Perspectives on the Quantum State

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Abstract

There are two main styles of interpreting the quantum state: either focusing on the fundamentality of the quantum state (a wavefunction or state realist view), or on how projection operators represent observable properties (an observable-first approach). Rather than being incompatible, I argue that these correspond to taking a 3rd person and 1st person perspective respectively. I further contend that the 1st person perspective - and the observable-first approach that goes with it - is better suited to explain measurement, based on the way that the metrology literature, as well as the work of Bohr, characterises measurement through the properties of a system. Finally, I show how the 1st person, observable-first approach can emerge in the world through the process of decoherence, hence showing the compatibility of the two approaches and resolving the need to choose absolutely between them.

Keywords: perspectivalism; wavefunction realism; emergence; decoherence; metrology; measurement;

1 Introduction

There are many different views on how to interpret the quantum state, and even when limiting the options to ontic views (as I do throughout this paper), there are still multiple alternatives for spelling out exactly what the quantum state represents and what claims about the world can be made based on it. Traditionally these views are seen as incompatible, leading to significant tensions in choosing between them. In this paper, I argue that there is no single correct answer; instead, the wavefunction should be interpreted differently when considered from different perspectives.

When trying to understand the world from a 3rd person perspective - independent of our presence in it - we should adopt wavefunction or state realism, in which the world is first and foremost a wavefunction (along the lines of [1–6]). Conversely, when our explanatory project is to understand the world as it relates to us in the 1st person perspective (by

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which I do not mean a subjective agent, but simply our physical embodiment at a certain level of reality - section 2.1 explores what exactly I mean by this) the quantum state should be interpreted in terms of observables and seen as a superposition of classically understood properties.

This switch in perspectives is not an epistemic trick or a purely instrumentalist view, but part of our realist commitments about the world. Perspectivalism may seem initially at odds with the realist aim to describe the world *as it really is* (or at least this seems to care only for the 3$^{\text{rd}}$ person perspective). But the realist literature has now considered for a long time that the world may not admit of a single unified description. Either through explicitly perspectival or pragmatic articulations of realism [7–9], but also in structural realism, which shifts the focus to mathematical structure permitting of multiple precisifications.[2] Structural realism is also closely connected to the emergence literature, in which higher level theories come with their own ontological commitments, justified by their novel explanatory value [11].[3] This is the line of reasoning I will follow: the 1$^{\text{st}}$ person, observable-first approach has important explanatory value relating to how measurements are thought of in the metrology literature; meanwhile the 3$^{\text{rd}}$ person perspective is better for assessing how we fit into the world as just another type of physical system. What is more, I will show how the 1$^{\text{st}}$ person perspective emerges through decoherence, hence illustrating the compatibility of the views and how the switch between them is grounded.

The core distinction between these perspectives lies in their treatment of the properties of quantum systems. The 1$^{\text{st}}$ person, observable-first view straightforwardly uses classical observable properties and commits, in some way, to using the eigenstate-eigenvalue link (henceforth the EEL) as a model for understanding what it means for these properties

[2]There are also many perspectival approaches to quantum mechanics specifically (see discussion in [10] for examples). These tend to fall under what I label as the 1$^{\text{st}}$ person perspective, although not exclusively (see section 2.1).

[3] Structural realists (I am thinking especially of ontic structural realists here) may argue that mathematical structure is all there is to reality, but even then they take seriously the questions of which ontological precisifications are more perspicuous to get a handle on an otherwise inexplicable reality, see discussion in [5] for example. This paper will accept this programme of emergence and not provide an in depth justification or explication of it. It is already widely used in understanding the emergence of classicality from quantum mechanics and this is an integral part of many of the different interpretations of the quantum state (e.g. [4, 6])

to have definite values. Projection operators represent observable classical properties and eigenvalues correspond to possible values of them. This is closely linked with the goal of explaining measurement. The metrology literature ([12–14]), as well as the way that Bohr [17–19] thinks about measurement, emphasizes the importance of attributing properties to systems based on empirical interactions, necessitating an observable-first interpretation that can capture how the quantum state is connected to empirical data.

In contrast, those who reject the observable-first view do so precisely because they want to understand how the world is independent of a measurement scenario. The 3rd person perspective aims to treat observers as just another type of quantum system and rejects the presupposition of classical properties inherent in the observable-first view. These two style of interpretation are at odds with each other and are taken to be incompatible alternatives, but both contain valuable explanatory projects: explaining measurement is necessary to understand the scientific method and often involves microscopic phenomena being amplified to the macroscopic level, meanwhile the 3rd person picture explains interactions within a unified framework and provides a basis for where classical concepts come from.

My focus here is on practical models of measurement and how we understand them to relate to the world, and not on the deeper measurement problem in quantum mechanics. There are interesting potential applications of a 1st person perspective to the measurement problem; this is starting to be looked at in work such as French's phenomenological approach [20]. However this is a much broader issue, by focusing here on how we view the quantum state, and how this relates to the metrology literature, we can gain clarity on one particular question: how we think about the properties of quantum systems in relation to measurement. Where it is necessary to think of the measurement problem, I will limit my discussion to interpretations that take unitary quantum mechanics as is and reject collapse - primarily the Everettian or Many Worlds approaches - and set aside modifications to the theory such as Bohmian Mechanics or dynamical collapse; although some of what is discussed here may carry over. In this context, 'measurement' is therefore taken to refer to producing empirical results within a single branch world. Although the observable-first approach is often linked to Copenhagen-style collapse interpretations, I treat it as distinct in this discussion.

The final element to put in place is the role of emergence and decoherence in all of this.

As I have said, I will show that the 1^{st} person perspective emerges through decoherence, which is essential if we are to see the two perspectives as compatible. A key aspect of measurement is the amplification of results from the microscopic to the macroscopic realm, a concept rooted in Niels Bohr's work and foundational to the decoherence program, which seeks to explain the emergence of classicality. Decoherence is assumed to occur at some stage during any measurement, making results observable in a laboratory setting. It is also crucial for understanding properties and the EEL: it is through decoherence that we obtain determinate properties in the classical world—or at least within a single Everettian branch. This perspectival approach will use decoherence to explain the emergence of the 1^{st} person perspective and justify the observable-first approach to measurement.

The paper will proceed as follows: In section 2, I will define the 1^{st} and 3^{rd} person perspectives and show how the observable-first and state or wavefunction realist approaches arise from each. I will focus on the properties of quantum systems and their role in measurement as the central point of contention between the two perspectives. In section 3, I will examine the metrology literature to argue that the 1^{st} person, observable-first view better accounts for measurement. Finally, in section 4, I will explore how the 1^{st} person perspective emerges through decoherence.

2 Perspectives and Properties

2.1 Which Perspectives?

The 3^{rd} person perspective is intuitive to most, and it is often seen as the default view in science: it is the world independent from us or without reference to our place in it. This could also be described as 'the view from nowhere'.[4] While this does not imply that there are no observers or that their roles cannot be modelled, it treats them as just another type of physical system, similar to the way third-person narration functions in literature. What often comes with this perspective is a desire to model the entirety of a target system and all of its interactions in the same terms to present a unified description

[4] As in Nagel [21], although Nagel associates the view from nowhere with objectivity, and correspondingly the 1^{st} person view to subjectivity, which is an connotation I wish to avoid here (even if he does not advocate rejecting the 1st person perspective entirely).

of the world. Some might deny that this is a perspective and rather call it a *lack* of perspective; but this easily slides into the assumption that this view is more fundamental than a perspective, an option I wish to avoid. Instead, the 3^{rd} person perspective is a particular way of modelling the world and looking for explanations of phenomena.[5]

In contrast, the 1^{st} person perspective requires a more detailed presentation to lay it out clearly and separate it from similar ideas. Importantly, this perspective does not equate to the viewpoint of a subjective agent, nor does it involve consciousness. The term 'person' serves as a placeholder to help clarify this perspective but is not an essential part of it, much like an observer can define a reference frame in special relativity. The 1^{st} person perspective is about being embedded into the world and modelling parts of it from that position. A physically embedded observer has certain modes of interaction with the world available to them and all empirical investigations proceed through these modes; we design and carry out measurements using the resources available to us. These interactions mediate our access to the world and characterise it in a certain way. However, we can distance ourselves from something too anthropocentric by focusing on theories of measurement – these depend not on practical human limitations but on conceptual constraints on what it means to make a measurement. While some anthropocentrism remains, this approach emphasizes the objective aspects of the world that facilitate empirical observation, rather than the subjective qualities of the observer.

Compared to other perspectival approaches, this presentation is most similar to Price's causal perspectivalism [22]. Causal perspectivalism focuses on an agent's view of the world from where they are, the knowledge they have of it, and how they can interact with it. My approach, however, shifts the focus away from subjective experiences or knowledge and onto the physical interactions possible for an observer in this perspective.[6] These

[5]Certain styles of realism (e.g. Chang's [7], see fn. 6), spell out very clearly how any form of scientific theory cannot escape from the linguistic and conceptual apparatus that has essentially been developed in our 1^{st} person perspective. As such in these approaches, the 3^{rd} person perspective should not be seen as somehow transcending these constraints but as a particular type of explanation within them. However, the ideas in this paper do not depend on adopting these approaches to realism.

[6] This differs from the perspectives referred to in Massimi's perspectival realism [8] that are defined in terms of social and historical position. These factors are not relevant here. It has similarities to Putnam's internal realism [9], but again with less focus on the individual. Chang's [7] or Barad's [23] discussions about situatedness is more similar still, especially with their focus on measuring apparatuses that is also

limits make certain concepts relevant as they are needed to explain how we fit into the world around us and how various phenomena relate to us. It is also possible to define a 1st person perspective that is not tied to a human observer, Adlam's moderate physical perspectivalism [10] describes something along these more general lines. *Any* system has a position and has certain capabilities for interaction; this is significant to many aspects of physics. But given that I am concerned primarily with how the 1st person perspective relates to the human act of measurement, I will not explore this more general idea and will just focus on the 1st person perspective of the human observer.

What is particularly relevant as the difference between these two perspectives for quantum mechanics is that the 3rd person perspective aims to model the world entirely within quantum mechanics and describe interactions within that level, while the 1st person perspective involves a macroscopic, classical, observer looking down (as it were) into the lower level of quantum mechanics.

2.2 Interpreting the Quantum State

Which perspective you take pushes you towards different styles of interpreting the quantum state. The 3rd person perspective, looking towards providing a unified model of reality, is inclined to focus entirely on the quantum framework and the concepts used there. Contrastingly the 1st person perspective, with its focus on how the world relates to us, tends to interpret the quantum state in terms of how quantum systems interact with observers such as ourselves, in other words in terms of observable properties. The existing accounts for interpreting the quantum state can be broadly mapped onto one or the other of these options. We will see that the most important difference between these perspectives comes

central here. However, all these are laying out new approaches to realism and exclude the 3rd person perspective completely with the claim that we cannot go beyond our perspective, which is not an aim here. The 1st person perspective, rather than being entirely ineliminable and the basis for a new realist view, is just a certain position from which to model the world. There are a lot of potential insights to take from these approaches to realism that would be applicable to the 1st person perspective as I discuss it here, including the rejection of straightforward correspondence versions of realism (where science and/or language are direct reflections of an underlying reality). And the resonance between these views and what is presented here means that if you are sympathetic to one you are likely to find value in the other. But it is outside the scope of this paper to attempt a full analysis of this, and what is presented here does not depend on it.

down to what properties we attribute to the quantum system.

Falling under the 3rd person perspective are approaches such as state or wavefunction realism, for example the views of Albert, Ney, Carroll, Wallace and Timpson [1–6]. While these views differ significantly in their specifics, they share a commonality: they take the quantum state literally as a representation of reality. For wavefunction realism the quantum state is seen as a vector in Hilbert or configuration space, often visualised using tools like the Bloch sphere[7]; each point in the sphere represents a unique state, with the poles serving as basis vectors that help us relate the state to observables. The focus is primarily on the mathematical structure, with observables derived from that foundation. For Wallace and Timpson's spacetime state realism, configuration space is not reified in the same way and instead an appeal to quantum field theory is made for the fundamental ontology: the state is associated with a region of spacetime. The state (or density operator) describes the properties of that region, even if they are not the sort of properties we are familiar with. This view rests on the failure of separability: the properties of a region cannot be accounted for as the combination of its component sub-regions.

How the fundamental quantum state produces the observable world we see is addressed to varying degrees among the different views. Carroll [3] and Wallace [6] do this most explicitly and consider it a matter of emergence. Under decoherent conditions, certain features of the state become robust and stabilised, these features can then be accurately be modelled using classical theory and the quantum details ignored. But even where the emergence of observable properties out of the quantum state is made explicit, all these views reject using observables or projection operators as the primary way of understanding the state. As Wallace and Timpson put it:

> "[R]egarding the state as encoding properties of the system in the traditional way is at best unhelpful and incomplete - many properties, like 'being in an entangled state' or 'being in some eigenstate of energy' or 'possessing an even number of zero amplitudes in configuration-space' cannot be expressed using the traditional approach. Focusing on projectors to represent properties

[7] I do not mean to imply that the Bloch sphere is *only* applicable to this interpretation of the state, merely that the Bloch sphere, as a tool for understanding, emphasises the wavefunction as a unique mathematical object.

is too crude to capture all of the interesting properties of the world when the quantum state directly describes ways the world is. At its worst, the traditional approach can be actively misleading." ([5], pg. 703)

This traditional way - or as I will label it, the observable-first approach - is what comes from taking the 1st person perspective. This interpretation sees the quantum state as a superposition of classically understood properties - by which I mean observable properties possessing definite values. In this view, projection operators represent these properties and identify possible measurements we can carry out on the state (although with the caveat that not all projectors correspond to viable measurements). The central novel feature of quantum mechanics, as understood in this framework, is that properties can exist in superpositions rather than having single, unique values, which is the hallmark of the classical world. This is often framed in terms of metaphysical indeterminacy, using the eigenstate-eigenvalue link (EEL) to explain property determination: when in an eigenstate, a property has a definite value (the eigenvalue); when in a superposition, the property is indeterminate.[8] This approach lends itself to language like 'the electron goes through both slits in the double slit experiment' or 'the cat is both dead and alive' (see [28]). The way the quantum state is talked about in the Copenhagen interpretation is an example of this view. More recently it is used by Neo-Copenhagenists or in Relational Quantum Mechanics.[9] Deutsch and Hayden's operator-valued fields [29]interpretation is another example of this, as is Busch and Jaeger's [25] ideas about unsharp quantum reality, and many approaches to quantum logic [30]. (Note here that I am not referring to these interpretations as a whole, or their answers to the measurement problem, but am focusing on their approach to the quantum state.) Notably, despite this being similar to epistemic approaches to the wavefunction, this can also be an ontic view and does not

[8]Explicit treatment of this can be found in [24–27].

[9] Relational Quantum Mechanics takes an explicitly epistemic interpretation of the wavefunction but its event ontology is constituted by the values of properties actualised in interactions between systems, so overall the interpretation is centred around classically understood properties despite the wavefunction itself having no ontic meaning. QBism also to some extent treats the quantum state in this way as a superposition is taken to represent possible outcomes. However, for QBists outcomes do not correspond to *properties* of a system but are just a guide to prediction and action. Although QBists claim to be realists about quantum mechanics, they acknowledge that how they understand this and what exactly they are realist about is still a work in progress; what is certain is that the quantum formalism is not descriptive of the world. So QBism would not count as an observable-first approach.

commit one to instrumentalism (see fn. 9). Neither does the observable-first approach necessitate collapse. Part of the reason the observable-first view is often frowned upon is that it is assumed to lead directly to these elements; but they are distinguishable (and section 4 will show how the observable-first view can fit into an Everettian style ontic picture through decoherence).

As is evident in the quote above, the core difference between the approaches is how they attribute properties to the quantum system. The observable-first approach is built around classically understood properties - like position, momentum etc; these are used to characterise quantum systems and are associated with projection operators and eigenstates. Contrastingly, while the state realist approach may recover familiar observable properties through emergence, the properties it is primarily interested in are ones relating directly to the quantum formalism and its unique concepts. Wallace argues strongly against the observable-first view, calling the EEL a "false friend" ([31], pg. 21) and asserting that it fails to account for actual physics practice, such as the common use of positive operator valued measurements (POVMs) rather than projector measurements (PVMs). This last claim is not necessary true; although the observable-first approach is undeniably built around the EEL and projector measurements there has been work done to generalise and extend it (e.g. [32])(section 3 explores what role the EEL actually plays in more depth). But all the state or wavefunction realist views reject the EEL as anything more than a pedagogical tool for explaining quantum mechanics. As they see it, no realistic quantum system can ever be accurately described as being in an eigenstate with infinitely precise boundaries, and where this is used it is just an idealisation.

Maudlin [33] also argues that operators and eigenstates don't help us understand what is going on with measurement because they do not provide a model of measurement as a physical process taking place within the device and are just an instrumental tool for making predictions.[10] He contends these concepts simplify measurement to statistics between the inputs and outputs that are predicted by applying measurement operators to the quantum state. For example, we might know that when some state is fed into a Stern-Gerlach apparatus of a particular orientation 50% of electrons will be deflected up and 50% down, but we will not know what goes on inside the device to produce this

[10] Although Maudlin goes on to argue for Bohmian mechanics, an interpretation I do not attempt to cover in this paper.

outcome.

In the other direction, however, proponents of observable-first views see the state and wavefunction realist approaches as overlooking how important observables and measurement were in the historical formulation of quantum mechanics, and as giving too much precedence to the mathematical structure while overlooking the empirical basis that the theory comes from.[11] These tensions between the observable-first approach and the state/wavefunction realists produce two opposing ways to understand the properties of quantum objects and how they relate to measurements. We must either uphold or reject the EEL, take operators as foundationally important or dismiss them as instrumental tools, describe quantum systems through classically understood properties with indeterminate values or understand the quantum world as introducing entirely new types of properties, among many other differences.

3 Properties and Measurement

3.1 A 1st Person Account of Measurement

I will now give reasons to think that the 1st person, observable-first view offers a better understanding of measurement, based on the way that metrological accounts of measurement rely on properties.

The assignment of properties to a system is foundational in measurement theory . It was central, for example, to Bohr's ideas about measurement:

> "In the first place, we must recognise that a measurement can mean nothing else than the unambiguous comparison of some property of the object under investigation with a corresponding property of another system, serving as a measuring instrument, and for which this property is directly determinable according to its definition in everyday language or in the terminology of classical physics." ([18], pg. 100)

Here we see a requirement for a translation into classical concepts, which I will discuss further shortly and in section 4, but more important is the emphasis on how measure-

[11] Adlam [10] discusses ideas along these lines as a motivator for perspectival views. She discusses how perspectivalists often see Everettianism as 'excessively impersonal' (borrowing from [21]).

ment is the coupling of a property of the system to a property of the measuring device. This characterisation of measurement is also found in current analyses of measurement in the field of metrology. Mari, Wilson, and Maul, in their book length exploration of the current field of metrology and the philosophy behind it [12], treat measurement as a process that takes a property of the object as the input and produces a value of that property (along with uncertainties and measurement errors) as an output.[12] This does not necessarily commit us to the view that there is 'one true value' out there in the world waiting to be discovered (such an assumption would come very close to requiring a hidden variable interpretation of quantum mechanics), nor does it deny that measurement can have a transformative effect on the property in question; but it does imply that the essence of measurement is to quantify a property of the object under investigation. Of course, qualitative measurements are possible, and often quantum measurements consist of observing things like interference patterns; these may have a quantitative aspect but it is not the straightforward production of a single value. But a fair proportion of our laboratory measurements of quantum systems do take this form. When you make a position measurement of a system you get a numerical value representing the location of the object (with some sort of appropriate reference to a metric, origin etc). When we measure the spin of a particle along a particular axis using a Stern-Gerlach device we get an up or down result.

In measurement theory, properties are thought of as follows:[13]

> "an empirical property of an object—and thus more specifically an empirical quantity of an object—such as the length of a rod or the reading comprehension ability of an individual is associated with a mode of empirical interaction of the object with its environment." ([12], pg 33)

There are two things to highlight here. First, there is a hidden assumption in this: measurement is specifically an *empirical* process that relates to us, and how we gain knowledge

[12]Some accounts of measurement talk about qualities instead but these are in turn defined as properties with specific orderings. While many ideas about measurement exist, the assumption that it rests on properties of the objects is commonly found across the different viewpoints. See [12–14, 16].

[13] Note that this does not commit to a specific metaphysics of properties - for example whether they are universals or particulars. Mari, Wilson, and Maul provide an extensive discussion of the options available for this and what they means for measurement that I refer the reader to.

of an object. As such, empirical interactions must be ones that we can relate back to us in our position as observers, and the properties must be ones that can form correlations with observers (even if it is through a chain and not directly). This is the foundation of what makes measurement a *measurement* as opposed to just another type of physical process. This gives us a clear connection between the 1st person, observable-first approach and measurement. The 1st person approach interprets the world in terms of its relation to us, with projection operators delineating the possible interactions quantum systems can have with us (with the implicit restriction that not all projection operators represent viable measurements). Characterising the quantum state in these terms gives us an adequate grasp of what aspects of reality can be measured and quantified. It allows us to define quantum systems as objects of *empirical* investigation.[14] This is no surprise given that measurement and empirical results are what the 1st person, observable-first approach is built around.

Second is the explicit idea that measurement relates to quantifiable values of properties, the observable-first approach is also evident here. When we interpret the numerical output of a measurement as quantifying a property this takes the form of a definite value with an uncertainty attached. This is the essence of the EEL: the EEL is designed to capture how a system in an eigenstate has a definite value when measured. It pins down what it even means to have a definite quantifiable value within quantum mechanics. This does not mean that *all* measurements must be projector measurements that put the system into eigenstates, POVM measurements are far more practical; but the EEL remains the interpretative starting point for understanding measurements even if we do not apply it strictly in every instance. For POVM measurements of position, for example, we commonly treat the system as being *sufficiently* localised around a position so that we can report the outcome of the measurement as $x \pm uncertainty$.[15] This effectively treats the systems as having definite observable properties, even if the EEL doesn't technically apply here. The fact that we can interpret this numerical output as quantifying an observable property of the system is the foundation of measurement theory.

[14] Adlam [10] also discusses how observation and empirical results are necessarily linked to perspectives not just in quantum mechanics but also in quantum gravity and relativity theory.

[15] Wallace states that this is the common approach to POVM measurements [31].

3.2 A 3rd Person Account of Measurement

Comparatively, the state or wavefunction realist views do not give a detailed account of how their view of properties relates to measurement. The view of measurement I have presented here is minimal: measurement is just the the quantification of empirical properties ([12, 16]). This minimal condition can even be applied in model-based or coherentist accounts of measurement, which explicitly tie the value to a property in a model of the measurement scenario rather than directly to the world, and take into account many of the arguments for measurement being theory laden ([12, 13, 15]). All these views of measurement share the common foundation of measurement as quantification.

The sort of properties the state or wavefunction realist approach deals with are not necessarily quantifiable ones; for example Wallace gives 'being in an entangled state' as a property under the state realist view. But this is not the sort of property that could present itself directly through measurement, instead it is a fact about the system that would be inferred from a pattern in measurements on properties like position or momentum. Generally an implicit appeal to decoherence is made to link the quantum state to the observables that measurement actually focuses on; observable properties are recovered in the decoherent regime and have a definite quantifiable value within each branch of the wavefunction.[16] More details on the mechanism of decoherence are given in section 4, this is undeniably an important aspect of measurement that is essential for producing observable results.

However, we frequently need to be able to think of the quantum system in terms of observable properties *before* any decoherence has taken place. Even if decoherence takes place at some stage in any measurement to produce observable results in the laboratory, our measurements are aimed at discovering something about the system *prior* to decoherence (for example which path information in interference experiments), and it would be counterintuitive to claim that our measurements only ever tell us about the decoherent regime. We may not always want to assign a unique definite value prior to decoherence taking place in the measurement, but we certainly think in terms of observable properties

[16]Mainly the explicit context of measurement is not addressed and decoherence is appealed to to explain how we get observable properties in general, with the implicit assumption that this covers measurement scenarios.

to characterise the object we are investigating and the possible measurements that might be done on it [28].[17] While we acknowledge the role that decoherence plays in producing observable values in the laboratory, it remains import to be able to conceptualise the system under investigation in terms of these properties from the start. This allows for a continuity between the numerical outputs of measurement and the system as it is set up prior to decoherence, and it puts the focus on the system under investigation - as a measurement should - rather than on the specifics of the measurement device and the decoherence that it induces.

The state or wavefunction realist *could* appeal to an alternative account of measurement that relaxes or gives up this commitment to quantifiable properties existing in the world (or in our model), for example Glick [34] argues along the lines of a state realist view that the definite observable properties found in measurements should be seen as functional roles that the system fulfils to a greater or lesser degree, characterised by the probability distribution over measurement outcomes. This option, however, relies on repeated measurements to examine the probability distribution and doesn't seem to have a clear answer for what any individual numerical outcome means; we can no longer maintain that it quantifies a property of the object but is instead some sort of measure of fit between the object and the functional property, the details of this are not spelled out. Similarly, more general operationalist or coherentist views of measurement could be applied, which take quantifiable properties to correspond to sets of operations that can be carried out. However, these views have known problems with them, such as a difficulty accounting for measurement uncertainty and transferability across measurement contexts (see [12, 14] for summary and discussion). If these options are viable, then they currently underdeveloped, especially when it comes to the additional challenges that quantum mechanics poses and the particular way in which state and wavefunction realist views treat properties. State and wavefunction realists *do* make a realist commitment to properties based

[17] Calosi and Wilson [26] argue along these lines that even within a world with widespread decoherence and stable observable properties we still need an observable-first approach (although they do not put it in these terms) and the idea of indeterminate properties to make sense of the coherent patches left over. They say this requires a 'disjunctive reading' of the quantum state where in general a superposition is interpreted as a multiplicity of worlds but in these leftover cases of systems not affected by decoherence it is interpreted as indeterminate observable properties. They do not give more details of what a disjunctive reading entails or give justification for it. I take the perspectival view in this paper to provide this.

on the quantum state, so spelling out how these properties fit into these more pragmatic accounts of measurement would be necessary. Given the success of understanding measurement as the quantification of empirical properties (and the possibility of reconciling this account with the state or wavefunction realist views that I offer in this paper) we should be wary about giving it up without a well-established alternative.[18]

This is not to say that there is no place for considering measurement interactions from the 3rd person perspective as just another type of physical interaction. We certainly must have a viable model of the processes and laws governing the measurement, and how the correlation between system and observer (or measuring device) is formed; we also frequently want to model observers as another type of quantum system. This is what Maudlin argued the observable-first view cannot do (see previous section) [33]. This, however, is confusing the role of operators in interpreting the state. It is certainly true that operators do not give the physical details of the measuring device, but this is not their purpose. Operators and eigenstates (corresponding to observables) should be understood as delineating the *properties* of the quantum object that will couple with the device and which can be numerically quantified. That is what it means to say we are interpreting the quantum state in terms of observables; we are not doing all of quantum mechanics with operators and nothing else, but rather using operators to characterise the state of a given system and its properties.

In the classical domain there is seemingly no difference between modelling interactions within a theory and explaining how the system correlates to us specifically. It is only in quantum mechanics where we start to recognise that we, as macroscopic systems, can only have limited types of interactions with the microscopic world. The empirical interactions of an object with its environment - which delineates its properties - will vary with different types of environment. The 1st person perspective is a way to capture the fact that we occupy a position in a classical, macroscopic domain and are best modelled in these terms, and all interactions that can form measurements for us will require an amplification up to that level through decoherence (this will be discussed further in

[18] My aim here is to show that the 3rd person, wavefunction or state realist views do not *currently* have an adequate account of measurement and not to prove absolutely that there are no viable options for them at all.

section 4). Certain properties are picked out by this and are given the label observable.[19] We can also recognise that this is not the only type of interaction the system might be involved in, and other interactions may require a different characterisation of the object's properties, and hence the 3^{rd} person, state realist view - which looks at modelling the world entirely within quantum mechanics - has a place as well. But the limits of the 1^{st} person perspective, and how they feed into to the process that we call measurement, are important to account for.

Additionally, it is often argued that measurement requires certain presuppositions. Bohr, as evidenced in the quote at the start of this section, certainly thinks so; his view is that measurement rests on certain classical concept, and on modelling ourselves in certain ways. More details of this will be explored in section 4, but here it suffices to say that if this is correct then we need an explanation of where those concepts come from and why they are justified. Considering measurements as tied to the 1^{st} person perspective can provide this; it allows us to examine how these concepts are built into that perspective and follow naturally from occupying it while also allowing a story to be told about where that perspective, and those concepts, are derived from without ending up in a vicious circularity.[20]

All in all, there are strong reasons to think that the 1^{st} person, observable-first approach has considerable explanatory power when it comes to measurement. Characterising quantum objects in this way captures how they present as objects of empirical investigation and delineates the quantifiable properties that measurement latches onto. The

[19]We can make a somewhat trite but perhaps useful connection between the empirical interactions with the environment discussed here and environmentally induced decoherence. Measurement always involves decoherence and hence always involves specific kinds of environments that perform this function. However, this does not exhaust the possible types of interactions for quantum systems and so we also have other types of interactions that an object can enter into. These would be taken to define other properties. Quantum mechanics is unique in that measurement can only be done via certain types of interactions.

[20]I am primarily referring to ontic prerequisite concepts such as separability between observer and observed. I emphasis this physicalist angle here so as to show that the 1^{st} person perspective need not be an appeal to a subjective, conscious agent. However, that does not rule out the possibility that epistemic or subjective presuppositions are playing a vital role; this could be a potential place to explore how perspectives could be used to understand the measurement problem. French's phenomenological approach [20] provides interesting ways to think about how epistemic, observer-dependent conditions can be worked into realist interpretations.

EEL is the foundation for interpreting the definite values presented upon measurement, even if it does not hold strictly. Adopting this as an interpretation of the quantum state, and not just an instrumental tool, maintains the conception of measurement as telling us something about the object. Quantum mechanics complicates our understanding of measurement and calls into question the idea of discovering an objective pre-existing value; but we still require the idea that measurement latches onto the properties of the object even if we accept that our actions may in some way transform what we are measuring. This also strengthens the need for the 3$^{\text{rd}}$ person perspective - once we recognise that our actions can't be ignored, and that how we can interact with a system does not exhaust the physical possibilities for that system, we are prompted to ask what the world looks like beyond these interactions, or what our actions look like from the outside; we have become more aware of how our 1$^{\text{st}}$ person perspective is limited. But it does not do away for the explanatory value and ineliminability of the perspective from which we perform measurements. Recognising that this *is* a perspective, and that it comes with restrictions, is crucial if we are to understand how quantum mechanics relates to empirical investigation.

4 Emergence of the 1$^{\text{st}}$ Person Perspective

I turn now to how the two perspectives, rather than being in opposition, are connected through decoherence, and show that the 1$^{\text{st}}$ person perspective emerges out of the underlying quantum reality. This relationship demonstrates that the two perspectives can coexist, eliminating the need to choose one over the other.

The dispute between the two perspectives rests on whether observables, the EEL, and measurement more generally, are taken to be a foundational part of quantum mechanics or whether decoherence makes them redundant. What I argue, on the contrary, is that decoherence does not *replace* these concepts but shows how and where we should apply them to interpret quantum mechanics; more specifically it shows where the 1$^{\text{st}}$ person, observable-first view fits into a broader 3$^{\text{rd}}$ person perspective. In short: decoherence produces a stable quasi-classical world in which observers operate, these observers rely on classical features and this implies that certain classical concepts are necessary for them to interpret the world.

It should be noted that in what follows I put aside criticisms and concerns about the success of the decoherence programme - such as whether it presupposes elements of classicality or a system-environment split - and assess it on what it *aims* to do.

I will start by reviewing the standard story about how decoherence produces observable properties and the mechanism that this focuses on. The basic idea, within the wavefunction or state realist views ([3, 6]), is that observable properties with definite values such as position and momentum are emergent properties established through decoherence. The fundamental ontology of the wavefunction (or spacetime regions) is not all there is.[21] Environmentally-induced decoherence selects a basis and eliminates inference effects, within each branch is appears *as if* collapse has occurred to give a single definite value. This occurs generally to produce the classical world but also in the specific case of measurements; the assumption is that *any* measurement involves decoherence at some stage, even when measuring interference effects (for example in the double slit experiment the electron is in a superposition when going through the slits but decoheres when it hits the screen). The measuring device is a complex system that acts as the environment in models of environmentally-induced decoherence.

The properties that emerge out of quantum mechanics do so through a specific process and the quantum objects that take on these properties are transformed in the process. The state is actively changed from a pure state or improper mixture into what is effectively a proper mixture, which can then be interpreted probabilistically. The 'effectively' here is crucial to decoherence. The argument is that the off-diagonal terms of the reduced density matrix, which are indicative of interference effects characteristic of quantum mechanics, are *effectively* zero and have negligible contributions to the dynamics of the system (see [36] for a technical presentation of this). This is what justifies treating these terms as zero and interpreting the resulting state as a probabilistic proper mixture with only diagonal elements. This is also done in a specific basis, which is what picks out the emergent property. Prior to decoherence we cannot attribute these emergent properties

[21] Not all versions of the wavefunction/state realist views rest on decoherence. Even with Everettian approaches it is possible to reject the centrality of decoherence (see [35] for a recent presentation). I focus here on the versions that do take decoherence to be an essential part of the story behind how we get observable properties. This represents the most detailed exploration of how these views relate to observable properties.

to the state, the interference terms are not negligible. Attributing classically understood properties such as precise position to the state is justified by decoherence taking place.

This mechanism is a formal way to derive classical mechanics, and the sort of objects and properties it deals with, out of quantum mechanics. But rather than just considering properties emerging through decoherence, I propose we also look at the *perspective* that emerges: the 1st person perspective. It is from this perspective that we are justified in taking an observable-first approach to interpreting the quantum state.

Looking at decoherence theory, there is plenty of evidence to support the idea that the 1st person perspective emerges out of the quantum world. (To reiterate, I will put aside potential criticisms of decoherence and focus on the conceptual project. The technical details of what I will discuss here are also beyond what is needed, they can be found in [36–38].) The central idea to be explored here is that establishing the classical world is what sets up the conditions needed for a macroscopic, classical observer to function - the 1st person perspective is defined in reference to such an observer.[22] The observer appears in the macroscopic classical domain and is reliant on its stability to function. Decoherence cannot presuppose the concept of an observer or have the observer play an active role in the mechanism, otherwise it cannot explain how we get these concepts out of a fundamentally quantum world. So the features of the world needed to make sense of observation must emerge.

As discussed above, the formal mechanism of decoherence involves deriving classical mechanics through looking at the effective diagonalization of the density matrix, or similarly deriving other key theoretical aspects of the classical world, such as classical information theory. Most of decoherence theory is concentrated on the physical mechanism behind this derivation and pays less attention to observers, which can be put in at the end (if at all). But the emergence of observers has been a prominent influence in the development of the decoherence programme. Two particular parts of the decoherence theory clearly exemplify how an observer should be situated in the resultant classical domain: the work of Gell-mann and Hartle [39] on modelling IGUSs (Information Gathering and Utilising Systems) in the decoherent histories framework and the more recent develop-

[22] Although, as discussed in section 2.2, the observer is a placeholder and not an essential part of the perspective.

ment of quantum darwinism [37]. The case of IGUSs in decoherent histories is more of a historical artefact that is not widely used today, but it is a good early example of how observers were taken to fit into decoherence and how decoherence was formulated with this in mind. Throughout the development of decoherent histories, the idea was that, once possible sets of histories were defined, accounting for observers and coming up with a *theory of experience* would be needed as a final step to help identify which histories tell sensible and persistent classical stories about the world, which would allow us to make predictions and retrodictions in the way we commonly do [38, 39]. Gell-mann and Hartle tried to do this using IGUSs, which were a basic model of an observer that takes in perceptual input, processes the information gained, and makes predictions based on it. System such as ourselves, which are types of IGUSs, "evolve to exploit" the stability the quasi-classical domain so as to do this ([39], p 245). The IGUSs are closely tied to the choice of coarse-grained operators that define the histories, and what information they take in and process is dependent on the classical properties represented by the operators.[23] Dowker and Kent [38] discuss how the exact role of IGUSs in Gell-mann and Hartle's work is somewhat unclear and not necessarily coherent. There are different options for how *active* a role the IGUSs play, it may be that they are slotted in at the end, or that they are necessary elements in the theory itself. But either way the aim of the project is clear: decoherence should produce the world in which observers such as ourselves operate.

This project has been taken up more recently in quantum darwinism, a development of decoherence focused on information theory that has been spearheaded by Zurek ([37] provides a recent thorough review). The main results from it are the derivation of the limits of classical information theory (such as bounds on the mutual information measure) and standards for intersubjectivity.[24] Some presentations of quantum darwinism take it to be producing a literal account of measurement indications [40], others take a more liberal reading along the lines of how IGUSs were modelled in decoherent histories. The

[23] Although Dowker and Kent argue that a theory of experience is still needed on top of a model of IGUSs to justify the assumption that the experience of an IGUS is indeed connected to the coarse-grained operators.

[24] Although whether this delivers intersubjectivity in the way implied in Wigner's friend type scenarios is debatable - what is meant by intersubjectivity in the context of quantum darwinism is the derivation of robust states that an observer can interact with with negligible disturbance, which is something taken for granted in classical observation.

latter view argues that the features of classicality that quantum darwinism derives are the conditions required for a human observer to evolve [41]; within the classical domain we can model observers and understand how they operate by taking advantage of these features. The general stability of the variables selected by decoherence allows for effective predictions and this means that observers, which require that sort of information input and output, can take advantage of that to navigate the world and act in their own interests.

The story of how observers fit into the world produced by decoherence has certainly not been told in its entirety. There are many remaining worries about the success of decoherence (including potential circularities in presuming classicality) and the full story of how observers operate is only loosely sketched out. The IGUSs in decoherent histories are the start of this project, quantum darwinism its current progress, but there is surely more needed. However, it is clear that this is part of the picture created by decoherence, and - conditional of course on the programme's success - it provides an account of how the position in the world that observers such as ourselves occupy emerges out of quantum mechanics and how observers are dependent on key features of classicality that ground our methods of observation.

So far this has all been thinking about observers in the style of the 3^{rd} person perspective: we are sitting as omnipotent, 3^{rd} person narrators describing how toy models of observers are slotted into the world. What does this mean for the nature of observers and the concepts that they use to describe the world from *their own* position? Here we can delve deeper into the connection between the 1^{st} person perspective and the observable-first approach.

The decoherence programme took much of its inspiration from the work of Niels Bohr (although whether it faithfully delivers what he actually envisioned is another matter - his work is notoriously hard to pin down and the decoherence programme merely uses it as a starting point, see for example the discussion of Bohr in [37]). Much of what Bohr says relates to the experimental capacities of an observer (which is central to how the 1^{st} person perspective is defined here as the situated position from which we interact with the world through measurement[25]) and he argues that classical concepts are required for

[25] It should also be noted that there is often a somewhat blurred distinction between the observer

this:

> "It is decisive to recognise that, however far the phenomena transcend the scope of the classical physical explanation, the account of evidence must be expressed in classical terms. The argument is simply that by the word "experiment" we refer to a situation where we can tell others what we have done and what we have learned and that, therefore, the account of the experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics." ([19], p. 209)

There are multiple ways this could be understood, and what is even meant by "the terminology of classical physics" is itself ambiguous. A common way of reading it is that Bohr believed that measurement required you to designate a subject doing the measuring (an observer) and an object being measured [23,42,43]. The observer has to be modelled as classical; all this really means is specifying how the observer must interact with the world to make that observation, which requires setting out a fixed state for the observer and how they materially interact with the world. This does not mean that the observer is in a new ontological category that cannot be reduced to quantum mechanics, merely that we must be able to ignore its quantum description, and the inevitable entanglement between them and the systems around them, to make sense of measurement.[26] This fixed description acts as a reference against which to compare the property being measured. This relates directly to what was argued in section 3: part of laying out the distinction between the observer and the observed system is describing the observed system in terms of its observable, quantifiable, properties [43].

How does decoherence try to deliver this? As caveated earlier, decoherence is inspired by Bohr but not a direct delivery of his ideas. Originally, decoherent histories (which started

and the apparatus of observation. I do not try to resolve this distinction; defining the observer in terms of how they can materially interact with the world and form physical correlations with it (which is the basis for observation) means that they are defined in terms of the apparatuses they can create, so the two concepts are inextricably linked.

[26]Bohr is often accused of positing that macroscopic and microscopic objects are ontologically different, but this misinterprets his epistemic claims as ontic ones. This separation between subject and object has been called *separability* [23,42].

out as consistent histories) was an extension of the Copenhagen interpretation in the work of Omnes, even if it now tends to be interpreted very differently (see [38,44] for a history). In later developments, decoherence captures Bohr's ideas by trying to explain why we have to switch into classical modes of description during measurement. Any measurement involves decoherence at some stage so as to produce an observable result in the lab. Widespread decoherence in the world creates the conditions for classical observers such as ourselves and explains why our perspective is inextricably linked to classical concepts: we are situated at the classical level and are reliant on classical features. Decoherence shows how this can be done without - as the Copenhagen Interpretation does - privileging the classical world over the quantum and presupposing classical concepts as fundamental; it produces the separation between the observer and the observed system, which is needed to make sense of measurement, from within quantum mechanics. Rocha, Rickles & Boge go so far as to say about the decoherent histories approach that "a quasi-classical world emerges to provide a home for Copenhagen interpretations." ([44], pg. 22).

The fact that the interactions of an observer with the quantum world through measurement *must* go via decoherence means that to understand our relation to the quantum world we have to use classical concepts to characterise the quantum systems and how we might investigate them. The physical specification of the measuring apparatus, and the processes such as decoherence that take place in it, are necessary because they lay out how the quantum world is related to us in our 1st person perspective. The emergence of the observers themselves can be understood from a 3rd person perspective as a result of the widespread decoherence in the world that produces a stable classical reality. But for an observer *in* the 1st person perspective, the observables of quantum mechanics and how they are instantiated in the measurement process must be the primary way of understanding how we relate to the quantum state.

The premise of emergence is that, at different levels, different concepts become explanatorily relevant and capture the structure of the world at that level of description. The metaphysical consequence of this is a plethora of ontologies suitable for different levels [11].[27] Observers such as ourselves exist at a certain level of reality and this selects certain concepts - such as the way that objects possess quantifiable properties that are apt for

[27] This programme of emergence is in many ways controversial and not universally accepted. I do not try to justify it in depth here. See fn. 3.

measurement - as being explanatory relevant for how the world is structured in relation to that level. We can forgot our position as observers and model other levels freely, this is the 3rd person perspective; but when it comes to modelling how we look at other levels *from our position as observers* we are restricted to the concepts that help define the level we exist at.

I have now described how, through decoherence, a perspective emerges in which the only means of interacting with the quantum world is through measurement and observation. This perspective requires us to primarily deal with the quantum state in terms of its observable properties, picked out by measuring apparatuses, and we must make these properties the basis for our understanding of how the quantum world relates to us; in other words it requires an observable-first approach to the quantum state. Widespread decoherence in the world creates the conditions for observers to occupy this position, and the fact that any measurement *will* contain decoherence reinforces it. But we can apply this view to the quantum state of a particular object we are interested in even when this object itself has not undergone decoherence, so long as *we* occupy the position created by decoherence. Any *possible* contact we could make with the state would be done on the basis of its observable properties, and so, when considering it from our perspective, these properties are necessary to formulate our questions about its nature.

5 Conclusion

This paper has identified how two styles of interpreting the quantum state - wavefunction or state realism and observable-first approaches - can be reconciled and understood through perspectives. Both serve distinct explanatory purposes and are needed to make sense of the world. Explaining the basis for measurement is an oft overlooked area, despite the centrality of measurement in quantum mechanics, and recognising that measurement depends on how properties in the quantum domain are characterised by observers such as ourselves establishes it as a process that *needs* such an explanation.

From the 1st person perspective, measurement is the foundational tool for understanding the world, and understanding the ontology of quantum systems through their observable properties is a natural, and necessary, way of making sense of our reliance on this process. At this emergent level this interpretation of the wavefunction has the most explanatory power. Adopting a perspectival view also allows us to talk far more easily about *prerequisites* of measurement. By acknowledging the perspective we are coming from when doing measurements, we can separate discussions of what goes into creating that perspective from questions about how measurement works. The broader 3$^{\text{rd}}$ person perspective can then explain how our 1$^{\text{st}}$ person perspective is formed and where the concepts that we rely on come from. But this should not take away from the importance of the 1$^{\text{st}}$ person perspective. From this point of the view, it is an objective fact that the world is describable in terms of observable properties and this is the best ontology we have for making sense of the world.

Recognising both the 1$^{\text{st}}$ and 3$^{\text{rd}}$ person perspectives - and not rejecting one in favour of the other - allows us to address the important question of how the world presents itself to us through measurement, while also enabling us to take a step back and imagine the world beyond us where we are just another type of physical system. The many different interpretations of quantum mechanics are torn between these two options and suffer for it. This paper describes how we could benefit from reconciling these perspectives and considering how our 1$^{\text{st}}$ person perspective is formed.

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