Decoherence, the measurement problem and realism

Peter Kearney[*]

8 November 2020

Contents

---

[*] Graduate student, The University of Queensland.

1 Introduction

Decoherence is a quantum mechanical phenomenon occurring in systems (typically of macroscopic scale) in interaction with their environment which results in the local and approximate suppression of distinctively quantum behaviour, such as quantum interference effects. The phenomenon of decoherence is a consequence of standard quantum mechanics and is experimentally well-confirmed. It is widely agreed that decoherence effects explain important aspects of the relationship between quantum mechanics and classical mechanics, the so-called "quantum-to-classical transition". It is also widely accepted that, as Schlosshauer and Camilleri put it, "the implications of decoherence are intimately related to interpretive issues of quantum mechanics ... in particular to the problem of measurement."[1] However, many commentators, including even proponents of the decoherence program, argue that decoherence does not solve the measurement problem, a key problem in the interpretation of quantum mechanics.[2] The issue is complicated by the fact

---

[1] Maximilian Schlosshauer and Kristian Camilleri, "The quantum-to-classical transition: Bohr's doctrine of classical concepts, emergent classicality, and decoherence," arXiv:0804.1609v1 [quant-ph] (2008).

[2] Amongst proponents of the decoherence approach, see H.D. Zeh, "The Program of Decoherence: Ideas and Concepts," in: Giulini et al. (eds), *Decoherence and the Appearance of a Classical World in Quantum Theory*: 16; Erich Joos, "Elements of Environmental Decoherence," in: P. Blanchard et al (eds), *Decoherence: Theoretical, Experimental, and Conceptual Problems*: 15.

that there are different characterizations of the measurement problem, and different views as to what constitutes a solution.

This paper will argue that decoherence can be seen as resolving the measurement problem, provided that one is willing to accept two key features of the resolution. The first is that the proposed resolution addresses only the "generic" measurement problem – "why do we get definite measurement outcomes?", rather than the "specific" measurement problem — "why do we get the particular outcome we do?"[3] The second feature of the proposed resolution is that measurement outcomes are *observer-dependent*, that is, measurement outcomes are only defined relative to a particular observational context, defined by a set of observational capabilities.

For many, this second feature will render the proposed resolution unacceptable because it seems to depart from the criterion of realism: the requirement that a scientific theory should (more or less accurately) describe an observer-independent reality. For the realist, the description provided by the theory should not include any dependence on or reference to an observer. I will argue, however, that evaluation of the decoherence resolution of the measurement problem against the criterion of "realism" requires a nuanced analysis of potentially applicable "realist" criteria. For example, it is sometimes argued that an approach to the quantum-to-classical transition should be regarded as "operationalist" or "instrumentalist" if the transition from quantum to classical descriptions depends on the empirical undetectability of deviations from distinctively quantum behaviour (as is the case on the decoherence analysis of the transition).[4] I will argue that this is based on an incorrect characterisation of "operationalism" or "instrumentalism" in the context of the quantum-to-classical transition.

While the issue of realism is often posed in a binary way – characterising an approach or interpretation as simply either realist or anti-realist – I suggest that interpretations can usefully be characterised along a spectrum as more or less realist, or correlatively, less or more observer-dependent. As one moves along the spectrum an increasingly objective viewpoint is adopted, in the sense of independence from any particular observational context. At one end of the spectrum (the most observer-dependent, least realist end) lie strongly instrumentalist approaches in which the experiences of individual

---

[3] These two aspects of the measurement problem are discussed in detail in section 3.2 below.

[4] See David Wallace, "Philosophy of Quantum Mechanics" in: Rickles (ed), *The Ashgate Companion to Contemporary Philosophy of Physics*: 38.

observers are taken to be ontologically primary, whereas the entities posited by the theory are regarded as mere tools in the hands of those observers to predict observations.[5] As one moves in the more realist (less observer dependent) direction, observations of individual observers are not taken as primary, but rather as secondary, derived from the (perhaps unobservable or not directly observable) entities posited by the theory, which are to a greater or lesser extent independent of particular observers or classes of observers. At the far realist end of the spectrum (which may or may not be attainable), all implicit or explicit reference to observers or observational contexts is eliminated so that all observational perspectives can be explained from an entirely observer-independent viewpoint. I designate this maximally realist ideal "Archimedean Realism", "Archimedean" because it seeks an Archimedean point from which the experience of all observers can be derived from a strictly observer-independent point of view.[6]

Based on this characterisation of the realist spectrum, I will argue that the decoherence approach to measurement outcomes is not instrumentalist because it derives the occurrence of measurement outcomes (observations) from the dynamical evolution of the quantum state, taking the latter as primary rather than the observations. Further, the decoherence framework transcends any of the particular perspectives of different observers and can relate those perspectives within the framework. It is thus to a certain extent observer-independent since it is not restricted to any particular observational context. However I will argue that the approach falls short of "full" observer independence (Archimedean Realism) because the properties of the "observer" (or, equivalently, "observational context") used in the analysis are assumed rather than derived, so that it does not provide an explanation of why certain particular observational contexts figure in our experience.

This paper is organised as follows. Section 2 provides a brief overview of "standard" quantum mechanics as a foundation for the following discus-

---

[5] Quantum Bayesianism might be seen as such a strongly instrumentalist approach to quantum mechanics. See Christopher A. Fuchs, N. David Mermin, and Rüdiger Schack, "An introduction to QBism with an application to the locality of quantum mechanics," *American Journal of Physics* 82 (2014).

[6] Huw Price refers to such an Archimedean view as follows: "One of the great projects in the history of modern thought has been the attempt to achieve the untainted perspective, the Archimedean view of reality — 'the view from nowhere', as the philosopher Thomas Nagel calls it." Huw Price, *Time's Arrow & Archimedes Point* (New York, Oxford: Oxford University Press, 1996): 4.

sion. Section 3 gives a brief introduction to the measurement problem and discusses the distinction between the "generic" and "specific" problems. Section 4 describes the decoherence approach to analysing measurement interactions and the way in which this can be seen as addressing the measurement problem. Various detailed objections to decoherence as a resolution of the measurement problem are considered, in the process drawing out further different aspects of the problem and the way in which, on the decoherence analysis, measurement outcomes are observer-dependent. Section 5 discusses in detail how the decoherence approach relates to instrumentalism on the one hand and Archimedean Realism on the other, arguing, as indicated above, that decoherence is not an instrumentalist approach but falls short of Archimedean Realism. I argue that proponents of the decoherence approach are faced with the choice of either adopting a fundamentally contextual approach which gives up on Archimedean Realism, or retaining the aspiration to Archimedean Realism and seeking deeper explanations of why certain observational contexts figure in our experience, through the positing of further physical structure which picks out certain observational contexts as "naturally occurring" in an observer-independent way.

2 "Orthodox" quantum mechanics

Decoherence does not in itself provide an "interpretation" of quantum mechanics. Rather, it is an application of the "standard" quantum mechanical formalism to specific system environment interactions which result in a local suppression of interference effects. To provide a solid foundation for the the following discussion, this section provides a brief presentation of "standard", "orthodox" or "conventional" quantum mechanics, as conventionally presented. This consists of the following elements.[7]

1. *States:* The possible states of a quantum system are represented by normalised vectors in some complex Hilbert space.

---

[7] This description follows David Wallace, "What is Orthodox Quantum Mechanics?" in: Alberto Cordero (ed). *Philosophers Look at Quantum Mechanics*: 285-312. Note that Wallace questions whether this orthodox presentation accurately represents the use of quantum mechanics in practice. In particular, he argues that the projection postulate and the eigenstate-eigenvalue link "do not in fact play any part in practical applications of quantum mechanics". The issue of the eigenstate-eigenvalue link is discussed further below.

2. *Observables*: To any physical quantity used to describe the system (often called an 'observable') is associated a self-adjoint operator on that same Hilbert space.

3. *Dynamics*: The state of a quantum system evolves over time according to the Schrödinger equation.

4. *The Born (probability) rule*: Suppose some quantity O has associated operator $\hat{O}$ which can be written $\hat{O} = \sum o_i \hat{\Pi}_i$ where the o_i are the distinct eigenvalues of the operator and $\hat{\Pi}_i$ projects onto the subspace of states with eigenvalue o_i . Then if O is measured on a quantum system with state $|\psi\rangle$, the only possible outcomes of the measurement are the eigenvalues o_i of the operator and the probability of the measurement giving result o_i is $Pr(O = o_i) = \langle\psi| \hat{\Pi}_i|\psi\rangle$.

5. *The projection postulate* (aka the collapse postulate): Suppose some quantity O, as above, is measured on a quantum system in state $|\psi\rangle$. Then the measurement induces a stochastic transition on the state, so that:

    (a) immediately after the measurement, the system is in one of the states $|\psi_i\rangle = \frac{\Pi_i|\psi\rangle}{||\Pi_i|\psi||}$

    (b) The probability that the system transitions into state $|\psi_i\rangle$ is given by $\langle\psi| \hat{\Pi}_i|\psi\rangle$.

6. *The eigenstate-eigenvalue link (E-E link):* Given a quantity O as above:

    (a) A system in state $|\psi\rangle$ possesses a definite value of O if and only if $|\psi\rangle$ is an eigenstate of $\hat{O}$, $\hat{O}\ |\psi\rangle = o_i|\psi\rangle$

    (b) In this case, the definite value is the associated eigenvalue o_i.

As Wallace notes, the Born rule can be derived from the projection postulate and the EE-link. Note further that using simply the Born probability rule, it is certainly the case that if the state is an eigenstate of an observable then measuring the observable will result in the corresponding eigenvalue with certainty. However the assumption that an observable has a definite value only if the state is in the corresponding eigenstate (call this the value-eigenstate link)[8] is not required by the Born rule and is an additional interpretive assumption. I will return in section 4.2.3 below to consider the role of the value-eigenstate link in the measurement problem.

3 The Measurement Problem

3.1 Aspects of the measurement problem

There are many different conceptions of the measurement problem, and obviously, the extent to which decoherence can contribute to its resolution depends on the precise conception of the problem.[9] This section presents an introduction to the measurement problem and distinguishes a number of different aspects of the problem. The presentation largely follows Schlosshauer.[10] Further aspects of the measurement problem are discussed in subsequent sections, in the course of discussing the decoherence approach to the problem.

A key issue underlying the measurement problem is that an undefined notion of "measurement" is used in the basic rules of quantum mechanics (specifically in the Born rule and the projection postulate: both rules are premised on the occurrence of a "measurement"). This is regarded by many physicists and philosophers as unacceptable in a fundamental theory such as quantum mechanics since the notion of "measurement" is inherently vague.[11] Furthermore, measurements are physical interactions, and if quantum mechanics is a fundamental theory, it should be possible to analyse measurements in terms of quantum theory itself, by describing the interaction between the system to be measured and the measuring apparatus, where both are described quantum mechanically.

Indeed quantum mechanics *can* be so used, but the quantum-mechanical

---

[8] Following Maximillian Schlosshauer, *Decoherence and the Quantum-to-Classical Transition* (Berlin, Heidelberg: Springer-Verlag, 2007): 59.

[9] For a useful overview of different formulations of the measurement problem in the context of standard quantum mechanics see Manuel Bächtold, "Five Formulations of the Quantum Measurement Problem in the Frame of the Standard Interpretation," *Journal of General Philosophy of Science* 39 (2008): 17–33.

[10] Maximillian Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics," *Reviews of Modern Physics* Volume 76 (October 2004): 1267-1305; Schlosshauer, *Decoherence and the Quantum-to-Classical Transition.*

[11] See John Bell, "Against measurement" in: John Bell, *Speakable and Unspeakable in Quantum Mechanics*: 213-231.

analysis of measurement raises a number of issues which constitute the "measurement problem." An idealised quantum description of measurement proceeds as follows.[12] Consider a system $\mathscr{S}$, represented by basis vectors $\{|s_n\rangle\}$ in a Hilbert space $H_{\mathscr{S}}$, which interacts with a measurement apparatus $\mathscr{A}$, described by basis vectors $\{|a_n\rangle\}$ spanning a Hilbert space $H_{\mathscr{A}}$ where the $\{|a_n\rangle\}$ are assumed to correspond to macroscopically distinguishable "pointer" positions that correspond to the outcome of a measurement. If $\mathscr{S}$ is initially in a superposition $\sum_n c_n|s_n\rangle$ and $\mathscr{A}$ is in the initial "ready" state $|a_r\rangle$ the linearity of the Schrödinger equation entails that the total system $\mathscr{S}\mathscr{A}$, assumed to be represented by the product Hilbert space $H_{\mathscr{S}} \otimes H_{\mathscr{A}}$, evolves according to

$$(\sum_n c_n|s_n\rangle)|a_r\rangle \quad \longrightarrow \quad \sum_n c_n|s_n\rangle|a_n\rangle \tag{3.1}$$

Here the initial superposition in the system "has been amplified to the level of the (typically macroscopic) apparatus, in the sense that the final superposition involves both the system and the apparatus".[13]

Schlosshauer defines three aspects of the measurement problem.[14]

1. *The problem of outcomes.* The standard rules of quantum mechanics do not permit attributing a definite value (or range of possible values) to the right-hand side of eq. 3.1 so it is not clear how any measurement outcome occurs as a result of the measurement interaction.

2. *The preferred-basis problem.* In quantum mechanics the observable which is measured is not uniquely defined by the quantum state. In the Born rule, outcomes of measurements depend on which observable is measured. Consequently, the right-hand side of eq. 3.1 can only represent a measurement outcome (or range of possible outcomes) if some preferred basis (corresponding to the projection operators of the observable) is defined. However the quantum mechanical measurement process represented by eq. 3.1 does not appear to pick out any such basis.

---

[12] Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics": 1269-1270.

[13] Schlosshauer, *Decoherence and the Quantum-to-Classical Transition*: 52.

[14] Ibid., 50-60; see also Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics": 1270-1272.

3. *The problem of the nonobservablility of interference.* In experiments such as the two-slit experiment interference patterns can be observed, which reflect the presence of quantum superpositions. However such interference patterns are not observed between macroscopically distinguishable "pointer" positions corresponding to the outcome of experiments. Despite this, the right-hand side of eq. 3.1 appears to represent a superposition of macroscopic pointer states. Why is it that no interference between such macroscopic states is observed?

These aspects of the measurement problem will be explored in greater detail below, in the context of evaluating the decoherence approach to the problem.

3.2 Different measurement problems: specific and generic, individual and statistical

A number of authors have drawn a distinction between two distinct measurement problems.[15] One can be described as the "generic" problem – "why do we get definite measurement outcomes?", the other as the "specific" problem – "why do we get the particular outcome we do?" In essence the specific problem is the problem of explaining why a particular outcome – as opposed to one of the other possible outcomes – occurs in a given run of an experiment, whereas the generic measurement problem is the problem of explaining how outcomes come about at all.[16] These same authors also suggest that the "specific" measurement problem is a pseudo-problem, resulting from a failure to accept that quantum mechanics is an irreducibly probabilistic theory.

---

[15] Jeffrey Bub, "The Measurement Problem from the Perspective of an Information-Theoretic Interpretation of Quantum Mechanics," *Entropy* 17 (2015): 7374-7386; Elise M. Crull, "Less Interpretation and More Decoherence in Quantum Gravity and Inflationary Cosmology," *Foundations of Physics* 45 (2015): 1019–1045; Časlav Brukner, "On the Quantum Measurement Problem" in: Bertlmann and Zeilinger (eds). *Quantum [Un]Speakables II*: 95-117. For a similar distinction, see also Schlosshauer, *Decoherence and the Quantum-to-Classical Transition:* 57.

[16] The terms "generic" and "specific" are due to Crull. Brukner and Bub instead refer to a "big" and "small" measurement problem, where the "big" problem refers to the specific problem and the "small" to the generic problem. Confusingly, Brukner's terminology has varied: in "On the Quantum Measurement Problem", Brukner takes the "big" measurement problem to be the "generic" problem (and the "small" the specific problem) but elsewhere he follows Bub in taking the "big" problem to refer to the specific problem and the "small" to the generic problem: see Maximilian Schlosshauer (ed), *Elegance and Enigma* (Berlin: Springer-Verlag, 2011): 143-4

For example, Brukner argues that

> If one accepts the possibility of quantum probabilities being fundamentally irreducible, [the specific problem] vanishes. ... Not only quantum mechanics, but every probabilistic theory in which probabilities are taken to be irreducible "must have" the [specific] problem. ... The lack of the [specific] problem in the probabilistic theories would contradict the very idea of having irreducible probabilities.[17]

Bub draws the distinction between the two problems as follows:

> The [specific] measurement problem is the problem of explaining how the dynamics of a quantum measurement process produces a definite outcome. The [generic] measurement problem is the problem of explaining how a classical probability distribution over macroscopic measurement outcomes emerges dynamically in a measurement process. On the information-theoretic interpretation, the [specific] measurement problem is a pseudo-problem. If the universe is genuinely indeterministic and measurement outcomes are intrinsically random, then it isn't possible to provide a dynamical explanation of how a system produces a definite outcome when it's measured—that's what it means for the measurement outcomes to be intrinsically random.[18]

Janssen refers to a closely related distinction between "ensemble" interpretations of the quantum state (in which the quantum state is taken to describe an ensemble of identically prepared physical systems) and "individual" interpretations in which the quantum state describes an individual physical system.[19] As she points out, an individual interpretation suggests that the problem of outcomes requires an explanation of how the right-hand side of eq. 3.1 is transformed into one of $c_n|s_n\rangle|a_n\rangle$ (a collapse of the superposition into one of its summands):

$$(\sum_n c_n|s_n\rangle|a_n\rangle) \quad \longrightarrow \quad |s_1\rangle|a_1\rangle \; or \; |s_2\rangle|a_2\rangle \; or \; ... \; |s_n\rangle|a_n\rangle \tag{3.2}$$

---

[17] Brukner, "On the Quantum Measurement Problem": 96-7.

[18] Bub, "The Measurement Problem": 7377.

[19] Hanneke Janssen, *Reconstructing reality: Environment-induced decoherence, the measurement problem, and the emergence of definiteness in quantum mechanics*, Master's thesis - Theoretical Physics Radboud University Nijmegen (philsci-archive.pitt.edu, 2008):13.

In the terminology introduced above, this corresponds to a solution of the specific measurement problem. However, under an ensemble interpretation, the problem of outcomes only requires an understanding of how the right-hand side of eq. 3.1 is transformed into a statistical mixture of states $|s_n\rangle|a_n\rangle$ each with probability $|c_n|^2$. This corresponds to Bub's description of the generic measurement problem as requiring an explanation of how a classical probability distribution over macroscopic measurement outcomes emerges in the measurement process.[20]

Since decoherence is based on "standard" quantum mechanics, which is undoubtedly a statistical theory, it cannot be expected to solve the specific measurement problem. At most decoherence could solve the generic measurement problem by showing that the superposition resulting from a quantum mechanical interaction between a system and a measuring apparatus can be understood as representing a probability distribution over definite outcomes.

4 Decoherence and the measurement problem

This section first presents an overview of the decoherence approach to analysing the measurement process, primarily following Schlosshauer.[21] I then proceed to consider various criticisms which have been made of the approach as a possible resolution of the measurement problem.

4.1 Suppression of interference and reduction to an approximate mixture

The decoherence program seeks to understand the emergence in quantum mechanics of approximately classical behaviour through the effects brought about by the quantum mechanical interaction of physical systems with their environment. It is based, as Schlosshauer observes:

> on the idea that ... nearly every physical system must interact in some way with its environment (for example, with the surround-

---

[20] Pessoa introduces a related distinction between, in his terminology, "collapse" as represented by eq. 3.2 above, as opposed to "decoherence", the transformation of the right-hand side of eq. 3.1 to a statistical mixture; see Osvaldo Pessoa Jr., "Can the decoherence approach help to solve the measurement problem?" *Synthese* 113 (1998): 324-5.

[21] Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics"; Schlosshauer, *Decoherence and the Quantum-to-Classical Transition.*

> ing photons that then create the visual experience within the observer), which typically consists of a large number of degrees of freedom that are hardly ever fully controlled. Only in very special cases of typically microscopic (atomic) phenomena ... is the idealization of isolated systems applicable so that the predictions of linear quantum mechanics (i.e., a large class of superpositions of states) can actually be observationally confirmed. In the majority of the cases accessible to our experience, however, interaction with the environment is so dominant as to preclude the observation of the "pure" quantum world [leading to] observable states ... corresponding to the "classical" properties of our experience. Interference between such states gets locally suppressed and is thus claimed to become inaccessible to the observer.[22]

In the context of measurement interactions, taking account of environmental interactions results in the following description of the measurement interaction (where the states $|e_0\rangle$, $|e_n\rangle$ represent initial and final states of the environment):

$$(\sum_n c_n|s_n\rangle)|a_r\rangle|e_0\rangle \quad \longrightarrow \quad \sum_n c_n|s_n\rangle|a_n\rangle|e_n\rangle \tag{4.1}$$

The density matrix for the right-hand side of eq. 4.1 is

$$\hat{\rho}_{\mathcal{SAE}} = \sum_{mn} c_m c_n^* |s_m\rangle|a_m\rangle|e_m\rangle\langle s_n|\langle a_n|\langle e_n| \tag{4.2}$$

As far as observations only on the $\mathscr{SA}$ subsystem are concerned we can consider only the local (or reduced) density matrix $\hat{\rho}_{\mathcal{SA}}$ obtained by "tracing out the unobserved degrees of freedom of the environment":

$$\hat{\rho}_{\mathcal{SA}} = \sum_{mn} c_m c_n^* |s_m\rangle|a_m\rangle\langle s_n|\langle a_n|\langle e_n|e_m\rangle \tag{4.3}$$

where $\hat{\rho}_{\mathcal{SA}}$ contains interference terms $|s_m\rangle|a_m\rangle\langle s_n|\langle a_n|$ $(m \neq n)$ since it cannot be assumed that the basis vectors of the environment $|e_n\rangle$ are necessarily mutually orthogonal. However, specific models of the system-environment interaction show that due to the large number of degrees of freedom of the

---

[22] Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics": 1273.

environment the states $|e_n\rangle$ of the environment rapidly approach orthogonality such that the reduced density matrix $\hat{\rho}_{\mathcal{SA}}$ becomes approximately orthogonal in the "pointer basis" $\{|a_n\rangle\}$:

$$\hat{\rho}_{\mathcal{SA}} \approx \sum_n |c_n|^2 |s_n\rangle|a_n\rangle\langle s_n|\langle a_n| \tag{4.4}$$

Consequently, the decohered local density matrix describing the probability distribution of the outcomes of a measurement on the system-apparatus combination is (approximately) identical to the mixed state density matrix that would be obtained if the $\mathscr{S}\mathscr{A}$ system were described by a proper mixture in which it is in one of the pure states $|s_n\rangle|a_n\rangle$ with probability $|c_n|^2$.

If the final state of the $\mathscr{S}\mathscr{A}$ system were indeed that proper mixture then the system-apparatus subsystem would be in one of the pure system-apparatus states with the specified probability, and the (generic) measurement problem would be solved (or never arise). In fact, as will be discussed in detail in section 4.2.2 below, the final state of the $\mathscr{S}\mathscr{A}$ system is *not* a proper mixture. However, the decoherence analysis shows that if the states $|e_n\rangle$ of the environment are approximately orthogonal and attention is restricted to measurements on the system-apparatus subsystem, then the subsystem will behave for all practical purposes *as if* it were in one of the pure system-apparatus states with the specified probability. On this basis decoherence can arguably be seen as resolving the (generic) measurement problem, at least for practical purposes.

Such a proposed resolution has however been subject to a range of criticisms. In the next section I turn to critically evaluate these criticisms and their implications for decoherence as a possible resolution of the measurement problem.

4.2 Criticisms and responses

In the following subsections I consider in turn a number of criticisms which have been made of the proposed decoherence-based resolution of the measurement problem. In each case I argue that the criticism can be countered provided that one is willing to accept two key features of the resolution. The first is that the proposed resolution addresses only the "generic" measurement problem, rather than the "specific" measurement problem. The second feature of the proposed resolution is that measurement outcomes are observer-dependent, in the sense that measurement outcomes are only defined relative to a particular observational context, defined by a set of observational capabilities.

4.2.1 Decoherence addresses the generic measurement problem

It is commonly noted that the decoherence analysis does not identify *which* of the outcomes occurs and on this basis it is claimed that it fails to solve the measurement problem.[23] If one regards an essential part of solving the measurement problem to be solving the *specific* measurement problem then decoherence does not achieve it. This limitation of decoherence is summed up by Tanona as follows:

> decoherence only mimics classicality in a statistical sense. It models the subsystem as a mixture that is interpretable as a classical mixture of different possible definite states. But it does not then account for specific results, for example, the electron going this way rather than that.[24]

This limitation of the decoherence approach is not surprising since decoherence relies on conventional quantum mechanics which is an inherently statistical theory. However, decoherence can be understood as addressing the *generic* measurement problem, understood statistically as "the problem of explaining how a classical probability distribution over macroscopic measurement outcomes emerges dynamically in a measurement process."[25]

4.2.2 Proper and improper mixtures: outcomes as observer dependent

A frequently made criticism of the decoherence approach is that the final approximately diagonal reduced density matrix of eq. 4.4 is an improper mixture rather than a proper mixture, and thus is not ignorance interpretable, that is, it cannot be interpreted as an ensemble of systems each in one of the

---

[23] Pessoa, "Can the decoherence approach help to solve the measurement problem?"; Stephen L. Adler, "Why decoherence has not solved the measurement problem: a response to P.W. Anderson," *Studies in History and Philosophy of Modern Physics* 34 (2003): 135–142.

[24] Scott Tanona, "Individuality and Correspondence: An Exploration of the History and Possible Future of Bohrian Quantum Empiricism," in: Jan Faye and Henry J. Folse (eds), *Niels Bohr and the Philosophy of Physics: Twenty-First-Century Perspectives*: 279.

[25] Bub, "The Measurement Problem": 7377.

pure states $|s_n\rangle|a_n\rangle$ with probability $|c_n|^2$. This is because it can be shown that if the reduced density matrix $\hat{\rho}_{\mathcal{SA}}$ of eq. 4.4 did represent such a pure mixture, the original final measurement state could not have been in the superposition $\sum_n c_n|s_n\rangle|a_n\rangle|e_n\rangle$.

This means that taking the reduced density matrix to be a pure mixture would be inconsistent with the predictions of quantum mechanics for measurement results on the whole $\mathscr{SAE}$ system. However the kinds of experiments which would be required to reveal such effects in the whole $\mathscr{SAE}$ system are in practice infeasible. They involve practically impossible recoherence of the environment and system. In some cases such measurements can even be impossible in principle: Omnes provides calculations suggesting that the size of a measuring apparatus required to reliably detect interference between macroscopic superpositions is larger than the size of the universe.[26]

The reduced density matrix can thus safely be treated as ignorance interpretable if it is assumed that such infeasible experiments are not performed. In other words, it is possible to justify taking the reduced state as ignorance interpretable on the basis that is *practically empirically indistinguishable* from an ignorance interpretable mixed state. Schlosshauer summarises the position as follows:

> For all practical purposes and for any local measurement performed on the system only, the statistics generated by the reduced density matrix ... of the system will then be (approximately) the same as those generated by the corresponding proper mixture (ensemble) of pure states.[27]

The restriction to local observables can be formalised by restricting the class of observables that can be applied to the system by excluding irrelevant or infeasible observations on the whole $\mathscr{SAE}$ system. This means restricting attention to an "effective" set of observables (represented by a set of operators in the formalism) which are, as Landsman puts it, "relevant to a local observer who/which is unable to perform highly nonlocal measurements".[28]

Now, the key point is that we can take the decoherence analysis as resolving the (generic) measurement problem *if we are willing to accept that*

---

[26] Roland Omnes, *The Interpretation of Quantum Mechanics* (Princeton: Princeton University Press, 1994): 307-9.

[27] Schlosshauer, *Decoherence and the Quantum-to-Classical Transition*: 333.

[28] N. P. Landsman, "Observation and Superselection in Quantum Mechanics," *Stud. Hist. Phil. Mod. Phys.*, Vol. 26, No. 1 (1995): 57.

measurement outcomes are only defined relative to a set of restricted observational capabilities. On such an approach, as Landsman observes,

> the essence of a 'measurement' lies in the non-observation, or irrelevance, of a certain part of the system in question ... Any event that 'happens' only comes into existence relative to such a choice of 'observables', and on the assumption of the ignorance interpretation of mixed states.[29]

On such an approach, then, the occurrence of definite outcomes is observer-dependent, or at least dependent on a specified set of observational capabilities, in the sense that measurement outcomes are only defined relative to a set of restricted observational capabilities.

4.2.3 The eigenstate-eigenvalue link

Sometimes the decoherence approach is criticised because it departs from the EE-link. For example, Bacciagaluppi complains that if a system is in a superposition of states then "the system simply lacks the properties that in the standard interpretation are associated with these states".[30]

It is certainly the case that the decoherence approach must depart from the EE-link, more specifically the value-eigenstate link, since it attributes definite values to the final superposition state resulting from a measurement even though that state is not a proper mixture of pure states. However, as discussed in section 2 above, the value-eigenstate link is not required by the quantum formalism, being rather an additional interpretive assumption. As Bub puts it

> The eigenvalue-eigenstate link is an interpretative principle, a *stipulation* about when an observable 'has a particular value,' that is not required by the kinematic structure of quantum mechanics. Alternative stipulations are possible.[31]

The decoherence resolution of the measurement problem thus depends on a *stipulation* that the reduced density matrix $\hat{\rho}_{\mathcal{SA}}$ of eq. 4.4 represents a

---

[29] Ibid., 45.

[30] Guido Bacciagaluppi, "Measurement and Classical Regime in Quantum Mechanics," in: Batterman (ed). *The Oxford Handbook of Philosophy of Physics*: 427.

[31] Jeffrey Bub, "Quantum Correlations and the Measurement Problem," *International Journal of Theoretical Physics* 53 (2014): 3366.

statistical distribution of definite outcomes. This stipulation is empirically justified by the fact that the reduced state is practically empirically indistinguishable from an ignorance interpretable mixed state, as discussed in the previous section. The stipulation can be seen, if you like, as “joining up” our experience of measurement outcomes with the quantum mechanical description of measurement.

4.2.4 Begging the question? – the measurement problem as a consistency problem

A criticism often made of the decoherence approach as a resolution of the problem of outcomes is that the solution assumes the Born rule which in turn *assumes* that there are definite outcomes of measurements (in the form of eigenvalues of observable operators). The charge is that decoherence thus assumes what it needs to prove.

Schlosshauer presents this line of criticism as follows:

> the trace operation, and thus the concept and interpretation of reduced density matrices, is based on the statistical interpretation and the usual measurement axioms of quantum mechanics ... consequently ... [the] existence of outcomes cannot be derived from any formal structure that is obtained by means of the trace rule, such as the reduced density matrix. Once the measurement axioms ... are dropped, we are left with a global entangled system–environment state that, according to the standard interpretation, does not allow us to say anything about the physical state of the system or to assign a particular outcome (i.e., a definite value of a physical quantity) to the system.[32]

Tanona also articulates this criticism:

> Using the partial trace to represent a subsystem of an entangled system is justified because it gets the measurement statistics right, and the claim that the subsystem will look decohered is a claim about what the subsystem will look like when it is measured. But measurement statistics are based on the Born rule, which describes results upon measurement, which of course in the

---

[32] Schlosshauer, *Decoherence and the Quantum-to-Classical Transition*: 333.

> standard interpretation is what you get upon collapse. So trying to use decoherence to avoid collapse does not really work.[33]

I suggest, however, that this criticism misconstrues what the problem of outcomes is and what is required for its resolution. Our everyday experience confirms the existence of measurement outcomes. The only reason their occurrence presents a *problem* is (apparently) quantum mechanics itself, since the quantum-mechanical model of measurement results in a superposition state which, it seems, cannot be regarded as a probability distribution over definite outcomes, according to the standard rules of the formalism.

Looked at in this way, the measurement problem is really a *consistency* problem – how can the *assumption* that measurements have outcomes be made consistent with the quantum-mechanical description of measurement as given in eqs. 3.1 and 4.1. As Bub puts it:

> The measurement problem is a consistency problem. What we have to show is that the dynamics, which generally produces entanglement between two coupled systems, is consistent with the assumption that something definite or determinate happens in a measurement process. The basic question is whether it is consistent with the unitary dynamics to take the macroscopic measurement 'pointer' or, in general, the macroworld as definite.[34]

Schlosshauer also points to the measurement problem as fundamentally a consistency problem. He refers to "the apparent dual nature and description of measurement in quantum mechanics" and observes that:

> On the one hand, measurement and its effect enter as a fundamental notion through one of the axioms of the theory [the Born rule]. On the other hand, ... we may model measurement as a physical interaction between two systems called "object" and "apparatus". What we would then intuitively expect—and perhaps even demand—is that when it's all said and done, measurement-as-axiom and measurement-as-interaction should turn out to be equivalent, mutually compatible ways of getting to the same final result. But quantum mechanics does not seem to grant us such simple pleasures. Measurement-as-axiom tells us that the

---

[33] Tanona, "Individuality and Correspondence": 279.

[34] Bub, "Quantum Correlations and the Measurement Problem": 3365.

> post-measurement quantum state of the system will be an eigenstate of the operator corresponding to the measured observable, and that the corresponding eigenvalue represents the outcome of the measurement. Measurement-as-interaction, by contrast, leads to an entangled quantum state for the composite system-plus-apparatus.[35]

I suggest that decoherence succeeds in providing the required resolution of the consistency problem, since it shows that observation of definite outcomes is compatible with the quantum mechanical analysis of measurement (albeit, given a number of assumed restrictions on what can be observed, as discussed in section 4.2.2). It can be seen as reconciling, in Schlosshauer's terminology, "measurement-as-axiom" with "measurement-as-interaction".

Furthermore, I suggest that the consistency proof provided by the decoherence analysis results in "measurement-as-interaction" *modifying* our understanding of "measurement-as-axiom". As I have argued above, in the decoherence analysis definite measurement outcomes only occur when decoherence has occurred and only relative to a restricted (local) class of observables. Thus in this approach, as I have argued, measurement outcomes are relativised to observers, or more specifically, observational capabilities. The Born rule itself contains no hint as to when it should be applied nor that definite outcomes may be observer-relative. The Born rule uses a notion of observer (and measurement) which lies outside the quantum-mechanical formalism whereas the decoherence analysis leads to an analysis of measurement from within the formalism which shows that measurement outcomes are relative to the observer (or, more precisely a set of observational capabilities). Further, the decoherence analysis suggests that application of the Born rule is only licensed when decoherence has occurred sufficiently to justify application of the rule, which in turn is always relative to specified local observational capabilities.

Similar comments apply in respect of the collapse postulate. Decoherence can be seen as a "no-collapse" approach, since in the decoherence approach the whole $\mathscr{SAE}$ system remains in a pure state, without collapse. The only collapse involved is an approximate, for all practical purposes "effective" collapse to an approximate statistical mixture of states for the sub-system $\mathscr{SA}$ and that statistical mixture is *derived* (given certain assumptions and approximations) from the uncollapsed state of the $\mathscr{SAE}$ system. As argued

---

[35] Schlosshauer (ed), *Elegance and Enigma*: 141.

above, the decoherence analysis suggests re-interpreting both the Born rule and the collapse postulate as being merely effective and observer-relative, that is, as embedding the collapse as an effective one within an overall "no-collapse" approach.

Another way of looking at this is that the decoherence analysis takes as its necessary *epistemological* starting point the occurrence of outcomes but it does not take the occurrence of such outcomes as *ontologically* or explanatorily primary. As Bitbol argues:

> Having been used as an indispensable starting point of an epistemic process is not equivalent to having more ontological weight than the end product of this very epistemic process. One should realize that choosing a starting point has no ontological implication at all.[36]

Returning to the initial charge of begging the question, we can see that the decoherence analysis takes the occurrence of outcomes as epistemologically given in our experience, but it takes the quantum state (in the form of the the whole "uncollapsed" $\mathscr{SAE}$ system state) as ontologically primary and shows how our experience of outcomes can be reconciled with that ontology, given various limitations on our observational capabilities. Importantly, that reconciliation depends on taking outcomes to be observer-relative, that is, dependent on the specification of an observational context, including a restriction to local observations.

4.2.5 Selection of a preferred basis and the system-environment split

The decoherence approach also seeks to resolve the preferred basis problem (see section 3.1 above) through an analysis of interactions with the environment. The most widely discussed proposal is that of Zurek, who proposes that the preferred pointer basis be taken as the basis which contains a reliable record of the state of the system, that is, the basis in which the system-apparatus correlations $|s_n\rangle|a_n\rangle$ are left undisturbed by the subsequent

---

[36] Michel Bitbol, "Decoherence and the Constitution of Objectivity," in Bitbol et al. (eds). *Constituting Objectivity*: 354.

formation of correlations with the environment (the *stability criterion*).[37] Schematically, this requirement can be represented as:[38]

$$|s_n\rangle|a_n\rangle|e_0\rangle \quad \longrightarrow \quad |s_n\rangle|a_n\rangle|e_n\rangle \, for \, all \, n. \tag{4.5}$$

The key motivation for the stability criterion is that a practically reliable measurement of the system by the apparatus will not be achieved if correlations between the system and the apparatus are not preserved under environmental interactions, given that any realistic measurement apparatus will be in continuous interaction with its environment.

Not just any basis will satisfy eq. 4.5 and the identification of a stable basis for a measurement interaction depends on a detailed analysis of the interaction. For simplified models of measurement interactions, Zurek has shown that a sufficient condition for the correlations between the eigenstates of the quantum system and the apparatus to remain intact under the evolution induced by the environment is that the apparatus-environment interaction Hamiltonian commutes with the pointer observable.

Zurek's result is somewhat technical but can be understood in simplified terms as follows.[39] For simplicity we consider only environmental interactions with the apparatus. We seek states $|a_i\rangle$ of the apparatus such that the composite apparatus-environment state, when starting from a product state $|a_i\rangle|e_0\rangle$ at time $t = 0$ remains in the product form $|a_i\rangle|e_i(t)\rangle$ at subsequent times $t > 0$ under the action of an interaction Hamiltonian $\hat{H}_{int}$. It can be seen that states $|a_i\rangle$ will satisfy this condition if they are eigenstates of the part of the interaction Hamiltonian $\hat{H}_{int}$ pertaining to the Hilbert state of the apparatus, since such states will be preserved by $\hat{H}_{int}$. It can be shown that this will be the case when the corresponding projector operators $|a_i\rangle\langle a_i|$ commute with $\hat{H}_{int}$ or, equivalently, when any apparatus observable $\hat{O}_A$ with eigenstates $|a_i\rangle$

$$\hat{O}_A = \sum_i \lambda_i |a_i\rangle\langle a_i| \tag{4.6}$$

---

[37] W. H. Zurek, "Pointer basis of quantum apparatus: into what mixture does the wave packet collapse?" *Physical Review D* Volume 24, Number 6 (15 September 1981): 1516-1525.

[38] Schlosshauer, *Decoherence and the Quantum-to-Classical Transition*: 75.

[39] See Schlosshauer, *Decoherence and the Quantum-to-Classical Transition*: 77-8 for more details.

commutes with $\hat{H}_{int}$.[40]

In most realistic cases, the stability criterion can usually only be fulfilled approximately. In further work, Zurek and others have developed methods (dubbed the "predictability sieve" strategy) which aim to determine the states of the system that are most robust in the presence of environmental interaction. Application of this method leads to a ranking of the possible preferred states with respect to their robustness under interaction with the environment. The most stable states will also be the most predictable in the sense that in those states loss of "information" about the state of the system is minimised.[41]

In further related work, Zurek and co-workers have considered how the environment of a system stably encodes information about the system and investigated the kind of information which is

> both redundantly and robustly stored in a large number of distinct fragments of the environment in such a way that multiple observers can retrieve this information without disturbing the state of the system, thereby achieving effective classicality of the state.[42]

This program of work has gone under the names "environment as a witness" and "quantum Darwinism" (the study of what information about the system can be stably stored and proliferated by the environment). This work has shown that the observable of the system that can be imprinted most completely and redundantly in many distinct subsets of the environment coincides with the pointer observable selected by the stability criterion and the predictability sieve.[43]

---

[40] Ibid., 77-8. This argument draws on the result that commuting operators share a common eigenbasis. See for example R. Shankar, *Principles of Quantum Mechanics*, 2nd edition (New York: Springer Science+Business Media, 1994): 43-4.

[41] Schlosshauer, *Decoherence and the Quantum-to-Classical Transition*: 82; W. H. Zurek, "Preferred states, predictability, classicality, and the environment induced decoherence," *Prog. Theor. Phys.* 89 (1993): 281-312.

[42] Schlosshauer, *Decoherence and the Quantum-to-Classical Transition*: 86.

[43] H. Ollivier, D. Poulin and W. H. Zurek, "Emergence of objective properties from subjective quantum states: Environment as a witness," *Phys. Rev. Lett.* 93 (2004): 220401 (1-4); H. Ollivier, D. Poulin, and W. H. Zurek. "Environment as a witness: selective proliferation of information and emergence of objectivity," *Phys. Rev. A* 72 (2005): 042113 (1-19).

There are two key issues which arise in relation to all of these approaches to selecting the preferred basis: justification of the selection criteria and the choice of a system environment decomposition.

Justification of the selection criteria. What justifies the choice of criteria such as stability and predictability for the selection of a preferred basis? The criteria can plausibly be motivated on pragmatic grounds because preservation of apparatus states and system-apparatus correlations in the presence of environmental interactions seem to be reasonable (indeed essential) criteria for a practically useful measurement process. However one can also ask more generally why it is that we observe outcomes in terms of the resulting preferred bases. Again, there is a certain plausibility in the idea that creatures such as us need to rely on stable and predictable correlations to practically navigate in the world and might as a result perceive the world in terms of such bases. However such proposed explanations face the problem of the choice of the system environment decomposition, discussed next.

Choice of system environment decomposition. All of the system environment interactions considered in the decoherence analysis (including in the predictability sieve and quantum Darwinism programs) depend on a prior decomposition of the total Hilbert space into subsystems. Preferred bases can only be derived based on criteria such a stability and predictability once a decomposition of the Hilbert space is chosen. Consequently to explain why we observe outcomes in terms of the preferred bases requires a prior explanation as to why we observe the world in terms of certain preferred decompositions into subsystems.

However, the required split between subsystem and environment is not dictated by quantum mechanics. As Tanona points out:

> The critical step in making a decoherence claim is the privileging of one incomplete description over a more complete one. As the incomplete description can claim to describe, at best, a particular subsystem, identifying the subsystem from the total system state is a precondition for decoherence. ...
>
> There are several ways in which one might ‘pick out’ a subsystem out of a tensor product space. The Hilbert space H of a state of a compound system in general has many tensor product factorizations $H_1 \otimes H_2$ ... Choosing a particular factorization ... corresponds to a particular subsystem division of what is otherwise indeterminate with respect to the independent existence

> of subsystems. Absent an independent justification for such a factorization, choosing one factorization over another is arbitrary because the other ones are also theoretically legitimate.[44]

A number of other authors have pointed out that the division into subsystems is not dictated by the underlying quantum mechanics. For example, Zanardi points out that

> Given a physical system S, the way to subdivide it in subsystems is in general by no means unique. ... Without further physical assumption, no partition has an ontologically superior status with respect to any other. Considering a given partition as privileged has a strong operational meaning, in that it depends on the set of resources effectively available to access and to control the degrees of freedom of S.[45]

Similarly, Zanardi et al argue that:

> the partition of a quantum system into subsystems is dictated by the set of operationally accessible interactions and measurements. The emergence of a multi-partite tensor product structure of the state-space ... [is] ... then relative and observable-induced.[46]

In summary, because the choice of system-environment split is not dictated by quantum mechanics, the decoherence based analysis of measurement outcomes requires the independent stipulation of a system-environment split, that is, a factorisation of the total Hilbert space into subsystems.

We have seen in section 4.2.2 above that in the decoherence-based solution to the (generic) measurement problem defended here the occurrence of definite outcomes is observer-dependent in the sense that measurement outcomes are only defined relative to a set of restricted observational capabilities. We now see that there is another aspect of this observer-relativity, since the decoherence analysis depends on a prior choice of system-environment split, which is not dictated by quantum mechanics and could potentially vary from observer to observer.

---

[44] Scott Tanona, "Decoherence and the Copenhagen Cut," *Synthese*, Vol. 190, No. 16 (November 2013): 3635.

[45] Paolo Zanardi, "Virtual Quantum Subsystems," *Physical Review Letters,* Volume 87, Number 7 (13 August 2001): 077901-4.

[46] Paolo Zanardi, Daniel A. Lidar and Seth Lloyd, "Quantum tensor product structures are observable-induced," *Physical Review Letters,* Volume 92, Number 6 (10 February 2004): 060402-1-4.

4.3 Decoherence as a resolution of the measurement problem

Drawing together the arguments of section 4.2, I contend that decoherence can be seen as providing a solution to the generic measurement problem provided that one is willing to accept that measurement outcomes are observer-dependent.

As argued in section 4.2.2, it is possible to justify taking the final approximately diagonal reduced density matrix $\hat{\rho}_{S\mathcal{A}}$ in eq. 4.4 as ignorance interpretable (that is, as representing an ensemble of systems each in a definite state, corresponding to definite measurement outcomes) on the basis that it is *practically empirically indistinguishable* from such ignorance interpretable mixed state, provided that attention is restricted to certain local observations on the system-apparatus subsystem. The decoherence analysis can thus be seen as resolving the (generic) measurement if we are willing to accept that measurement outcomes are only defined relative to such a set of restricted observational capabilities.

Such an identification of the density matrix of eq. 4.4 as representing an ensemble of systems each in a definite state, corresponding to definite measurement outcomes, departs from the value-eigenstate link. However, as argued in section 4.2.3, the value-eigenstate link is not required by the quantum formalism, being rather an additional interpretive assumption. Once it is understood that whether an observable "has a particular value" is a matter of stipulation, the way is open to stipulate that the reduced density matrix $\hat{\rho}_{S\mathcal{A}}$ in eq. 4.4 represents a statistical distribution of definite outcomes. The stipulation is in turn empirically justified by the fact that the reduced state is practically empirically indistinguishable from an ignorance interpretable mixed state, given a restriction on what observations can be made on the whole $\mathscr{S}\mathscr{A}\mathscr{E}$ system.

The observer-dependence of measurement outcomes in this approach arises from, first, the adoption of a system-environment decomposition as required for the decoherence analysis to operate (as argued in section 4.2.5 above) and secondly on the restriction to certain local observations on the system-apparatus subsystem. Neither of these can be derived from quantum mechanics alone. Thus, on this approach, measurement outcomes are only defined relative to a specified observational context, comprising a system-environment decomposition and a restriction to certain local observations on the system-apparatus subsystem.

I have argued in section 4.2.4 that the measurement problem should be understood as a consistency problem and that decoherence succeeds in providing the required resolution of the consistency problem, since it shows that observation of definite outcomes is compatible with the quantum mechanical analysis of measurement (given a number of assumed restrictions on what can be observed). Importantly, that reconciliation depends on taking outcomes to be observer-relative, that is, dependent on the specification of an observational context.

For many, the observer-dependence of measurement outcomes will render the proposed decoherence-based resolution of the measurement problem unacceptable on the grounds that it departs from realism – the idea that a scientific theory should (more or less accurately) describe an observer-independent reality. I turn in the next section to evaluate the extent to which the observer-dependence of measurement outcomes is compatible with a realist view of scientific theories.

5 Decoherence, observer-dependence and realism

5.1 Observer-dependence and realism

As foreshadowed in the introduction, I argue that assessing the "realism" or otherwise of the decoherence explanation of measurement outcomes is not a straightforward binary assessment. Rather, the decoherence approach needs to be assessed against a realist spectrum ranging from a radically instrumentalist view at one end to Archimedean Realism at the other. As one moves along the spectrum an increasingly objective viewpoint is adopted, in the sense of independence from any particular observational context. Recall that Archimedean Realism seeks to explain the experiences of all observers from a completely observer-independent "context-free" perspective, a "view from nowhere", in Nagel's terminology.[47] This can be contrasted with the view at the extreme anti-realist end of the spectrum, which takes the experiences of observers as primary: the view from "here".[48] The goal of Archimedean

---

[47] Thomas Nagel, *The View From Nowhere* (New York, Oxford: Oxford University Press, 1986).

[48] Ibid., 70.

Realism is closely related to the program of “closing the circle” which, as described by Shimony, seeks

> to understand the knowing subject as an entity in nature ... Such a program aims at the integration of epistemology with the natural sciences and metaphysics. It intends to show how ... the resulting view of the world can account for the cognitive powers of the knowing subject. For brevity I shall refer to this program as *“closing the circle.”*[49] ...
>
> The program envisages the identification of the knowing subject (or more generally, the experiencing subject) with a natural system that interacts with other natural systems. In other words, the program regards the first person and an appropriate third person as the same entity. From the subjective standpoint the knowing subject is at the center of the cognitive universe, and from the objective standpoint it is an unimportant system in a corner of the universe.[50]

Archimedean Realism seeks to “close the circle” by explaining the experiences of observers from a totally objective point of view, completely independent of any particular observational perspective.

5.2 Decoherence is not instrumentalist

Quantum mechanics has traditionally been regarded as difficult to understand as a realist theory because it includes an irreducible reference to “measurement” in its fundamental postulates (specifically the Born rule and the collapse postulate). Incorporating such a primitive reference to measurement seems to introduce an ineliminable reference to an observer (or at least an observational context) in the basic premises of the theory. A theory which takes “measurement” as a primitive can be seen as lying at the instrumentalist end of the spectrum since it seems to eschew any attempt to explain what a measurement *is*, or how measurement outcomes come about.

As argued in section 4.2.4 above, decoherence provides an analysis of how measurement outcomes can occur without any use of a primitive “collapse”

---

[49] Abner Shimony, “Reality, causality and closing the circle,” in: Abner Shimony, *Search for a Naturalistic Worldview*, Vol. 1: 21.

[50] Ibid, 40.

postulate: it shows how a statistical version of an “apparent collapse” can occur in the sense of an approximate reduction to a mixed state, but without assuming any collapse of the global quantum state. It seeks to provide a dynamical explanation of the occurrence of measurement outcomes (in the sense of addressing the generic measurement problem) based on the unitary evolution of the quantum state under certain interaction Hamiltonians. Consequently, it is not instrumentalist since it seeks an underlying physical explanation of measurement outcomes. It might be objected that at root the decoherence approach retains reference to a primitive notion of measurement since it utilises the Born rule to justify its analysis. However, as argued in section 4.2.4 above, the decoherence analysis, while taking the occurrence of measurement outcomes as an epistemological starting point, ends up explaining such outcomes from a deeper reality, namely the unitary evolution of the quantum state. The production of outcomes is thus no longer an unanalysed primitive of the theory.

Decoherence can thus be taken as lying some way along the realist spectrum. It does not take observational outcomes as a primitive but seeks an explanation of the occurrence of measurement outcomes based on the dynamical evolution of the quantum state.

5.3 Decoherence is realist but not conservatively realist

While decoherence is thus not an instrumentalist approach, the decoherence analysis of measurement retains an implicit reference to an “observer” since the explanation of measurement outcomes is, as argued in section 4.3 above, relative to a class of observers (or, more specifically, a class of observational capabilities). This dependence of measurement outcomes on a class of observational capabilities sometimes leads to the criticism that the decoherence approach to measurement outcomes is “operationalist” or “instrumentalist”, that it is “merely” a tool to predict experiments rather than a description of independent reality. As Wallace puts it:

> There is no exact translation between classical and quantum descriptions, only one whose imprecisions are too small to be detected empirically. But if QM — if science generally — is merely a tool to predict results of experiments, it is unclear at best that we should be concerned about ambiguities which are empirically

> undetectable in practice.[51]

Similar concerns underlie the often-made criticism that a derivation of measurement outcomes which is relative to a set of observational capabilities (as in the decoherence approach) is merely a solution "for all practical purposes", rather than a reflection of independent reality.

I contend, however, that it is incorrect to dismiss an approach as "operationalist" simply because the translation to a classical description is defined only relative to a class of observational capabilities. Realism requires that measurement outcomes be explained from a (comparatively) observer independent theory but it does not require that measurement outcomes be *themselves* observer-independent. To insist that measurement outcomes be observer-independent is simply to beg the question against an analysis which concludes that they *are*.

According to the decoherence analysis, classical reality (including the occurrence of definite measurement outcomes) *is* approximate and observer-relative in a way which can be explained from a deeper theory, that is, quantum mechanics. Relevant here is Landsman's distinction between two kinds of realism, which he calls A-realism and B-realism. The first "maintains that there exists a real world independently of the observer, and that one can make objective, observer-independent statements about it."[52] The second claims that "this postulated real and independently existing world coincides with, or at least incorporates, the classical world of 'events' and 'facts' that we observe around us". He argues that an advocate of decoherence type solutions to the measurement problem

> will definitely reject B-realism at least when analysing such solutions, for it is the whole point of these approaches to show that under certain conditions the classical world emerges relative to, say, local observables. From the point of view of a B-realist, such solutions are at best valid 'for all practical purposes' (FAPP), and thus a large body of criticism on ... decoherence approaches can be summarized simply by saying that these approaches do not conform to B-realism. We believe that this type of critique is ... blind to the fact that the notion of classical reality itself is

---

[51] Wallace, "Philosophy of Quantum Mechanics": 38.

[52] Landsman, "Observation and Superselection in Quantum Mechanics": 47.

> only valid FAPP (and not quantum mechanics, or resolutions of the measurement problem based on it).[53]

Adopting the somewhat more descriptive term "conservative realism" for Landsman's B-realism, we can say that the decoherence approach to measurement outcomes does not conform to conservative realism. However, I contend that the decoherence is nevertheless a realist approach since it derives (observer-dependent) measurement outcomes from a deeper, comparatively observer-independent, reality (namely the unitary evolutionary of the whole quantum state). Indeed once it is accepted that measurement outcomes are observer-dependent, as suggested by the decoherence approach, then the decoherence analysis of measurement outcomes can be understood as *less anthropocentric* than conservative realism. As Khalfin and Tsirelson put it:

> It is hard to adopt the idea that our classical reality is singled out not by nature in itself, but by our specific position within nature. However, it is this idea that seems to be the next step away from our anthropocentrism. We acknowledge that another observer may disagree with us not only on the meaning of "up" and "down," but even on the meaning of classical reality.[54]

It should be noted here that the observer-relativity of classical reality is mitigated in a number of ways. The class of "observers" with respect to which classical reality is defined does not include any reference to subjectivity or consciousness: the class of observers is defined only by reference to certain specific (limited) physical capacities. Further, classical reality is objective and "observer-independent" in a restricted sense in that the class of observers can be defined sufficiently broadly so as to include all human observers in typical circumstances so that classical reality is the same for all those observers ("weak objectivity" in d'Espagnat's terminology).[55]

Decoherence re-contextualises classical reality as being only "weakly objective", not fully objective in the sense of existing from a completely observer-independent point of view. However decoherence is nevertheless

---

[53] Ibid., 47-8.

[54] Leonid A. Khalfin and Boris S. Tsirelson, "Quantum/Classical Correspondence in the Light of Bell's Inequalities," *Foundations of Physics*, Vol 22, No. 7 (1992): 904.

[55] Bernard d'Espagnat, *On Physics and Philosophy* (Princeton: Princeton University Press, 2006): 94.

a (comparatively) realist approach since it does not take classical measurement outcomes as simply given, but rather derives them from a wider framework (quantum mechanics), within which classical reality (and measurement outcomes) are shown to be observer-dependent. Further, the decoherence framework is capable of relating the perspectives of different observers, again within a wider frame. If the different capabilities of different observers (that is, the different classes of observable accessible to the different observers) are specified then decoherence analysis can derive the "classical reality" accessible to those different observers. The decoherence framework thus transcends any of the particular perspectives of different observers and can relate those perspectives within the framework. The decoherence analysis is thus not "context bound" in the way that classical reality is. It situates classical reality as observer-dependent within a broader (comparatively observer-independent) realist perspective.

5.4 Decoherence: Contextual or Archimedean Realism?

While the decoherence analysis transcends any particular observational context, the decoherence approach can only explain the appearance of definite outcomes once an observational context is specified. Such an observational context depends on a split between a subsystem (the system-apparatus subsystem) and the environment, and a restriction to local observations on the subsystem only. As we have seen in section 4.2.5, however, the required split between subsystem and environment is not dictated by quantum mechanics. While it is clear that certain subsystem partitions are preferred in our experience, decoherence cannot on its own explain why that is so, because, as Hemmo and Shenker observe,

> When one appeals to the structure of the interactions in the universe, say the decoherence interaction, or the fact that the interactions between macroscopic systems are local, one presupposes the factorization that features in our experience of the total set of degrees of freedom.[56]

---

[56] Meir Hemmo and Orly Shenker, "Why the Many Worlds Interpretation of Quantum Mechanics Needs More Than Hilbert Space Structure," in: Peels et al. (eds), *Scientific Challenges to Common Sense Philosophy*: 63-4.

Thus, while decoherence can show how measurement outcomes *can* occur, in the sense that their occurrence is consistent with unitary quantum mechanics, once a system-environment split is specified, it cannot on its own show that measurement outcomes *must* occur, given quantum mechanics alone, since it cannot derive from quantum mechanics alone the relevant observational contexts.

To explain the fact that we experience measurement outcomes decoherence requires the specification of an observational context. Consequently the decoherence explanation of measurement outcomes falls short of the ideal of Archimedean Realism, which would require that our experience of measurement outcomes be explained from a completely observer-independent theory. While observational contexts relevant to our experience can be taken as pragmatically given on the basis of observation and experience, Archimedean Realism would require that an explanation of why these observational contexts figure in our experience be provided from an underlying "context-free" theory.

The proponent of the decoherence approach can respond to this situation in one of two ways, the first adopting a fundamentally contextual approach which gives up on Archimedean Realism, the second retaining the aspiration to Archimedean Realism and seeking deeper explanations of why certain observational contexts figure in our experience.

5.4.1 Decoherence as contextually realist

The first, contextual, approach suggests that a solution of the measurement problem does not require a *derivation* of classical reality from the quantum formalism without further assumptions, but only a demonstration that the occurrence of definite outcomes is *consistent* with the quantum formalism, given certain assumptions (derived from experience) about the division of the world into local subsystems. For example, Bitbol argues that:

> one only needs to demonstrate (and one has indeed demonstrated by means of the decoherence theories) that when applied to a preliminary anthropocentered division of the world into objects, apparatuses ... environment, the quantum probability theory is not unable to give us back the mutually exclusive event-structure which human experimenters need to posit as a basic methodolog-

> ical assumption.[57]

This means in effect to give up on the aspiration to "close the circle". The "preliminary anthropcentered division of the world" is not derived but taken as given in experience without further explanation. The contextual approach is content to accept, as Karakostas argues:

> the impossibility of a perspective-independent account, since one must at the outset single out an experimental context (determined by a set of co-measurable observables for the context-cum-quantum system whole) and in terms of which the definite result of a measurement can be realized ...[58]

Such a view gives up the project of "closing the circle":

> There is no such a thing as a 'from nowhere' perspective or a universal viewpoint. ... It would have to include within a hypothetically posited ultimate theory an explanation of the conditions for observation, description and communication which we ourselves, as cognizant subjects, are already subjected to.[59]

The contextual approach suggests a Bohr-style Copenhagen-like position in which classical reality and definite outcomes are only obtained once an observational context is supplied, but that observational context is not supplied by the fundamental formalism. Such a Copenhagen-style role for decoherence is proposed by Tanona, who suggests that

> the [quantum] states describe the appearance of properties in different contexts ... . Quantum states then determine both how a system will evolve in time in a closed system and how the system will appear in interactions in an open system. ... We may think of states as reflecting real features of reality but by themselves not reflecting the relational perspective of those in a measurement context ... [60]

---

[57] Michel Bitbol, "Form and Actuality" in: Mugur-Schächter and van der Merwe (eds), *Quantum Mechanics, Mathematics, Cognition and Action Proposals for a Formalized Epistemology*: 403.

[58] Vassilios Karakostas, "Forms of quantum nonseparability and related philosophical consequences," *Journal for General Philosophy of Science* 35 (2004): 306.

[59] Ibid.

[60] Tanona, "Individuality and Correspondence": 284.

We should note, however, that the decoherence analysis goes beyond the original version of Bohr's version of Copenhagen interpretation in which the observational context had to be specified in purely classical terms. Decoherence allows the observational context to be specified and analysed within quantum mechanics, for example by a preferred factorisation of Hilbert space and set of preferred observables (although it does not determine which contexts apply). It should also be noted that the analysis is not tied to any one observational context – it is capable of analysing any specified context. However, it does not explain why the particular contextual perspectives that *we* occupy are constrained in the way they seem to be.

A contextualist decoherence approach can nevertheless be seen as a (comparatively) realist approach, since it derives observational outcomes from a deeper underlying reality which is not bound to any particular observational context. However the approach is not Archimedean realist since it can only derive observational outcomes once certain observational contexts are specified, and does not explain why the the particular contextual perspectives that we occupy are constrained in the way they seem to be.

5.4.2 Seeking Archimedean Realism

Rather than settling for a contextually realist theory, the proponent of the decoherence approach could seek to explain why the particular contextual perspectives that we occupy are constrained in the way they seem to be. Some proponents of the decoherence program have made suggestions for providing such an explanation. For example, Zurek seeks to motivate the stability criterion by arguing that creatures such as us need to rely on stable correlations to practically navigate in the world. This leads to the idea that evolutionary considerations might be able to account for the fact that the bases selected by the stability and predictability criteria are those in which we perceive and act upon the world. As Zurek puts it,

> Our senses did not evolve for the purpose of verifying quantum mechanics. Rather, they have developed in the process in which survival of the fittest played a central role. There is no evolutionary reason for perception when nothing can be gained from prediction. And, as the predictability sieve illustrates, only quantum states that are robust in spite of decoherence, and hence, effectively classical, have predictable consequences. Indeed, classical

> reality can be regarded as nearly synonymous with predictability.[61]

This seems a plausible story, and might form part of an explanation of why we experience measurement outcomes as we do. However, the analysis of robustness and predictability based on decoherence requires a prior factorisation of the global Hilbert space into subsystems. If we are going to be able to derive the preferred bases in which we experience measurement outcomes, those preferred factorisations must be specified *before* any evolutionary story can be told.

This strongly suggests that an explanation of why we experience measurement outcomes as we do will require the postulation of additional physical structure which singles out certain factorisations as physically preferred. This will involve, as Hemmo and Shenker suggest, the addition of "laws, or structure, to Hilbert space, from which it will follow that the decoherence basis is physically preferred"[62] or, as Barnum puts it, "additional structure such as preferred bases or subsystem decompositions that represent other aspects of physics ... 'nails in Hilbert space,' ... "[63]

The program of trying to add additional physical structure to explain why it is that certain bases seem to be preferred in our experience has been pursued by, for example, Carroll and Singh[64] and Tegmark[65] who speculatively propose certain features of the Hilbert space of the universe and fundamental interaction Hamiltonians which could give rise to local, separable systems. For example, Carroll and Singh seek a specific kind of Hamiltonian for which "there is a natural decomposition of Hilbert space in which physics looks local," and postulate a preferred factorisation of global Hilbert space

---

[61] W. H. Zurek, "Decoherence and the Transition from Quantum to Classical – Revisited," *Los Alamos Science* Number 27 (2002): 22. See also Simon Saunders, "Decoherence, Relative States, and Evolutionary Adaptation," *Foundations of Physics* Vol. 23, No. 12 (1993): 1569; Thomas Durt, "Anthropomorphic Quantum Darwinism as an Explanation for Classicality," *Foundations of Science* 15 (2010): 177–197.

[62] Meir Hemmo and Orly Shenker, "Quantum Mechanics as a Theory of Probability," in: Hemmo and Shenker (eds.) *Quantum, Probability, Logic*: 347.

[63] H. Barnum, "Coordinating quantum agents' perspectives: convex operational theories, quantum information, and quantum foundations," arXiv:quant-ph/0611110 (2006): 9.

[64] Sean M. Carroll and Ashmeet Singh, "Mad-Dog Everettianism: Quantum Mechanics at Its Most Minimal," in: Aguirre et al. (eds). *What is Fundamental?*: 95-104.

[65] Max Tegmark, "Consciousness as a state of matter," *Chaos, Solitons & Fractals* 76 (2015): 238–270.

> in which there exist low-entropy states for which entanglement grows at a minimum rate. That will be the factorization in which it is useful to define robust pointer states in one of the subsystems, while treating the other as the environment.[66]

Such proposals postulate a physically preferred factorisation which can account for our experience. They take our experience as a datum, but seek a more fundamental completely observer-independent explanation of the factorisations involved, based on additional physical structure. However, such proposals are at this stage very speculative, and whether such a program can ultimately achieve the Archimedean goal very much remains to be seen.

6 Conclusion

I have argued that decoherence can be seen as resolving the measurement problem provided one is willing to accept two key features of the proposed resolution: firstly, it addresses only the "generic" measurement problem; and secondly measurement outcomes are revealed as observer-dependent, that is, measurement outcomes are only defined relative to a particular observational context, predicated on a subsystem-environment split and a restriction to certain local observables. I have argued that the observer-dependence of measurement outcomes is consistent with realism, in the sense that the measurement outcomes are derived from a quantum-mechanical reality that underlies the process of decoherence. However the decoherence approach currently falls short of the ideal of Archimedean Realism which seeks an entirely observer-independent account of why the particular observational perspectives that we occupy are constrained in the way they seem to be. I have suggested that to achieve that ideal the decoherence approach would need to be supplemented with additional physical structure which singles out some Hilbert space factorisations as physically preferred. Any such postulation is at this point in time very speculative and it remains to be seen whether it can succeed. If not, then decoherence, while properly regarded as (comparatively) realist, lying some way along the realist spectrum, would ultimately be a fundamentally contextual, observer-dependent theory, falling short of the ideal of Archimedean Realism.

---

[66] Carroll and Singh, "Mad-Dog Everettianism": 101.

References

[1] Adler, Stephen L. “Why decoherence has not solved the measurement problem: a response to P.W. Anderson,” *Studies in History and Philosophy of Modern Physics* 34 (2003): 135–142.

[2] Aguirre, Anthony, Brendan Foster and Zeeya Merali (eds). *What is Fundamental?* (Springer Nature Switzerland AG, 2019).

[3] Bacciagaluppi, Guido. “Measurement and Classical Regime in Quantum Mechanics,” in: Batterman (ed). *The Oxford Handbook of Philosophy of Physics*: 416-459.

[4] Bächtold, Manuel. “Five Formulations of the Quantum Measurement Problem in the Frame of the Standard Interpretation,” *Journal of General Philosophy of Science* 39 (2008): 17–33.

[5] Barnum, H. “Coordinating quantum agents’ perspectives: convex operational theories, quantum information, and quantum foundations,” arXiv:quant-ph/0611110 (2006).

[6] Batterman, Robert (ed). *The Oxford Handbook of Philosophy of Physics* (Oxford: Oxford University Press, 2013).

[7] Bell, John. “Against measurement,” in: John Bell, *Speakable and Unspeakable in Quantum Mechanics*: 213-231.

[8] Bell, John. *Speakable and Unspeakable in Quantum Mechanics* (Cambridge: Cambridge University Press, 1987).

[9] Bertlmann, R and A. Zeilinger (eds). *Quantum [Un]Speakables II* (Springer International Publishing Switzerland, 2017).

[10] Bitbol, Michel. “Form and Actuality,” in: Mugur-Schächter and van der Merwe (eds). *Quantum Mechanics, Mathematics, Cognition and Action, Proposals for a Formalized Epistemology*: 389-430.

[11] Bitbol, Michel. “Decoherence and the Constitution of Objectivity,” in Bitbol et al. (eds). *Constituting Objectivity*: 347-357.

[12] Bitbol, Michel, Pierre Kerszberg and Jean Petitot (eds). *Constituting Objectivity, Transcendental Perspectives on Modern Physics* (Springer Science + Business Media B.V., 2009).

[13] Blanchard, P., D. Giulini, E. Joos, C. Kiefer, and I-O. Stamatescu (eds). *Decoherence: Theoretical, Experimental, and Conceptual Problems, Lecture Notes in Physics No. 538* (New York: Springer, 2000).

[14] Brukner, Časlav. "On the Quantum Measurement Problem" in: Bertlmann and Zeilinger (eds). *Quantum [Un]Speakables II*: 95-117.

[15] Bub, Jeffrey. "Quantum Correlations and the Measurement Problem," *International Journal of Theoretical Physics* 53 (2014): 3346–3369.

[16] Bub, Jeffrey. "The Measurement Problem from the Perspective of an Information-Theoretic Interpretation of Quantum Mechanics," *Entropy* 17 (2015): 7374-7386.

[17] Carroll, Sean M. and Ashmeet Singh. "Mad-Dog Everettianism: Quantum Mechanics at Its Most Minimal," in: Aguirre et al. (eds). *What is Fundamental?*: 95-104.

[18] Cordero, Alberto (ed). *Philosophers Look at Quantum Mechanics*, Synthese Library 406 (Springer Nature Switzerland AG, 2019).

[19] Crull, Elise M. "Less Interpretation and More Decoherence in Quantum Gravity and Inflationary Cosmology," *Foundations of Physics* 45 (2015): 1019–1045.

[20] d'Espagnat, Bernard. *On Physics and Philosophy* (Princeton: Princeton University Press, 2006).

[21] Durt, Thomas. "Anthropomorphic Quantum Darwinism as an Explanation for Classicality," *Foundations of Science* 15 (2010): 177–197.

[22] Earman, John. "Some Puzzles and Unresolved Issues About Quantum Entanglement," *Erkenntnis* 80 (2015): 303–337.

[23] Elby, Andrew. "The 'Decoherence' Approach to the Measurement Problem in Quantum Mechanics," *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association,1994* Volume One: Contributed Papers (1994): 355-365.

[24] Faye, Jan and Henry J. Folse (eds). *Niels Bohr and the Philosophy of Physics: Twenty-First-Century Perspectives* (London: Bloomsbury Academic, 2017).

[25] Fuchs, Christopher A., N. David Mermin, and Rüdiger Schack. "An introduction to QBism with an application to the locality of quantum mechanics," *American Journal of Physics* 82 (2014): 749-754.

[26] Gell-Mann, Murray and James B.Hartle. "Classical equations for quantum systems," *Physical Review D* Volume 47, number 8 (April 1993).

[27] Giulini, D., E. Joos, C. Kiefer, J. Kupsch, I.-O. Stamatescu, and H. D. Zeh. *Decoherence and the Appearance of a Classical World in Quantum Theory* (Berlin, Heidelberg, New York: Springer-Verlag, 1996).

[28] Halvorson, Hans. "To Be a Realist about Quantum Theory," in: Lombardi et al. (eds). *Quantum Worlds, Perspectives on the Ontology of Quantum Mechanics*: 133-163.

[29] Hemmo, Meir and Orly Shenker. "Why the Many Worlds Interpretation of Quantum Mechanics Needs More Than Hilbert Space Structure," in: Peels et al. (eds). *Scientific Challenges to Common Sense Philosophy*: 61-70.

[30] Hemmo, Meir and Orly Shenker. "Quantum Mechanics as a Theory of Probability," in: Hemmo and Shenker (eds.) *Quantum, Probability, Logic*: 337-351.

[31] Hemmo, Meir and Orly Shenker (eds). *Quantum, Probability, Logic*, Jerusalem Studies in Philosophy and History of Science (Springer Nature Switzerland AG: 2020).

[32] Janssen, Hanneke. *Reconstructing reality: Environment-induced decoherence, the measurement problem, and the emergence of definiteness in quantum mechanics*, Master's thesis - Theoretical Physics Radboud University Nijmegen (philsci-archive.pitt.edu, 2008).

[33] Jauch, J.M. "The problem of measurement in quantum mechanics," *Helvetica Physica Acta* 37 (1964): 293-216.

[34] Joos, Erich. “Elements of Environmental Decoherence,” in: P. Blanchard et al (eds). *Decoherence: Theoretical, Experimental, and Conceptual Problems, Lecture Notes in Physics No. 538*: 1-17.

[35] Karakostas, Vassilios. “Forms of quantum nonseparability and related philosophical consequences,” *Journal for General Philosophy of Science* 35 (2004): 283–312.

[36] Karakostas, Vassilios and Pandora Hadzidaki. “Realism vs. Constructivism in Contemporary Physics: The Impact of the Debate on the Understanding of Quantum Theory and its Instructional Process,” *Science & Education* 14 (2005): 607–629.

[37] Khalfin Leonid A. and Boris S. Tsirelson. “Quantum/Classical Correspondence in the Light of Bell’s Inequalities,” *Foundations of Physics*, Vol 22, No. 7 (1992): 879-948.

[38] Landsman, N. P. “Observation and Superselection in Quantum Mechanics,” *Stud. Hist. Phil. Mod. Phys.*, Vol. 26, No. 1 (1995): 45-73.

[39] Lombardi, Olimpia, Sebastian Fortin, Cristian López, and Federico Holik (eds). *Quantum Worlds, Perspectives on the Ontology of Quantum Mechanics* (Cambridge: Cambridge University Press, 2019).

[40] Mugur-Schächter, Mioara and Alwyn van der Merwe (ed). *Quantum Mechanics, Mathematics, Cognition and Action, Proposals for a Formalized Epistemology* (Kluwer Academic Publishers, 2002).

[41] Nagel, Thomas. *The View From Nowhere* (New York, Oxford: Oxford University Press, 1986).

[42] Ollivier, H., D. Poulin and W. H. Zurek. “Emergence of objective properties from subjective quantum states: Environment as a witness,” *Phys. Rev. Lett.* 93 (2004): 220401 (1-4).

[43] Ollivier, H., D. Poulin, and W. H. Zurek. “Environment as a witness: selective proliferation of information and emergence of objectivity,” *Phys. Rev. A* 72 (2005): 042113 (1-19).

[44] Omnes, Roland. *The Interpretation of Quantum Mechanics* (Princeton: Princeton University Press, 1994).

[45] Peels, Rik, Jeroen de Ridder and René van Woudenberg (eds). *Scientific Challenges to Common Sense Philosophy* (New York: Routledge, 2020).

[46] Pessoa Jr., Osvaldo. "Can the decoherence approach help to solve the measurement problem?" *Synthese* 113 (1998): 323–346.

[47] Price, Huw. *Time's Arrow & Archimedes Point* (New York, Oxford: Oxford University Press, 1996).

[48] Rickles, Dean (ed). *The Ashgate Companion to Contemporary Philosophy of Physics* (Aldershot: Ashgate Publishing Limited, 2008).

[49] Saatsi, Juha. "Scientific Realism Meets Metaphysics of Quantum Mechanics," in: Alberto Cordero (ed). *Philosophers Look at Quantum Mechanics*: 141-162.

[50] Saunders, Simon. "Decoherence, Relative States, and Evolutionary Adaptation," *Foundations of Physics* Vol. 23, No. 12 (1993): 1533-1585.

[51] Shankar, R. *Principles of Quantum Mechanics*, 2nd edition (New York: Springer Science+Business Media, 1994).

[52] Schlosshauer, Maximillian. "Decoherence, the measurement problem, and interpretations of quantum mechanics," *Reviews of Modern Physics* Volume 76 (October 2004): 1267-1305.

[53] Schlosshauer, Maximilian. *Decoherence and the Quantum-to-Classical Transition* (Berlin, Heidelberg: Springer-Verlag, 2007).

[54] Schlosshauer, Maximilian (ed). *Elegance and Enigma* (Berlin: Springer-Verlag, 2011).

[55] Schlosshauer, Maximilian and Kristian Camilleri. "The quantum-to-classical transition: Bohr's doctrine of classical concepts, emergent classicality, and decoherence," arXiv:0804.1609v1 [quant-ph] (2008).

[56] Shimony, Abner. "Reality, causality and closing the circle," in: Abner Shimony, *Search for a Naturalistic Worldview*, Vol. 1: 21-61.

[57] Shimony, Abner. *Search for a Naturalistic Worldview,* Vol. 1 (Cambridge: Cambridge University Press, 1993).

[58] Tanona, Scott. “Decoherence and the Copenhagen Cut,” *Synthese*, Vol. 190, No. 16 (November 2013): 3625-3649.

[59] Tanona, Scott. “Individuality and Correspondence: An Exploration of the History and Possible Future of Bohrian Quantum Empiricism” in: Jan Faye and Henry J. Folse (eds). *Niels Bohr and the Philosophy of Physics: Twenty-First-Century Perspectives*: 253–288.

[60] Tegmark, Max. “Consciousness as a state of matter,” *Chaos, Solitons & Fractals* 76 (2015): 238–270.

[61] Wallace, David. “Philosophy of Quantum Mechanics” in: Rickles (ed). *The Ashgate Companion to Contemporary Philosophy of Physics*: 16-98.

[62] Wallace, David. “What is Orthodox Quantum Mechanics?” in: Alberto Cordero (ed). *Philosophers Look at Quantum Mechanics*: 285-312.

[63] Zanardi, Paolo. “Virtual Quantum Subsystems,” *Physical Review Letters,* Volume 87, Number 7 (13 August 2001): 077901 (1-4).

[64] Zanardi, Paolo, Daniel A. Lidar and Seth Lloyd, “Quantum tensor product structures are observable-induced,” *Physical Review Letters,* Volume 92, Number 6 (10 February 2004): 060402 (1-4).

[65] Zeh, H.D. “The Program of Decoherence: Ideas and Concepts,” in: Giulini et al. (eds). *Decoherence and the Appearance of a Classical World in Quantum Theory*: 5-34.

[66] Zurek, W. H. “Pointer basis of quantum apparatus: into what mixture does the wave packet collapse?” *Physical Review D* Volume 24, Number 6 (15 September 1981): 1516-1525.

[67] Zurek, W. H. “Preferred states, predictability, classicality, and the environment induced decoherence,” *Prog. Theor. Phys.* 89 (1993): 281-312.

[68] Zurek, W. H. “Decoherence and the Transition from Quantum to Classical — Revisited,” *Los Alamos Science* Number 27 (2002): 2-25.