated from the measurement and preparation arrangements?

Bell [19] transformed part of this metaphysical debate into a testable mathematical condition by showing that hidden-variable theories which satisfy Bell's locality condition cannot account for all the correlations predicted by quantum mechanics. The Kochen-Specker theorem proves that in Hilbert spaces of three dimensions or more, it is impossible to assign definite values in advance to all

observable quantities while at the same time maintaining their functional relationships and ensuring that these values are independent of the measurement context [20]. However, neither of these theorems demonstrates that a mind-independent world does not exist; rather, they rule out a certain classical form of realism—that is, a world made up of local and separable objects each possessing complete sets of noncontextual values. Quantum mechanics calls for a revision of the content of ontology, not for the rejection of ontological questions.

That is the reason why several realist interpretations are still possible. Bohmian mechanics keeps the particles having definite positions but allows for nonlocal guidance. Everett regards the universal wave function and its branching structure as real. GRW-type theories alter the dynamics so that collapse becomes an objective process. All of these interpretations demonstrate that quantum theory does not logically require instrumentalism, yet they also show that empirical success is not enough to determine a unique ontology. The PBR theorem puts the question in a different light: instead of directly asking whether the world consists of particles, branches, or collapse events, it examines whether the quantum state can act like a classical probability distribution and can represent only our ignorance of one and the same underlying reality.

4. The PBR Theorem

4.1. ψ-Ontic and ψ-Epistemic Models

A central question in the foundations of quantum theory is whether the quantum state, usually written as ψ, describes reality itself or only tells us about our knowledge of a system. In this paper, "ψ-ontic" and "ψ-epistemic" are used in the technical sense defined below: they classify ontological models, that is, models that posit an underlying ontic state, according to whether the probability distributions over ontic states associated with distinct pure states can overlap. In a ψ-ontic model, systems prepared in different pure states are always in different ontic states. In a ψ-epistemic model, at least two distinct pure states are compatible with one and the same ontic state, so that the difference between them can be read as a difference in information about a single underlying reality. This technical notion must be kept apart from the broader view that quantum states express an agent's subjective degrees of belief. Interpretations of the latter kind, of which QBism is the best-known example [24], do not posit any ontic state that the quantum state could be ignorance about, and they therefore fall outside the ontological-models framework altogether [25].

The framework for ontological models that was developed by Harrigan and Spekkens [26] provides a clear formulation of the question of whether the quantum state is real. Assume that, following a preparation, the system has an ontic state λ, the full range of possible ontic states constituting a space Λ. The preparation of the quantum state $|\psi$ leads to ontic states being produced according to a distribution $\mu_{\psi}(\lambda)$. The probability of obtaining outcome k when the measurement M is carried out is given by a response function $\xi(k|M,\lambda)$. The model has

to reproduce the Born statistics:

$$P(k|\psi,M)=\int_{\Lambda}\xi(k|M,\lambda)\mu_{\psi}(\lambda)\mathrm{d}\lambda.$$

where the distributions connected with two different pure states $|\psi$ and $|\varphi$ have an overlap on a region of positive measure, the same value of λ may result from either of the two preparations. In this case, even complete knowledge of λ would not be enough to determine which quantum state had been prepared, and the difference between the states could be seen as a difference in the agent's information regarding an underlying reality. A model in which at least one pair of distinct pure states has overlapping distributions in this sense is referred to as ψ-epistemic; this overlap-based definition is the only sense of "ψ-epistemic" used in the rest of this paper. However, if the supports of the distributions associated with any two distinct pure states are disjoint, then λ in principle determines ψ, and the model is called ψ-ontic.

The distinction is very useful, but it is often exaggerated. For 'ψ-ontic' to hold means merely that different quantum states lie in non-overlapping parts of physical reality; it does not imply that ψ exhausts λ. As a clear example, Bohmian mechanics shows that the wave function has an ontological status, yet the full state also involves the particle configuration. It is therefore necessary to keep the two questions apart: one concerning whether the quantum state represents an objective physical difference and the other concerning whether the quantum state is the complete ontology. The PBR theorem mainly addresses the first of these questions and does not resolve the second.

4.2. The Structure and Benefits of the Argument

Apart from the general ontological-models framework, the PBR theorem also assumes preparation independence. Intuitively, if two systems are each prepared independently by separate apparatuses, then the ontic state space of the combined system must allow for the respective independent combinations and the joint distribution must factorize into the product of the distributions of the two individual preparations. Now, if the distributions connected with the nonorthogonal states $|0$ and $|+$ have an overlap in a region Δ, then when the two systems are prepared independently there is a nonzero probability of a joint ontic state in $\Delta\times\Delta$ under each of the four preparations: $|0|0$, $|0|+$, $|+|0$, and $|+|+$.

Quantum theory also allows for a joint measurement with four possible outcomes, each of which has zero probability under one of the four preparations. In the case of a joint ontic state that lies in the common overlap region, the response functions have to assign positive probability to at least one of the outcomes since the total of the probabilities of all the outcomes is one. However, whichever outcome is given a positive probability conflicts with the quantum preparation that excludes that particular outcome. Thus, the assumption of an overlap leads to a contradiction.

Strictly speaking, this two-system construction establishes the contradiction

only for the selected pair $|0\rangle$ and $|+\rangle$. The general result extends it to an arbitrary pair of distinct nonorthogonal pure states by using a sufficiently large number n of independently prepared copies; the closer the two states are, the larger n must be. If each preparation yields an ontic state in the overlap region with probability at least $q > 0$, independence implies that all n systems lie in that region together with probability at least q^n, and an entangled measurement on the n systems can be chosen so that each of its 2^n outcomes has zero probability under at least one of the 2^n product preparations. (Orthogonal states, being perfectly distinguishable, cannot have overlapping distributions in any model that reproduces the quantum predictions.) An ontological model which is able to reproduce the predictions of quantum theory and at the same time satisfies preparation independence must therefore assign nonoverlapping ontic distributions to any two distinct pure states [5].

The first important advantage of the PBR theorem is that it turns a rather vague metaphysical question into one that involves clearly stated assumptions, defined classes of models, and specific consequences. It makes it clear that the analogy with classical statistical mechanics cannot be taken over without restriction; a classical distribution might express only our lack of knowledge about the actual point in phase space, while a quantum state generally cannot represent ignorance of a preparation-independent λ that is shared by different pure states. Secondly, the theorem imposes physical limitations on philosophical views; a ψ-epistemic interpretation can no longer be regarded as merely a semantic preference, since it must either identify the assumption it is rejecting, alter the way composite systems are put together, or make use of a notion of state outside the framework. Thirdly, similar to Bell and Kochen-Specker, the PBR theorem shows a methodological advance in the field of quantum foundations in that formal results can place constraints on metaphysics even if no single theorem is able to determine a full ontology.

4.3. What PBR Does Not Prove

The strength of the PBR theorem lies in the precision of its assumptions, and it is precisely those assumptions that determine the boundaries of the theorem. Firstly, it is a conditional result within the ontological-models framework; preparation independence is not a logical truth, and while giving it up involves certain theoretical drawbacks, it is still a feasible option within the space of possible models. As Leifer [25] points out, ψ-ontology theorems should be evaluated according to the independence, continuity, and distinguishability assumptions that each one makes; they cannot be combined to form an unconditional "proof that the wave function is real."

Secondly, the fact that the distributions are disjoint does not mean that the wave function is a material field in spacetime, that the quantum state provides a complete description of the system, or that it is an absolute intrinsic property belonging solely to the system. Moreover, PBR cannot establish scientific realism as a

whole; the existence of a world independent of the mind, the referential function of theoretical language, and the rationality of believing in unobservable entities still need further support from the no-miracles argument, experimental practice, and the history of theoretical change. PBR also does not decide between Bohmian particles, Everettian branches, collapse events, or other concrete ontologies.

Thirdly, in the Harrigan-Spekkens framework λ is generally taken to be the complete and absolute ontic state of a single system at a given time. Relational quantum mechanics directly challenges this approach. A quantum state is not simply about one system; it is relative to another physical system with which it has interacted or with respect to which it is described. If all the relevant facts are incorporated from the beginning into an absolute λ for a single system, then the central claim of the relational theory has already been ruled out before the test even begins [27]. This therefore does not allow relational approaches to ignore PBR; it means that the system to which the theorem is applied must be specified accurately.

To take a robust reconciliation, we can let λ stand for the complete physical state of affairs, together with the preparation relation. In this relationalized ontic space, PBR might still demand that different pure states correspond to different regions of physical reality. The differences in such a case, though, could pertain to how the system is situated with respect to its preparation apparatus rather than to which intrinsic wave function it has independently of all relations. For this reason, Oldofredi and Calosi [28] claim that PBR and relational quantum mechanics can coexist in peace. The present paper accepts the more moderate and safer conclusion: although PBR gives the quantum state an ineliminable ontological status, it does not determine whether that status should be understood as an entity, an intrinsic property, or a relational fact.

This reconciliation must, however, show that preparation independence still holds once the ontic state is relationalized; otherwise it would establish no more than a conceptual possibility. Consider the PBR scenario, in which two systems S_1 and S_2 are prepared by separate devices P_1 and P_2. On the present proposal, the ontic state associated with the first preparation is $\lambda_1 = (\sigma_1, r_1)$, where σ_1 comprises whatever nonrelational features S_1 may have and r_1 is the relation established between S_1 and P_1 by the preparing interaction; $\lambda_2 = (\sigma_2, r_2)$ is defined in the same way for S_2 and P_2. What belongs to each preparation is therefore the relation between a system and its own preparation device and nothing else: the procedure establishes no relation between S_1 and P_2 or between S_2 and P_1, and the two devices do not interact with each other. Preparation independence then states that, when the two preparations are carried out separately, the joint distribution over (λ_1, λ_2) is the product of the two single-preparation distributions, so that every combination of relational states allowed by the individual preparations is also allowed for the pair. Including the system-apparatus relations does not violate this assumption, because each relation is fixed by a single local preparation and the factorization applies to it exactly as it would to an in-

trinsic state. Independence would fail only if the two relations were themselves correlated, for instance through a common cause, a shared environment, or an earlier interaction between the devices; but in those circumstances the preparations would not count as independent in the first place. Under this condition the PBR argument goes through unchanged in the relationalized space, and its conclusion receives a definite relational reading: distinct pure-state preparations give rise to disjoint distributions over ontic states that include these system-apparatus relations, so that the ontic difference required by PBR can be located in how each system stands relative to its own preparation device rather than in an intrinsic wave function.

4.4. Differentiating between Systems, Relations, Quantum States, and Particles

The preceding analysis raises a natural question: if the quantum state is connected with physical reality, is there still a reason for distinguishing between systems, relations, quantum states, and particles? Yes, there is: they lie at different logical levels, and reducing them all to one category would turn realism about a representation into the reification of what that representation describes. Table 1 summarizes the role that each of these concepts plays in the present account and indicates whether PBR determines its status.

Table 1. The ontological levels of systems, relations, quantum states, and particles.

Concept	Role Played in This Paper	Does PBR Determine Its Status?
Quantum system	A quantum system is a physical entity that can be prepared, interact, and act as a relatum. The individuality of such a system may be "thin" and does not have to involve a complete intrinsic essence independent of its relations.	While PBR assumes that a prepared system exists, it does not specify whether that system is fundamentally a particle, a field, an event, or something else.
Relations and events	The relations and events are the objective physical facts that arise in the processes of preparation, measurement, entanglement, and interaction. They are independent of human consciousness but occur between specific systems.	Although PBR can be expressed in a relationalized state space, this by itself does not mean that relations are more fundamental than relata.
Quantum state ψ	The quantum state ψ is a theoretical way of representing the preparation history, the relations between different systems, and the associated physical dispositions; although it has ontological significance it does not thus become an independent "substance".	Within the framework of its assumptions, PBR rules out overlap between the distributions of different pure states, but it does not prove that ψ is complete, intrinsic, or directly reified.
Particle	With respect to particles, some interpretations—such as the position particles in Bohmian mechanics—adopt a concrete ontology. However, they need not hold the same fundamental status in quantum field theory or in other interpretations.	PBR says nothing about whether particles exist or about the properties they have.

The assertion that "the quantum state is a physical property" is only valid if it is explicitly qualified by the fact that it refers to an objective rather than arbitrarily subjective difference in the physical state. It is not necessary for this property to be complete, absolute, intrinsic, or to be possessed by the system when it is isolated. The fact that this limitation is pointed out has no effect on realism; it is merely what prevents realism from making ontological commitments that the formal result does not justify.

5. The Positive Case for Moderate Relational Realism

5.1. Four Principles

The "moderate relational realism" referred to in this paper is based on four principles. The first of these is mind-independence, which means that it is not the observer's beliefs or consciousness that determine whether an interaction takes place, what outcomes become facts and which correlations arise between systems. In this context, an "observer" may be any physical system that takes part in an interaction; it does not have to be a conscious person.

The second point is that relations and relata are co-fundamental. Quantum entanglement, contextuality, and relational quantum mechanics all indicate that physical properties cannot be understood as intrinsic labels attached to separate objects in a universal way. However, a relation can only constitute a concrete physical fact if it is realized by concrete systems. This paper therefore opposes the radical structuralist view that there are relations but no objects. Systems and relations are not two layers that are arranged in a temporal or explanatory sequence; rather, systems are individuated by the networks of relations into which they can enter, and relations can only be realized between systems. The view combines moderate structural realism with a stronger emphasis on the system-relativity of state facts.

The third point is the non-reification of representation. Within the ontological-models framework, the quantum state cannot be mere information about an underlying ontic state, since, under the PBR assumptions, different preparations cannot correspond to the same complete ontic state. Nevertheless, an extra argument is needed in order to move from "ψ distinguishes physical realities" to "ψ is itself an independent entity". A map can give an accurate representation of terrain without being of the same kind of object as the terrain. The quantum state can objectively record a dispositional structure set up by a preparation relation: for a given reference system, an interaction, and a measurement, it specifies which events may take place and with what probabilities. These 'dispositions' are not expectations in a conscious mind; they are counterfactual patterns stably supported by a physical arrangement.

The fourth point is what might be called perspectival objectivity involving fallibility. Although every statement regarding a state must indicate the system with respect to which it is made, indexicality does not amount to subjectivity. Just as velocity is relative to a frame of reference yet can still be entirely objective, so too

the relational index of a quantum fact can be obtained through physical interaction and restricted by consistency conditions. It is the epistemological concern of relational realism to determine when descriptions from different systems can be compared, which facts become stable at macroscopic levels through decoherence, and how information leaves physical records that are accessible to later systems, not to provide a basis for unrestricted relativism.

5.2. The Reasons Why this View Is better than the Three Extremes

First, it is better to adopt a moderate form of relational realism than to go for a purely epistemic view of the quantum state. Two such views must be distinguished here. The first is a ψ-epistemic ontological model in the technical sense of Section 4.1, in which nonorthogonal preparations correspond to overlapping distributions over one and the same space of ontic states. For models of this kind that satisfy preparation independence and the other assumptions of the theorem, the PBR argument leads to a contradiction. The second is the view that a quantum state is nothing but an agent's degrees of belief and does not describe any underlying ontic state, as in QBism [24]. PBR does not directly exclude this second view, since the view rejects the ontological-models framework from the outset [25], and the PBR-based criticism is accordingly restricted to the first. Against the second view, the case for relational realism is explanatory rather than demonstrative. Relational realism asserts that the various preparation procedures result in different actual physical states of affairs in the world, thus providing an objective basis for the differing quantum predictions. In this way it retains the most plausible aspect of the no-miracles argument—that is, quantum theory enables accurate and repeatable intervention in different laboratories because it reflects real dispositions and relational structures, not simply because it organizes the expectations of individual agents. A purely subjective reading is not refuted by this consideration, but it must account for the stability of quantum statistics across agents and laboratories without appealing to physical states of affairs that the quantum state represents.

Second, it is better than the extreme reification of the wave function. A Hilbert-space vector can be represented in various bases, a ray has global-phase redundancy, and a many-body wave function is usually defined on a high-dimensional configuration space. Hence, there is a need for further bridge principles if a mathematical object is to be identified directly with matter in spacetime. Moderate relational realism does not hold that a concrete interpretation cannot provide such principles; it only rejects the idea that they are direct consequences of PBR. This position acknowledges the physical significance of the quantum state while at the same time being honest regarding the underdetermination among the Bohmian, Everettian, collapse, and relational interpretations.

Third, it is better than radical ontic structural realism which gets rid of all relata. A structure that has no concrete realizers is hard to tell apart from an isomorphic abstract mathematical structure, and by keeping 'thin systems' it is possible to

state which things interact with which, where a record is kept, and why an event is a concrete occurrence without having to reintroduce entities that have all the usual classical intrinsic properties. Oldofredi's [7] bundle-theoretic approach to relational quantum mechanics also demonstrates that a system can be made up of its physical properties and relations without having to assume the existence of a substratum completely independent of them.

Beyond these three extremes, compatibility with PBR does not by itself favour the relational account over nonrelational realist alternatives that also respect the theorem and also deny that the wave function is the complete ontology. Bohmian mechanics is the clearest example: it is ψ-ontic but supplements the wave function with determinate particle positions [1]. Collapse theories of the GRW type [3], when supplemented with a local ontology of matter or events, belong to the same class but also change the dynamics itself. The relational account is preferable to such alternatives on two grounds. First, it adds no structure beyond what standard quantum mechanics already uses: it neither posits additional variables whose detailed behaviour outruns anything a measurement can reveal, as Bohmian trajectories do, nor alters the Schrödinger dynamics with new physical constants, as collapse theories do. Its ontology consists of the systems, interactions, and outcomes in terms of which the theory already states its predictions. Second, it treats contextuality and the dependence of outcomes on the measurement arrangement as features of the ontology itself, rather than as effects to be generated by a nonlocal guidance law that, in a relativistic setting, requires a preferred foliation of spacetime. These are comparative theoretical virtues, namely economy and naturalness, rather than a proof that the nonrelational alternatives are false, and the relational account pays for them with relative facts and with the consistency postulate discussed in Section 5.3. They nevertheless supply a positive reason, beyond mere compatibility with PBR, for locating the ontological significance of the quantum state in relations.

5.3. The Point at Which Metaphysics and Epistemology Come Together

This position goes beyond giving a reply to the question "What is there?" by also rephrasing the question "How do we know?" In a metaphysical sense, the world comprises systems capable of interacting, the relational facts which are realized in such interactions, and the dispositional structures maintained by those facts. Regarding semantics, statements concerning quantum states still have truth conditions, but a full statement must include the relevant index: that system S is in state ψ relative to system O, not merely that S possesses ψ. As for epistemology, our beliefs are justified by repeatable preparation, Born statistics, interference, entanglement correlations, and by records that are distributed among the apparatuses. This kind of justification is public and open to correction rather than being limited to the experience of an individual subject.

The question of how relational facts come to be common knowledge is the most

important one for this position, and answering it requires two distinct ingredients. The first is a consistency principle. The proposal adopts the cross-perspective link postulate of Adlam and Rovelli [29]: if an observer A measures a variable V of a system S and undergoes no interaction that destroys the information about V stored in A's physical variables, then a second observer B who subsequently measures the physical variable representing A's information about V will obtain a result that matches A's result. This principle does not follow from the unitary dynamics alone. Relative to B, unitary quantum mechanics fixes only the correlation between A's record and S; it does not by itself say that what B finds coincides with the outcome that occurred relative to A. The postulate therefore functions as an additional interpretive principle, and Adlam and Rovelli introduce it as such.

The second ingredient is decoherence, which plays a different role. Decoherence makes certain records stable within particular environments and over certain timescales, so that interference between the alternatives they register becomes practically undetectable and many different subsequent systems can read them in approximately the same way. Di Biagio and Rovelli call facts of this kind stable facts: relative facts whose relativity can, for practical purposes, be ignored [30]. Decoherence thus explains when a record can be treated as stable and why it remains accessible, but it does not by itself guarantee that different observers who consult the record will agree; that guarantee is supplied by the postulate. Together, these mechanisms do not cause every relative fact to become an absolute fact from a "view from nowhere". Instead, they show how a scientific community can still establish a stable and reproducible empirical world. Objectivity is not understood as the absence of all perspectives but is rather defined as explicit indexing, physical production, cross-perspectival constraint, and public testability.

Moderate relational realism therefore keeps the three commitments of scientific realism in a disciplined way: it asserts, metaphysically, the existence of systems and relational facts that are independent of the mind; it takes, semantically, properly indexed quantum claims to be literal; and, epistemically, it makes only those commitments to content which are jointly supported by no-go theorems, stable experiments, and structures that are preserved across theories. It does not guarantee that the ontological list given by any current interpretation is true; rather, it holds that quantum science has reached certain negative and structural conclusions which are highly reliable—namely, that the world cannot be described entirely as a set of local, separable objects possessing noncontextual intrinsic values, and that, in ontological models satisfying preparation independence, differences between quantum states cannot in general be reduced to ordinary ignorance of one and the same underlying state.

6. Objections and Replies

6.1. Objection One: PBR Has Already Shown That the Quantum State Is an Intrinsic Entity

It is possible for a critic to claim that, if the ontic distributions connected with

different ψ values do not overlap, then ψ must be a real property of the system itself and relationalization is just a way of avoiding the theorem. However, this reasoning confuses "the ontic state determines ψ" with "ψ completely describes the ontic state and is intrinsic to it". The mathematical result of PBR deals with the relationship between the supports of the distributions in a given ontic space. It is the interpretation of the model that decides whether the variables in that space refer to intrinsic properties of a single system or to relations between a system and an apparatus. As Bohmian mechanics demonstrates, it is possible for a model to be ψ-ontic without being ψ-complete. Relational models further state that the physical fact which distinguishes ψ may include a system index. The position advocated here does not oppose PBR; rather, it accepts the nonoverlap condition within a relationalized λ-space.

It cannot, nevertheless, employ "relation" as a free label for any counterexample. In order to provide a relational account it is necessary to state which systems are involved in the relation, at what level preparation independence holds, and also how the complete Born statistics are obtained. Section 4.3 answers the first two questions. The relata relevant to each preparation are the prepared system and its own preparation device, so that in the PBR scenario the ontic state of the pair includes exactly two preparation relations, one between S_1 and P_1 and one between S_2 and P_2; preparation independence is the assumption that the distribution over these two relations factorizes when the devices are separate and uncorrelated. Under this assumption the PBR argument applies without modification, and the nonoverlap it establishes concerns the relations that the preparations produce. As for the third question, the measuring device enters only through the response functions. Since the preparation relation determines the pure state, the response function can simply assign to each outcome the probability that the Born rule gives for that state, so the complete Born statistics are recovered. What the present proposal does not yet provide is a unique and complete dynamical theory. This limitation shows clearly the correct scope of PBR: the theorem is capable of eliminating certain classes of models but cannot on its own construct a complete ontology.

6.2. Objection Two: If Relations Depend on Systems, Then Intrinsic Objects Remain Fundamental

Another argument is that there can be no relation unless there are already existing objects, and if objects are included, then relational realism simply reduces to ordinary object realism. This objection supposes that the related entities must first have a full intrinsic identity. Moderate relational realism, on the other hand, accepts a less strict condition: distinct physical bearers take part in interactions and retain sufficient continuity within a causal-relational network so as to be traceable. Their identities can be determined jointly by their relational profiles, their spatiotemporal positions, and their actual histories. Therefore, relations and relata are interdependent and not reducible to one another.

It is not a logical circle but a case of co-fundamentality; both a node and the network to which it belongs can be included in a fundamental description, it being unnecessary to first define the node in a language that has no edges and then introduce the edges afterwards. The difference between a physical system and an abstract placeholder lies in the former's concrete causal capacity and its history of events. By keeping the thin relata, the question 'What instantiates the structure?' is also answered, for the structure is instantiated by actual interactions among systems that are capable of carrying records.

6.3. Objection Three: Relative Facts Undermine Objective Truth and Lead to Contradictions

It might appear that the same proposition is both true and false if system S has a value with respect to O but has no such value with respect to P. However, the two statements are not in fact the same complete proposition; by omitting the relational index a contradiction seems to arise. It is possible for both "S has value a relative to O" and "S has no determinate value a relative to P" to be true. The real difficulty is not a formal contradiction but whether different observers will end up with incompatible records when they later compare them. Research carried out by Pienaar [31], Healey [32], and others demonstrates that relational quantum mechanics requires a substantive theory of consistency; simply adding subscripts does not overcome every instance of the measurement problem.

Moderate relational realism therefore regards cross-perspectival coordination as a necessary condition of realism rather than taking it for granted. The consistency principle it relies on is the cross-perspective link postulate described in Section 5.3: when B measures the physical variable in which A's undisturbed record of a measurement on S is stored, B's result matches A's. Because this principle is postulated rather than derived from the unitary dynamics, the position openly accepts it as an additional interpretive commitment, to be judged by its coherence with the rest of quantum theory and by the absence of conflicting records in practice. Decoherence does not do the same work. It explains why certain records become robust and accessible to many systems, and so identifies the circumstances in which the postulate can be applied, but it does not on its own ensure that the records of different observers agree. Scientific objectivity does not require that all systems have a completed absolute state description before they interact; what it does require is that when records are actually compared, they comply with the probabilistic constraints of quantum dynamics and with this consistency postulate. A relational model which fails to meet this requirement should be dismissed. Relationality does not serve as an escape from contradiction.

6.4. Objection Four: The Position Offers No New Predictions and Simply Compromises in the Face of Underdetermination

Since moderate relational realism is not a dynamical theory on the same level as Bohmian mechanics or GRW, it does not by itself produce new numerical predic-

tions. This does limit the position, but it does not make it meaningless. Its role is to determine which ontological conclusions are supported by the present physical results, which remain dependent on interpretation, and where the boundaries of acceptable theorizing are. PBR, Bell, and Kochen-Specker all alter the space of possible world pictures by means of negative constraints. It is a proper function of the philosophy of science to organise those constraints into a clear set of ontological commitments.

"Compromise" is not the same as arbitrariness. The view clearly upholds mind-independence, the objectivity of relational facts, the existence of thin systems, and the non-purely-epistemic character of quantum states. It also clearly rejects thoroughgoing instrumentalism, the unconditional reification of the wave function, and structuralism without relata. These commitments could be revised by a more complete quantum field theory, a future theory of quantum gravity, or by experiments that examine cross-perspectival consistency. The fact that selective realism is fallible is a fundamental aspect of the position, not proof that it has no content.

6.5. Objection Five: Rejecting Absolute Quantum States Undermines Scientific Realism

In the end, a critic might maintain that realism has to offer a perspective-free description of "the world as it really is" and that anything short of this is no more than a form of constructive empiricism. The basic tenet of scientific realism is that the world is not brought about by our beliefs, that theoretical statements have truth conditions which are constrained by the world, and that successful theories can enable us to acquire limited knowledge about unobservable reality. It is not necessary for every real quantity to be unindexed. Spatiotemporal distance, velocity, and gauge-dependent quantities all demonstrate that dependence on a reference structure does not negate physical reality. A truly antirealist position would regard the quantum state merely as a predictive tool and would be unwilling to believe in the physical structure which is responsible for its success. The view currently under discussion explicitly acknowledges the existence of objective relational facts and dispositional structures and it undermines naive absolutism, rather than scientific realism itself.

7. Conclusions

The article makes use of the ontological status of the quantum state in order to re-examine the long-standing controversy between metaphysics and epistemology within the framework of quantum mechanics. Although the conventional criteria of truth, belief, and justification indicate that a claim to knowledge cannot be completely separated from the way the world actually is, these alone are not sufficient to determine the mode of existence of theoretical entities. Scientific realism goes beyond this minimal stance by making metaphysical, semantic, and epistemic commitments. The no-miracles argument provides support for these commitments, while the pessimistic meta-induction and interpretive underdetermination

require them to remain selective and fallible.

The change from classical to quantum mechanics is not a move from 'reality' to 'no reality'; rather, it involves the loss of the universal validity of a classical approach which includes determinate values, noncontextuality, separability, and probability based on ignorance. Bell and Kochen-Specker place limitations on local or noncontextual classical ontologies. In the ontological-models framework and assuming preparation independence, PBR rules out ordinary overlap accounts according to which different pure states express ignorance of the same underlying state. The positive aspect of this conclusion is that the differences between quantum states have an ineliminable physical significance; its limitation is that it does not prove that the wave function is complete, absolute, intrinsic, or directly identical to material reality, and it does not determine whether particles, branches, or collapse events make up the fundamental ontology.

Under the conditions mentioned, the paper has upheld a form of moderate relational realism. It holds that there is a world independent of the mind, which includes concrete systems and the way in which they interact; it considers both relations and relata to be equally ineliminable; it states that the quantum state objectively describes a dispositional structure set up by the preparation history and by the interactions between systems without being directly identified with an independent entity; and it regards knowledge as being obtained via stable records, constraints that arise from different perspectives and are secured by an explicit cross-perspective consistency postulate, and publicly testable practice. This view accepts the challenge that PBR poses for ψ-epistemic ontological models yet avoids the transition from ψ-onticity to the reification of the wave function.

The response to quantum mechanics from a philosophical point of view therefore shows four closely related tendencies: a shift from accepting the entire theory in a realist manner to adopting it only selectively; a move from a view of objects based on their intrinsic properties to one based on relations and structure; a transition from an absolute, unindexed description of things to a form of perspectival objectivity that is physically constrained; and a change from an ontology mainly based on intuition to one that is guided by no-go theorems and explicit assumptions about the models. Quantum mechanics does not remove the difference between "What is the world?" and "How do we know?" Instead, it forces these two questions to refine and correct each other. A fully developed kind of quantum realism should not assert that it has a complete list of things as seen from a God's-eye view. Rather, it should indicate which structural facts are firmly supported by theory and experiment, which ontological commitments remain dependent on interpretation, and how further evidence might lead to their revision.

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