THE ROLE OF DECOHERENCE IN THE EMERGENCE OF DEFINITE PROPERTIES

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Environmental decoherence is widely held to be the key to understanding the emergence of classicality in a quantum universe. However, in conjunction with traditional principles of interpretation, decoherence leaves unanswered a fundamental question, a version of the quantum measurement problem: Why should macroscopic objects have definite properties at all? I critically evaluate a variety of interpretive strategies intended to parlay the formal results of decoherence into the definiteness, or apparent definiteness, of familiar macroscopic properties. I argue that the crucial role of environmental decoherence in accounting for definite properties is effecting the dynamical decoupling of components of the global quantum state for which these properties are definite.

This role of decoherence is most evident in the context of the Everett interpretation, where considerations regarding branch dynamics lead naturally to the conclusion that dynamical autonomy (non-interference) of branches is a restriction on any division of the global quantum state into branches. Environmental decoherence results in the requisite dynamical autonomy for branches in which familiar macroscopic observables are definite, thus providing a natural and principled way to identify an interpretation basis.

The modal interpretation, with its property ascription rule based on the spectral decomposition of the reduced state, secures the right definite properties only in those cases in which it picks out properties that correspond almost exactly with the non-interfering components of the global quantum state. I argue that the non-interference of these components should be accorded interpretational significance in its own right; then the right properties

can be specified without recourse to the distinctive property ascription rules of the modal interpretation.

Finally, I criticize attempts of decoherence theorists to account for definite properties by appeal to effects of decoherence such as approximate diagonality of the reduced state and preservation of correlations with respect to a set of privileged states. I argue that definiteness can be accounted for by looking not to these effects but to their cause, the dynamical autonomy of the environmentally-privileged components of the global quantum state. Precisely because they are dynamically autonomous, these states can be accorded physical significance in their own right.

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1.0 INTRODUCTION

It is among the most ordinary facts of life that the objects of our experience, tables and chairs and cats and dogs, have definite values for familiar physical quantities like position and momentum. Even if Fido does not stay in one place when commanded, he does at each moment have some well-defined position. In this respect Fido is unlike the microscopic systems—atoms, electrons, etc.—described by quantum theory, which according to quantum theory sometimes have no definite values for quantities like position and momentum. Quantum theory's characterization of microscopic systems in terms of states for which such familiar quantities have no definite values is central to its great predictive success. But quantum theory seems to imply that a similar indefiniteness for these familiar quantities should likewise obtain for the ordinary, macroscopic objects of everyday experience. This problem is known as the measurement problem because the implication can be made particularly clear in context of a measurement: if a quantum system has no definite position, for example, then a measurement of position performed on the system should spread the indefiniteness of the system's position into an indefiniteness of the macroscopic properties of the measuring device. Schrödinger's cat is the most famous illustration of the absurd consequences that seem to follow from the apparently obvious assumption that macroscopic objects are themselves ultimately quantum systems and hence described accurately by quantum theory: a cat whose life or death is made to depend on the outcome of a measurement on a quantum system that has no definite value for the measured quantity should, according to quantum mechanics, end up in a state indeterminate between alive and dead. The measurement problem is the puzzle of how to reconcile the apparent definiteness of the familiar properties of macroscopic objects with the indefiniteness that is apparently predicted by quantum theory given their ultimately quantum nature.

Within the past twenty-five years, a "new orthodoxy" (Bub 1997: 207) has developed about how to explain the emergence of classical behavior in a quantum universe. This orthodoxy takes the process of environmental decoherence to be a key to understanding the transition from quantum to classical. This approach insists that it is essential to recognize that in contrast with the microscopic quantum systems for which interference phenomena can be observed, macroscopic systems are never isolated. They are always immersed in and interacting with an environment. That is, they are continually subject to interactions with countless external microscopic systems such as photons and air molecules; they also have internal "environments," insofar as the macroscopic degrees of freedom that we are capable of observing for a given object interact with countless microscopic degrees of freedom within the object. This interaction with the (internal and external) environment has the consequence that macroscopic quantum systems are always highly entangled with their environments, and a result is *decoherence*, the extremely rapid vanishing of interference between macroscopically distinguishable states. Roughly, the interaction of the system with its environment can be said to privilege a particular set of pure states in the Hilbert space of the system and to lead to the rapid decay of the interference terms in the reduced state of the system, expressed in terms of these privileged states.

This process explains why the interference phenomena characteristic of isolated quantum systems are not observed in macroscopic objects. However, in conjunction with traditional principles of interpretation, decoherence leaves unanswered a fundamental question about the emergence of classical reality: Why should macroscopic objects have definite properties at all? In other words, decoherence seems to leave intact the measurement problem outlined above. In the dissertation I critically evaluate a variety of interpretive strategies that have claimed to be able to parlay the formal results of decoherence into the definiteness, or apparent definiteness, of familiar macroscopic properties. I argue that the crucial role of environmental decoherence in accounting for the definiteness of properties is the dynamical decoupling of components of the global quantum state for which these properties are definite.

Decoherence is often discussed in connection with (the many variants of) the Everett interpretation of quantum mechanics. The primary role ascribed to environmental decoherence in this context is that it provides a criterion for the choice of a preferred basis and hence a solution to the preferred basis problem, long considered to be the decisive weakness of the Everett interpretation. In chapter 2, I undertake an examination of Everett's own exposition of his interpretation, and I show that considerations regarding branch dynamics in his writings lead naturally to the conclusion that dynamical autonomy of branches is a restriction on any division of the global quantum state into branches. In the light of these considerations, the significance of environmental decoherence is that it results in the requisite dynamical autonomy for branches in which familiar macroscopic observables are definite. Hence the appeal to decoherence as a way to solve the preferred basis problem and specify a division of the global state into branches can be seen as arising naturally in context of the Everett interpretation, rather than as an appeal to a consideration essentially foreign to the interpretation. The dynamical autonomy of branches that results from decoherence accounts for the impossibility of detecting the presence of other branches in the global quantum state; it also explains why Everett's interpretation, which comes equipped with a rule for assigning only instantaneous probabilities, should be compatible with assigning to transitions that result from measurements the same transition probabilities that are native to collapse quantum mechanics.

In chapter 3, I examine the role of environmental decoherence in the modal interpretation, which emphasizes a kinematical effect of decoherence: decoherence ensures that the reduced state of a macroscopic system is approximately diagonal with respect to the decohering variable. Advocates of the modal interpretation had originally hoped that this approximate diagonality would ensure that the definite properties ascribed to macroscopic objects by the modal interpretation—the quantities that precisely diagonalize the reduced state—would be extremely close to familiar macroscopic observables. It is now widely recognized that this is not the case in general, and that for some models the modal interpretation assigns highly nonclassical properties to systems subject to decoherence. But in contexts where the modal interpretation does secure the definiteness of the desired properties, some advocates of the modal interpretation attribute to decoherence a secondary, dynamical role: environmental decoherence ensures that states corresponding to distinct possible values of the decohering variable do not interfere with each other but evolve essentially autonomously. Some advocates of the modal interpretation appeal to this absence of interference to constrain the dynamics of possessed properties of decohering systems. I argue that once this dynamical effect of the interaction with the environment, namely the non-interference of certain components of the global state, is accorded interpretive significance, it threatens to undercut the modal interpretation. Consideration of the modal interpretation's successes and failures at securing the "right" definite properties shows that it succeeds precisely in those cases in which it picks out properties that correspond almost exactly with the non-interfering components of the global quantum state determined by environmental decoherence. If the non-interference of these components is taken as having interpretational significance in its own right, the right properties can be specified without recourse to the distinctive property ascription rules of the modal interpretation.

In chapter 4, I critically examine the attempts of decoherence theorists, particularly Zurek, to account for the emergence of definite properties on the basis of decoherence. I argue that the consequences of environmental decoherence typically emphasized in this literature—diagonality of the reduced density matrix with respect to a set of states privileged by the environmental interaction, or the fact that only correlations with respect to these privileged states can be stable under the interaction with the environment—do not by themselves account for definite properties or the appearance thereof, and that emphasis on these effects obscures their cause, the dynamical autonomy of certain privileged components of the global quantum state. I also argue that attempts to account for the appearance of definite properties via a many-minds interpretation that takes dynamically independent states of an observer's brain to correspond to distinct conscious experiences are poorly motivated; they must implicitly make use of an interpretational principle that, if applied more generally, would account for the actual, and not merely apparent, definiteness of the desired properties.

2.0 EVERETT AND DECOHERENCE

As the study of decoherence has risen to prominence in the past two decades, interest in Hugh Everett's interpretation of quantum mechanics has risen sharply as well. The two are widely seen as complementing each other: The Everett interpretation is viewed as providing a framework in which decoherence effects can account for the definiteness and classical behavior of the properties of macroscopic objects. And the phenomenon of decoherence is viewed as providing a solution to a central problem for the Everett interpretation, the preferred basis problem.

The purpose of this chapter is to examine one of these directions of support, by considering what role there is for decoherence to play in the Everett interpretation. I will show that the alliance between decoherence and the Everett interpretation with regard to the preferred basis problem is not merely a marriage of convenience; considerations regarding branch dynamics within Everett's interpretation lead naturally to the conclusion that decoherence plays a key role in the specification of a preferred basis. Along the way, I show that within the Everett interpretation, decoherence can explain why detection of other branches should be a practical impossibility. I also show that decoherence can explain why Everett's interpretation, which comes equipped with a rule for assigning only instantaneous probabilities—specifically probabilities for branches in the total quantum state at a time—should be compatible with assigning to transitions that result from measurements the same transition probabilities that are native to collapse quantum mechanics.

2.1 EVERETT'S INTERPRETATION

Everett intends his formulation of quantum mechanics to be a generalization of what he calls "the conventional or 'external observation' formulation of quantum mechanics," that will avoid the latter's limitations and inconsistencies. The conventional formulation he has in mind is that of von Neumann; its limitations arise from two features: (i) it interprets the quantum state of a system as providing information "only to the extent of specifying the probabilities of the results of various observations which can be made *on* the system *by* external observers"(Everett 1957: 454), and (ii) it postulates a collapse of the quantum state, securing definite measurement outcomes by stipulating that observation by an external observer induces a discontinuous collapse of the state of the observed system to an eigenstate of the observed quantity. The first feature has the consequence that the conventional formulation can attach no meaning to the quantum state of a system *not* subject to external observation, such as the universe as a whole; such a system can have no quantum mechanical description. The second has the consequence that the process of observation or measurement itself must remain outside the purview of the theory, treated merely as a "black box" interaction resulting in collapse. For if observation were treated as a physical interaction between subsystems of a closed system, subject to quantum mechanical description, it would have to be considered to unfold continuously according to the unitary quantum dynamics—contradicting the supposition that observation induces a discontinuous and non-unitary collapse of the state of the system being observed.

Everett's formulation of quantum mechanics is based upon two core principles that are opposed to features (i) and (ii) of the conventional formulation. First, all physical systems, including observers and the entire universe, are subject to quantum mechanical description; in particular, the universe itself can, in theory, be assigned a quantum state. Second, the quantum state of a closed system evolves always and exclusively according to the unitary quantum dynamics. Observation or measurement in particular is an interaction governed by the unitary dynamics. Everett's project is to formulate an interpretation of this theory that describes how "to put the mathematical model of the theory into correspondence with experience" (Everett 1957: 455), and then to show that the theory thus interpreted can duplicate the predictions of the empirically successful conventional formulation. The primary question he must address is, how is empirical content to be associated with the mathematical description of a system afforded by the quantum state? Everett declares that the formalism must serve as a guide to the answer: "The wave function is taken as the basic physical entity with *no a priori interpretation*. Interpretation only comes *after* an investigation of the logical structure of the theory." (1957: 455)

2.1.1 The Measurement Problem

Treating measurement as an interaction governed by the unitary dynamics, Everett is faced with a version of the measurement problem: Under the unitary dynamics, an ideal measurement on a system initially in a superposition of eigenstates of the measured observable results in an entangled state of measured system + measuring apparatus. But according to the standard way of interpreting quantum states (the eigenvalue-eigenstate link), such a state represents a state of affairs in which *no* definite measurement outcome has taken place. Since the composite system is entangled, the apparatus is assigned no pure state at all, much less an eigenstate of the pointer observable as required to secure a definite pointer reading by the lights of the eigenvalue-eigenstate link.

The same problem recurs if an observer now looks at the apparatus to determine the result of the measurement. Since the state of measured system + apparatus is a superposition of eigenstates of the pointer observable, an observation, modeled as a measurement of the pointer observable, results in an entangled state of measured system + apparatus + observer. Following Everett, let us adopt a generalized notion of an "observer" as a physical system, equipped with a memory register, that is capable of measuring a given physical quantity and recording the result in its memory. This could be a human observer, or merely a device like a measuring apparatus that makes a physical record of the measurement result.[1] Measurement

[1] Here is what Everett says about how observers are to be modeled:

> We have the task of making deductions about the appearance of phenomena to observers which are considered as purely physical systems and are treated within the theory. . . . It will suffice for our purposes to consider the observers to possess memories (i.e., parts of a relatively permanent nature whose states are in correspondence with past experiences of the observers). . . . As models for observers, we can, if we wish, consider automatically functioning machines, possessing sensory apparatus and coupled to recording devices capable of registering past sensory data and machine

is an interaction between an observer and an object system (which could, for example, be a microscopic particle, a macroscopic measuring apparatus, or even a composite particle-apparatus system) in which the state of the observer's memory register becomes coupled to the measured quantity of the object system. Then we can summarize the implication of the unitary dynamics for both conscious observers and mechanical apparatuses: A measurement interaction between observer and object system, when the object system is initially in a superposition $\sum_i c_i |\chi_i\rangle$ of eigenstates the observed quantity, results in an entangled state

$$\sum_i c_i |\chi_i\rangle |x_i\rangle \tag{2.1}$$

of object system + observer. Here $|\chi_i\rangle$ is an eigenstate of the measured quantity and $|x_i\rangle$ is the memory state of the observer representing a record of the corresponding eigenvalue x_i. Neither object system nor observer can be assigned a pure state, and therefore no observables of either subsystem have definite values according to the eigenvalue-eigenstate link.

Everett acknowledges that his view implies that an entangled object system-observer state like (2.1) is the result of a typical measurement interaction. And he agrees that such a state does not represent the occurrence of a single definite measurement outcome, so that this implication would seem to conflict with experience. Nevertheless, he thinks an entangled state like this can be reconciled with the *appearance* of a definite outcome. His explanation appeals to the fact that the post-measurement state (2.1) is a *superposition of product states*, each of which *does* represent the occurrence of a definite outcome. Commenting on this superposition, Everett says:

> There is no longer any independent system state or observer state, although the two have become correlated in a one-one manner. However, in each *element* of the superposition, $[\,|\chi_i\rangle |x_i\rangle\,]$, the object-system state is a particular eigenstate of the observation, and *furthermore the observer-system state describes the observer as definitely perceiving that particular system state*. This correlation is what allows one to maintain that a measurement has been performed. (Everett 1957: 459)

He takes the presence of definite memory states *within* the entangled global state to have

configurations. . . . For such machines we are justified in using such phrases as "the machine has perceived A" or "the machine is aware of A" if the occurrence of A is represented in the memory. (Everett 1957: 457) implications for the interpretation of the formalism. In effect, he says that in order to "put the mathematical model of the theory into correspondence with experience," one must look not to the global state as a whole but to the orthogonal product states, interpretable via the eigenvalue-eigenstate link as representing distinct definite outcomes, of which the global state is a superposition. For a single ideal measurement, the set of outcomes represented by these product states is the same as the set of possible outcomes according to the conventional approach.

Everett's approach to the measurement problem purports to account for definite outcomes by finding a collection of states describing *all possible* outcomes within the post-measurement state, rather than construing the post-measurement state as representing a *single* definite outcome. And Everett insists that all of the outcomes thus described by elements of the global state are equally real—perhaps because he thinks that saying that only one is real would be tantamount to positing collapse. This is the claim for which he is famous, of course: he insists that all possible outcomes of a measurement really occur.

2.1.2 Branches and Probabilities

To show that it makes the same predictions as the conventional theory, Everett applies his theory to sequences of measurements. One important result he obtains is that repeated ideal measurements of a single observable on a single system will lead to repeated records of the same result in each element of the resulting superposition. Thus, if an ideal measurement on an object system initially in the state $\sum_i c_i |\chi_i\rangle$ results in the global state $\sum_i c_i |\chi_i\rangle |x_i\rangle$, then an immediate repetition of the measurement on the same system results in the state

$$\sum_i c_i |\chi_i\rangle |x_i, x_i\rangle ,$$

where each term represents the observer as obtaining one result, the eigenvalue x_i, twice. Everett concludes from this repeatability of measurements that his theory can account for the appearance of collapse: "It will thus *appear* to the observer, as described by a typical element of the superposition, that each initial observation on a system causes the system to 'jump' into an eigenstate ... and thereafter to remain there for subsequent measurements on the same system" (1957: 459).

Everett also considers a sequence of measurements of a single observable with eigenstates $|\chi_i\rangle$ and eigenvalues x_i on a collection of n object systems all prepared in the same state, $|\phi\rangle = \sum_i c_i |\chi_i\rangle$. Let the observer's memory state before the first measurement be $|\text{ready}\rangle$, so that the total state of object systems + observer is the product state

$$|\phi\rangle |\phi\rangle \cdots |\phi\rangle |\text{ready}\rangle .$$

After the first measurement, the total state is

$$\sum_i c_i |\chi_i\rangle |\phi\rangle \cdots |\phi\rangle |x_i\rangle ,$$

after the second measurement it is

$$\sum_{i,j} c_i c_j |\chi_i\rangle |\chi_j\rangle |\phi\rangle \cdots |\phi\rangle |x_i, x_j\rangle ,$$

and after n measurements it is

$$\sum_{i,j,\ldots,k} c_i c_j \cdots c_k |\chi_i\rangle |\chi_j\rangle \cdots |\chi_k\rangle |x_i, x_j, \ldots, x_k\rangle , \tag{2.2}$$

where the memory state of the observer is identified by the sequence of eigenvalues recorded as measurement results. Once again, the global state after each measurement is a superposition of states representing definite outcomes, and the set of outcomes thus represented at each stage is exactly the set of possible outcomes according to the conventional theory.

Everett notes an important feature of this example: the evolution of the global state induced by each measurement interaction in the sequence effectively acts separately on each term in the global state. Thus the mth measurement transforms each term into a superposition:

$$|\chi_i\rangle \cdots |\chi_l\rangle |\phi\rangle |\phi\rangle \cdots |\phi\rangle |x_i, \ldots, x_l\rangle \longrightarrow \sum_m c_m |\chi_i\rangle \cdots |\chi_l\rangle |\chi_m\rangle |\phi\rangle \cdots |\phi\rangle |x_i, \ldots, x_l, x_m\rangle$$

Everett describes this process in terms of the *branching* of observer states:

> Thus with each succeeding observation (or interaction), the observer state "branches" into a number of different states. Each branch represents a different outcome of the measurement and the *corresponding* eigenstate for the object-system state. All branches exist simultaneously in the superposition after any given sequence of observations.
>
> The "trajectory" of the memory configuration of an observer performing a sequence of measurements is thus not a linear sequence of memory configurations, but a branching tree, with all possible outcomes existing simultaneously in a final superposition with various coefficients in the mathematical model. (Everett 1957: 459–460)[2]

Tracking the evolution of each term separately, we can see that the evolving collection of terms in the global state does indeed have a branching structure, as depicted diagrammatically in figure 1 for a sequence of two measurements on identically prepared object systems.

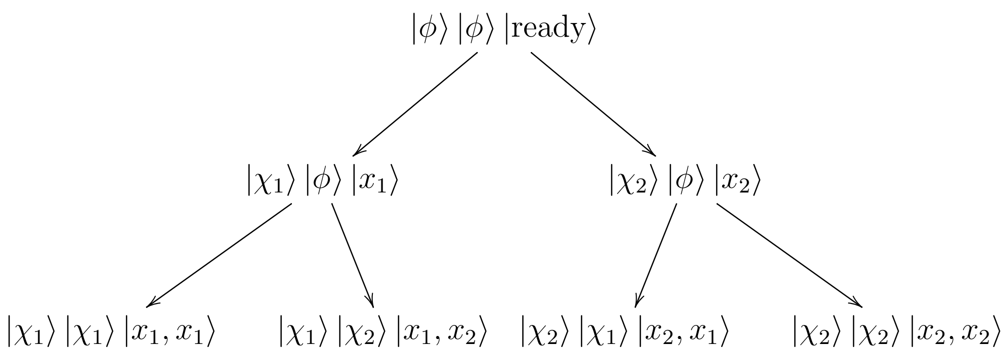

Figure 1: A diagrammatic representation of the branching structure of states induced by two measurements performed by an observer on a pair of identically prepared object systems initially in the state $|\phi\rangle = c_1\,|\chi_1\rangle + c_2\,|\chi_2\rangle$. The three levels in the diagram, from top to bottom, represent the branches in the global state at three times: an initial time t_0, a time t_1 after the first measurement, and a time t_2 after the second measurement. The three states of the entire closed system at these three times are

$$
\begin{aligned}
|\Psi(t_0)\rangle &= |\phi\rangle\,|\phi\rangle\,|\text{ready}\rangle \\
|\Psi(t_1)\rangle &= c_1\,|\chi_1\rangle\,|\phi\rangle\,|x_1\rangle + c_2\,|\chi_2\rangle\,|\phi\rangle\,|x_2\rangle \\
|\Psi(t_2)\rangle &= c_1^2\,|\chi_1\rangle\,|\chi_1\rangle\,|x_1, x_1\rangle + c_1c_2\,|\chi_1\rangle\,|\chi_2\rangle\,|x_1, x_2\rangle \\
&\quad + c_2c_1\,|\chi_2\rangle\,|\chi_1\rangle\,|x_2, x_1\rangle + c_2^2\,|\chi_2\rangle\,|\chi_2\rangle\,|x_2, x_2\rangle.
\end{aligned}
$$

[2] This quotation suggests a certain ambivalence on Everett's part about what exactly the metaphors of "branching" and "branch" are supposed to describe. He says that the *observer state* "branches" and that the *trajectory of the observer's memory configuration* is a branching tree. But he also says that a branch represents—in addition to a definite observer state—"the corresponding eigenstate for the object system state." So here the term "branch" (now used as a noun rather than a verb) apparently *includes the state of the object system* as well as the state of the observer. I use the term in the latter sense, so that I will write (as Everett does not) of the global state branching.

In order to derive statistical predictions for measurement outcomes, Everett defines a probability measure on the orthogonal states in a superposition. Subject to a few specified conditions—in particular, the condition, "analogous to the 'conservation of probability' in the classical case," "that the measure assigned to a trajectory at one time shall equal the sum of the measures of its separate branches at a later time" (1957: 460)—Everett shows that the only possible measure is the amplitude-squared measure. This measure assigns to the state $|\Phi_i\rangle$ in the superposition $\sum_i a_i |\Phi_i\rangle$ the probability $|a_i|^2$, where the states $|\Phi_i\rangle$ form an orthonormal set. This defines a probability distribution over a set of orthogonal states appearing as terms in a post-measurement superposition, and hence over possible records of measurement outcomes. For Everett, the probabilities thus obtained are to be thought of as quantifying the "typicality" of a particular branch of the global state.

Applied to the above example of a sequence of measurements of a single quantity on identically prepared object systems, this probability measure gives the following result: The probability of each of the branches in the final superposition (2.2) is

$$\Pr\Big(|\chi_i\rangle\,|\chi_j\rangle \cdots |\chi_k\rangle\,|x_i, x_j, \ldots, x_k\rangle\Big) = |c_i|^2\,|c_j|^2 \cdots |c_k|^2 .$$

This quantity gives the probability or typicality of this branch, and hence of the observer state it describes; it can be interpreted as the probability of obtaining a memory sequence $(x_i, x_j, \ldots, x_k)$ as a result of the given sequence of measurements. The very same probability is assigned to the sequence of outcomes $(x_i, x_j, \ldots, x_k)$ by conventional quantum mechanics—although in the conventional approach this quantity is interpreted as the probability of a sequence of measurement-induced collapses. The product form of the probability for this sequence of outcomes allows Everett to associate with each outcome x_l the probability $|c_l|^2$. And although in his view these quantities do *not* specify the probability for each possible outcome to occur *to the exclusion of any other*, they can be used to predict the expected relative frequencies of outcomes just as though they did—provided only that we understand "expected" to mean "expected for an observer described by a typical branch." Thus it will appear to an observer that each measurement in the sequence has a definite outcome x_l with probability $|c_l|^2$: "the probabilistic assertions of [measurement collapse] *appear* to be valid to the observer described by a typical element of the final superposition" (Everett 1957: 459).

Everett shows that—if we interpret his measure over states as giving the probability of the corresponding sequences of outcomes, or of the subjective experiences thereof—his theory gives results that are in agreement with conventional quantum mechanics for a range of measurement schemes. In addition to a sequence of measurements of the same quantity on identical systems, he considers an arbitrary sequence of measurements of different, and generally incompatible, observables on a sequence of object systems, allowing for multiple observations (of a single quantity or of different quantities) on individual systems. He considers also schemes involving multiple observers, who make measurements on a single system, or on distinct but correlated systems, and communicate their results to each other. In every case, his theory agrees with the conventional theory about the possible (sequences of) outcomes, where these are given in his theory by the branches of the final global state corresponding to definite memory states; and his theory also associates with sequences of outcomes and with individual outcomes the same probabilities as the conventional approach. He concludes:

> Many further combinations of several observers and systems can be studied within the present framework. The results of the present "relative state" formalism agree with those of the conventional "external observation" formalism in all those cases where that familiar machinery is available. (Everett 1957: 462)

Everett then leaves us with the following picture, for the simple closed systems consisting of one or more observers and one or more object systems that he considers: The entire closed system is described by a unitarily evolving global state. Although this global state is typically an entangled state that assigns no definite pure states to observers or object systems, it is a superposition of product states describing definite memory configurations of the observers, and corresponding definite states of the object systems. Measurements effect a branching of these product states, with each pre-measurement product state evolving into a collection of product states describing distinct measurement outcomes. The evolving global state may thus be described as a collection of branching product states. A natural probability distribution over the product states or branches in the global state at each time can be defined, and this distribution allows each measurement, each branching event, to be described as a probabilistic event, for which each resulting branch can be assigned a relative probability (conditional upon the particular pre-measurement state and the given measurement interaction). The relative probability thus assigned to each branch resulting from a measurement corresponds precisely with the probability assigned to the corresponding measurement outcome in the conventional theory.

2.1.3 Defining Branches

Everett's picture of a quantum universe as a collection of continually branching worlds of definite properties and experiences is certainly intriguing. But in some important respects the picture is underspecified. In particular, the central metaphor of branching states is insufficiently spelled out. How exactly are these product states that play a central role in the interpretation, the branches of the global state, to be specified at any one time? How are these branches to be tracked over time? Everett does not answer these questions in the general case, nor does he provide principled answers even in the context of his models of simple measurement schemes. He simply exhibits a particular way in which, for these schemes, the evolving global state might be viewed as a superposition of product states that branch with each measurement, and shows how probabilities might be associated with each result of each branching event. That the resulting description of these simplified measurement schemes in terms of branching states and probabilities corresponds closely in certain respects with the predictions of the conventional approach is impressive—but it also prompts suspicion that branches and probabilities are simply picked out so as to secure such correspondence for these simple models. A genuine interpretation of collapse-free quantum mechanics, applicable to realistic cases, would seem to require a more principled interpretive approach.

The first and central question concerning the specification of branches is often referred to as the preferred basis problem. This is essentially the question, how precisely is the global state at any one time to be carved up into branches? In his discussions of simple measurement schemes, Everett grants special interpretive significance to a decomposition of the global state into terms that assign definite memory states to observers. In doing so, he is helping himself to one very special expansion of the global state, which can be expressed in terms of any basis of observer states. Mathematically the choice of expansion is arbitrary. And almost all possible choices represent the global state as a superposition of observer states that are *not* definite memory states but superpositions of these. Since the choice of expansion is not dictated by the formalism, it seems that Everett affords special interpretive significance to the expansion in terms of definite memory states simply in order to secure definite outcomes.[3]

One reason this choice seems problematic for Everett is that it seems to violate his stated maxim of letting interpretation be guided by the structure of the formalism. But an even more serious problem has to do with the fact that "the basis of definite memory states" is not a well-defined set of states—except in toy models where such states are precisely specified in constructing the model. The general strategy of assigning special interpretive significance to memory states of observers would seem to require a precise specification, in terms of the formalism, of "observer" and "memory state." Otherwise the strategy is hopelessly vague, since it simply isn't clear just what expansion should be used to ensure that all human memories, instrument readings, printed records, and so on, are definite. As J. S. Bell puts the criticism, Everett's interpretation of the global state requires a decomposition of the global state into branches for which "vaguely anthropocentric instrument readings" are definite (1987: 97); but "if instrument readings are to be given such a fundamental role should we not be told more exactly what an instrument reading is, or indeed, an instrument, or a storage unit in a memory, or whatever?" (1987: 96)

This is a pressing problem for Everett, since it introduces into his interpretation the same critical vagueness that plagues the conventional formulation of quantum mechanics. A central tenet of that formulation states that a measurement by an external observer results in collapse of the state of the measured system to an eigenstate of the observed quantity. Without a formal definition of "measurement," "observer," and "observed quantity," this tenet fails to specify precisely when collapse occurs (and thus precisely when the unitary dynamics is suspended). Everett's interpretation dispenses with collapse, but it still depends essentially on identifying "observers," broadly understood, and a vaguely-specified preferred variable—the "memory observable"—in order to extract empirical information from the global quantum state. In sum, although we can find in Everett a rough and ready answer to the question,

[3] "This preference for a particular set of operators is not dictated by the mathematical structure of the wave function ψ. It is just added (only tacitly by Everett, and only if I have not misunderstood) to make the model reflect human experience." (Bell 1987: 96)

"How are branches to be specified?" the answer—"In terms of definite memory states of observers"—is unsatisfactory as part of a fundamental interpretive principle. The preferred basis problem then takes the form of the demand for a specification of a preferred basis or preferred quantity in fundamental physical terms. The demand that observers be attributed definite experiences or records within each branch of the global state constrains the choice of a preferred basis, but certainly does not adequately specify such a basis except in very simple models.

A second question about how branches are to be specified concerns the evolution of branches over time. A particular expansion of the global state at a time gives a set of product states or branches at a single time. Supposing that we have a principle for selecting a particular expansion at each time, the unitarily evolving global state defines an evolving collection of instantaneous states or branches. But how are these branches to be understood as evolving over time? How are multiple branches at one time to be identified as the successors of a single earlier branch? The very metaphor of branching states seems to assume that this can be done.

Everett does apparently identify some branches as successors of others in the measurement schemes he considers. What is his criterion? A tempting answer is that he traces succession of branches simply via memory states, taking memory sequences as specifying the temporal succession of the memory states of observers and thus of branches (since branches in his examples are picked out precisely by definite memory states). Certainly Everett does treat memory sequences as accurately representing an observer's past history (as represented in figure 1). But I think the accuracy of memories is not merely *stipulated* as a way of identifying observer states over time; rather, Everett assumes a branch dynamics grounded directly in the formalism, from which it *follows* that memory sequences in his examples accurately reflect the past. Everett treats branches as evolving simply via the unitary dynamics governing the evolution of the global state. Everett says that "each element [of the global superposition] separately obeys the wave equation," so that the evolution of the whole is equivalent to the separate evolution of each term (1957: 458). This suggests the following criterion for identifying branches over time: given the unitarily evolving global state $|\Psi(t')\rangle = U(t', t)\,|\Psi(t)\rangle$, a later branch $|\Phi^j_{t'}\rangle$ is a successor of an earlier branch $|\Phi^i_t\rangle$ just in case

$$\langle \Phi^j_{t'}|U(t',t)|\Phi^i_t\rangle \neq 0.$$

This amounts to the condition that the later branch appears as a term with nonzero coefficient in the state obtained by unitarily evolving the earlier branch from t to t'. Note that according to this criterion, the memories of observers in Everett's examples do accurately reflect the past, since the measurement interactions in his examples—which are supposed to be implemented by the unitary dynamics—do not modify, but only add to, existing memory sequences.

Contrary to what was said before, then, Everett *does* specify a principled answer to the question of how branches evolve over time. And his answer—that branches evolve via the unitary dynamics governing the evolution of the global state—fits perfectly with his aim of interpreting the formalism without adding anything extraneous to it. That Everett provides a principled answer to this question is notable, since it is typical of critiques of Everett's interpretation to state that a workable version of the interpretation would need to supplement it first with some specification of a preferred basis, and second with some rule for identifying branches over time, i.e. a rule connecting elements of the preferred basis at different times into persisting branches. That this is the proper order in which these elements need to be introduced—preferred basis first, branch dynamics second—is standardly assumed (see, e.g. Barrett (1999)). Everett's specification of a branch dynamics suggests a possibility of reversing the order of these demands, letting the branch dynamics guide the choice of a preferred basis. Ultimately, I will argue that dynamical considerations do in fact allow one to specify a suitable preferred basis in the Everett interpretation. But to draw out the relevant dynamical considerations, I turn now to consider a very early objection to Everett.

2.2 WHY OBSERVERS ARE AWARE OF ONLY ONE BRANCH

One of the earliest objections to Everett's interpretation says that the multiplicity of observed outcomes it posits is incompatible with experience, which shows that only one outcome is observed. In his original 1957 paper, Everett mentions the objection and gives a brief reply in a footnote:

> *Note added in proof.*—In reply to a preprint of this article some correspondents have raised the question of the "transition from possible to actual," arguing that in "reality" there is—as our experience testifies—no such splitting of observer states, so that only one branch can ever actually exist. Since this point may occur to other readers the following is offered in explanation.
>
> The whole issue of the transition from "possible" to "actual" is taken care of in the theory in a very simple way—there is no such transition, nor is such a transition necessary for the theory to be in accord with our experience. From the viewpoint of the theory *all* elements of a superposition (all "branches") are "actual," none any more "real" than the rest. It is unnecessary to suppose that all but one are somehow destroyed, since all the separate elements of a superposition individually obey the wave equation with complete indifference to the presence or absence ("actuality" or not) of any other elements. This total lack of effect of one branch on another also implies that no observer will ever be aware of any "splitting" process. (Everett 1957: 459–60)

Everett's response to the objection comes in the last two sentences of the passage. He argues that it is "unnecessary to suppose that all but one [of the branches] are somehow destroyed" on the basis of two premises: First, he says that "all the separate elements of a superposition individually obey the wave equation with complete indifference to the presence or absence ('actuality' or not) of any other elements"; this premise asserts that *branches are dynamically independent* of each other. Second, he says that "this total lack of effect of one branch on another also implies that no observer will ever be aware of any 'splitting" process'; this premise says that *if branches are dynamically independent, then splitting will be undetectable.*

2.2.1 The Feeling of Splitting

Before we go on to evaluate Everett's argument, a remark about his argument as a reply to the objection is warranted. In short, Everett's reply seems to miss the point of the objection. According to the objection, experience shows that only one branch exists after a measurement. In other words, a multiplicity of incompatible states describing the observer + object system composite is incompatible with what an observer actually sees. Everett says in reply that the various distinct states or branches of the composite system cannot influence each other. But it is not clear how this lack of interaction is supposed to put to rest the objectors' worry about the simultaneous reality of multiple observation states describing a single person. Consider the dialectical situation: Everett claims that when an observer performs a measurement, the observer's memory state, a state representing what the observer is aware of, splits into multiple states, so that after the measurement the observer is simultaneously described as having witnessed multiple incompatible outcomes. The heart of the objection seems to be that splitting—or perhaps more precisely, the condition of having undergone a multiplication of one's state, so that one is described at once by a number of incompatible observation states—would involve a bizarre experience on the part of the observer.[4] Everett's claim that branches evolve independently does nothing to allay this worry. To defend his theory against this objection, Everett needs to explain how his claim that an observer somehow witnesses *all possible outcomes* of a measurement can be reconciled with observers' actual experiences, which are invariably experiences of *only one outcome* for each measurement.

Though Everett's reply does not address the heart of the objection, a better reply is available to him. Everett's interpretation provides the resources to explain why the multiplicity of states describing the observer is not incompatible with experience in the intended sense. The observer does not feel a split—i.e. does not have an experience of all outcomes occurring at once—simply because of a basic interpretational maxim: *property ascriptions are essentially branch-relative.* Each subsystem (including the observer) can be assigned a state only relative to a branch, specified by choosing one state for a particular subsystem (1957: 456). Since the physical properties of a system are determined by its state, these too can be assigned only relative to a given branch. Thus, in the post-measurement state, where the state of the observer is correlated with that of the measured system, an observer can only be assigned a state relative to a given branch. Although many incompatible states

[4] Bryce DeWitt begins his discussion of this same objection to the Everettian view by pointing out that a real observer would be constantly interacting with a vast number of microscopic systems. Therefore, DeWitt says, a real observer would be in a far more "schizophrenic" state than "the imaginary friend, described by Wigner, who is hanging in suspended animation between only *two* possible outcomes of a quantum measurement." He then states the objection itself: "Here we must surely protest. None of us feels like Wigner's friend. We do not split in two, let alone into 10^{100+}!" (DeWitt 1973: 161) Clearly DeWitt also takes the heart of the objection to be the worry that the splitting of an observer's state would involve a very peculiar experience for the observer.

of the observer appear in the overall superposition, *relative to any given branch* within this superposition the observer is described by precisely *one* of these states. The observer is represented as observing (or remembering) each one of the possible outcomes of the measurement in some branch; but in no branch is the observer represented as observing them all. Thus the observer cannot be described as having an experience (or memory) of all possible outcomes occurring together. The global state as a whole, in which all of the various possible observer states are found, does not assign any one state—and hence does not assign an experience or a memory—to the observer.

2.2.2 Why Are Other Branches Undetectable?

As a reply to the objection that a multiplicity of observer states is incompatible with an observer's experience, Everett's argument misfires. Everett ought to have invoked the branch-relativity of property ascriptions instead. But Everett's argument is not wholly irrelevant to the question of the adequacy of his interpretation. For once it is clear that according to this interpretation the experiences of actual observers are to be described relative to individual branches, and hence that there is no danger of actual observers being able to feel or otherwise directly experience the posited multiplicity of their own states, a more subtle worry arises: perhaps the existence of other branches, even if not directly observable, could be detected by indirect means. In particular, how can we be sure that the presence of multiple branches in the total quantum state will not affect the probabilities of future events for an observer described by one of these branches? How, in other words, can we rule out the possibility that the existence of multiple branches will result in interference effects detectable within a single branch?[5] Even if an observer's experience is described by the observer's state within a single branch, it might still be possible for the observer to become aware of the existence of other branches if the evolution of the observer's state (relative always to a particular branch) could be influenced by the presence of other branches in the universal quantum state. This is the

[5] Another way of putting the same question: In practice, physicists assume a collapse of the quantum state upon measurement, and throw away all terms in a superposition except the one representing the observed outcome for the purposes of making predictions about events that occur later. How can we be sure that Everett's interpretation, in which all the terms are retained, will not lead to different predictions than the (highly successful) collapse model?

worry that Everett's argument, with its appeal to the dynamical independence of branches, seems meant to put to rest.[6] This is a reasonable worry, and so it is reasonable to determine whether Everett's argument successfully addresses it.

Recall Everett's two premises: He says that *branches are dynamically independent*: "All the separate elements of a superposition individually obey the wave equation with complete indifference to the presence or absence ('actuality' or not) of any other elements." And he says that *if branches are dynamically independent, then splitting will be undetectable*: "This total lack of effect of one branch on another also implies that no observer will ever be aware of any 'splitting' process." Consider these two premises in turn. The first, the premise that branches are dynamically independent, can be read as a statement of the linearity of the quantum dynamics: Given the evolution operator $U(t, t_0)$ for a closed system, if the state of the system at time t_0 is a superposition $\sum_i c_i |\Phi_i\rangle$, then the state at time t is

$$U(t, t_0)\left(\sum_i c_i |\Phi_i\rangle\right) = \sum_i c_i U(t, t_0) |\Phi_i\rangle .$$

Thus we can think of the time evolution of the entire superposition as independently evolving each component. That is, we can say that a given component $|\Phi_i\rangle$ of the quantum state of the closed system evolves into $U(t, t_0) |\Phi_i\rangle$, whether $|\Phi_i\rangle$ is itself the complete state of the system, $|\Psi\rangle = |\Phi_i\rangle$, or just one component in a superposition $|\Psi\rangle = \sum_i c_i |\Phi_i\rangle$. And hence we can consider each component as evolving under the action of $U(t, t_0)$, "with complete indifference to the presence or absence" of any other components, as Everett says. So there is a mathematically well-defined sense in which branches, as components of the global state, are dynamically independent.

Now consider Everett's second premise, which says that if branches are dynamically independent, then splitting will be undetectable. The thought behind this premise is that the evolution of an observer's state (i.e., the history experienced by an observer) is determined by the evolution of the branch associated with the state of the observer; if the evolution of this branch is not sensitive in any way to the presence or absence of other branches, then

[6] Indeed, Everett apologists might claim that it was reasonable for him to give the argument he did in response to the objection, on the following grounds: Someone who thoroughly understood Everett's interpretational principles would not see what I have called the heart of the objection as a real problem for his interpretation. Thus Everett might well have hit on this second worry as the only viable objection in the neighborhood of the one raised by his correspondents.

the evolving state of the observer will be indifferent to the presence of other branches, and so the observer described by this state will be unable to determine whether other branches exist. Everett argues that since branches *do* evolve independently, in the sense made precise in terms of the linearity of the dynamics, other branches will be undetectable.

However, the conclusion does not follow. The dynamical independence of branches, where this is taken to refer to the linearity of the dynamics, does not rule out the possibility of interference between branches. Two components that are distinct branches at one time could evolve in such a way that both contribute to a particular branch (or to multiple branches) at a later time so as to produce interference effects; that the unitary dynamics can be considered to act separately on each component of a superposition does not preclude this possibility. Indeed, there is something ironic about taking the quantum dynamics to rule out the possibility of distinct branches becoming combined, since in the words of Bell, "it even seems reasonable to regard the coalescence of previously different branches, and the resulting interference phenomena, as *the* characteristic feature of quantum mechanics" (1987: 135). Something like this occurs of course in the double-slit experiment: components of the wavefunction of a particle that are at one time non-overlapping and can be considered as describing distinct states of the particle later recombine, producing observable interference effects. If the same thing can happen to distinct branches describing definite memory states of an observer, then this could give rise to detectable interference effects from which an observer could infer the presence of multiple branches in the global quantum state. An example of a measurement scheme where such detectable interference effects would arise is given in the next section.

Once we recognize that the quantum dynamics does not by itself guarantee that the evolution of an observer's state is indifferent to the presence or absence of multiple branches in the global quantum state, we see that the measurement schemes Everett considers in presenting his theory—schemes in which the claimed indifference does hold—are special cases. Section 2.4 will turn to examine just what is special about them, and to seek more general features of measurement schemes that would guarantee the desired "indifference" to the presence of other branches.

2.3 INTERFERENCE BETWEEN BRANCHES

It will be helpful to look to a simple example to see just how interference provides a counterexample to Everett's inference from dynamical independence of branches (linearity) to the undetectability of other branches. David Albert (1986) provides just the example we need: a toy model that illustrates how interference between distinct branches could in principle be detected by means of measurement.

2.3.1 Albert's Example

In the example, a spin-$\frac{1}{2}$ particle $\mathcal{P}$ is prepared in the initial state $a\,|+\rangle + b\,|-\rangle$, where $|+\rangle$ and $|-\rangle$ are the eigenstates of the spin observable σ_y. An observer measures σ_y on $\mathcal{P}$, and records the result in memory system $\mathcal{M}_1$.[7] The state of $\mathcal{P} + \mathcal{M}_1$ after this measurement is

$$|\alpha\rangle = a\,|+\rangle\,|`+'\rangle + b\,|-\rangle\,|`-'\rangle\,.$$

Next, the observer measures an observable A that has $|\alpha\rangle$ as an eigenstate, and records the result in memory system $\mathcal{M}_2$. The state of $\mathcal{P} + \mathcal{M}_1 + \mathcal{M}_2$ after the measurement of A is then

$$|\alpha\rangle\,|`\alpha'\rangle = \big(a\,|+\rangle\,|`+'\rangle + b\,|-\rangle\,|`-'\rangle\,\big)\,|`\alpha'\rangle\,, \tag{2.3}$$

where $|`\alpha'\rangle$ is the state of $\mathcal{M}_2$ indicating that the result $A = \alpha$ has been recorded. If we now include in the description of the initial state the pre-measurement "ready" states of $\mathcal{M}_1$ and $\mathcal{M}_2$, we can describe the evolution of $\mathcal{P} + \mathcal{M}_1 + \mathcal{M}_2$ in terms of a sequence of three states: The initial state,

$$|\Psi(t_0)\rangle = \big(a\,|+\rangle + b\,|-\rangle\,\big)\,|\text{ready}\rangle\,|\text{ready}\rangle\,,$$

has one branch; the state after the first measurement,

$$|\Psi(t_1)\rangle = a\,|+\rangle\,|`+'\rangle\,|\text{ready}\rangle + b\,|-\rangle\,|`-'\rangle\,|\text{ready}\rangle\,, \tag{2.4}$$

[7] The example presented here is actually a slightly simplified version of Albert's measurement scheme. Albert includes the state of two measuring devices (one used to measure σ_y and one used to measure A) and also of a second observer, who reports the result of the A-measurement to the first observer. Nothing essential is lost by simplifying the story by leaving out the measuring devices and the second observer.

has two branches; and the state after the second measurement,

$$|\Psi(t_2)\rangle = a\,|+\rangle\,|`+\text{'}\rangle\,|`\alpha\text{'}\rangle + b\,|-\rangle\,|`-\text{'}\rangle\,|`\alpha\text{'}\rangle\,, \tag{2.5}$$

also has two.[8]

The interesting feature of this example is that the second measurement allows the observer, as described by either one of the branches in the final state, to infer that a second branch exists in the global state. The second measurement gives the result $A = \alpha$ with certainty, which at t_2 indicates to the observer that the overall state of the system at t_1 was not $|+\rangle\,|`+\text{'}\rangle\,|\text{ready}\rangle$, as it would have appeared to the observer relative to this branch, nor was it $|-\rangle\,|`-\text{'}\rangle\,|\text{ready}\rangle$, as it would have appeared relative to that branch. The observer can infer that the overall state was instead a superposition of these branches—specifically the superposition given by equation (2.4)—and therefore, knowing how the measurement of A would affect this state, the observer can further deduce that the overall state of measured-system-plus-observer after the second measurement is (2.5). Thus the observer described by the branch $|+\rangle\,|`+\text{'}\rangle\,|`\alpha\text{'}\rangle$ can know that there is a second branch $|-\rangle\,|`-\text{'}\rangle\,|`\alpha\text{'}\rangle$ in the total quantum state, and vice versa. Albert, who calls our observer "friend no. 1," puts the point this way:

> Now, what is going on in this state is that friend no. 1 still simultaneously inhabits two different and mutually exclusive Everett worlds (in one, $\sigma_y = +\frac{1}{2}$, and in the other, $\sigma_y = -\frac{1}{2}$), but now, in each of those two worlds separately, friend no. 1 knows that $A = \alpha$; he knows, that is, that another world exists. (Albert 1986: 501)

2.3.2 Interference in Albert's Example

Now that we have in hand an example showing the possibility in principle of detecting other branches, let us examine the role of interference in this example. Consider the global states in Albert's example before and after the measurement of A:

$$|\Psi(t_1)\rangle = a\,|+\rangle\,|`+\text{'}\rangle\,|\text{ready}\rangle + b\,|-\rangle\,|`-\text{'}\rangle\,|\text{ready}\rangle$$
$$|\Psi(t_2)\rangle = a\,|+\rangle\,|`+\text{'}\rangle\,|`\alpha\text{'}\rangle + b\,|-\rangle\,|`-\text{'}\rangle\,|`\alpha\text{'}\rangle\,,$$

[8] Here and throughout the rest of the chapter states are divided into branches relative to the definite memory states of the observer, e.g., states of $\mathcal{M}_1 + \mathcal{M}_2$ of the form $|`\pm\text{'}\rangle\,|`\alpha\text{'}\rangle$.

Both states have two branches, and there would seem at first glance to be a particularly simple relationship between the two branches that make up the earlier state and the two branches that make up the later state. It looks as though the measurement of A simply changes the state of $\mathcal{M}_2$ in each branch from $|\text{ready}\rangle$ to $|\text{`}\alpha\text{'}\rangle$ while leaving the branch otherwise unchanged. That is, it looks as though the measurement of A effects the change

$$|\pm\rangle\,|\text{`}\pm\text{'}\rangle\,|\text{ready}\rangle \longrightarrow |\pm\rangle\,|\text{`}\pm\text{'}\rangle\,|\text{`}\alpha\text{'}\rangle \tag{2.6}$$

within each branch. This would fit nicely with the picture of measurement and branching that Everett paints: a measurement performed when the total state is already a superposition of multiple branches unfolds within each branch separately, and the result in one branch has no impact on the result in the other branch. The memory of an earlier measurement outcome in each branch is left unchanged, and the latest measurement simply adds a new memory to the one already recorded.

But we can check whether this simple picture of the change induced by the measurement of A is correct by calculating directly the state that would result from a measurement of A given the pre-measurement state $|+\rangle\,|\text{`}+\text{'}\rangle\,|\text{ready}\rangle$ by itself, and the state that would result given $|-\rangle\,|\text{`}-\text{'}\rangle\,|\text{ready}\rangle$. To do this we first need to specify additional eigenstates of A, so that the two states $|+\rangle\,|\text{`}+\text{'}\rangle$ and $|-\rangle\,|\text{`}-\text{'}\rangle$ can be written as linear combinations of eigenstates of A. Let us rename $|\alpha\rangle$ as $|\alpha_1\rangle$, and then choose A so that two of its eigenstates are[9]

$$|\alpha_1\rangle = a\,|+\rangle\,|\text{`}+\text{'}\rangle + b\,|-\rangle\,|\text{`}-\text{'}\rangle$$
$$|\alpha_2\rangle = b^*\,|+\rangle\,|\text{`}+\text{'}\rangle - a^*\,|-\rangle\,|\text{`}-\text{'}\rangle\,.$$

Let us also rename the memory state $|\text{`}\alpha\text{'}\rangle$ as $|\text{`}\alpha_1\text{'}\rangle$ and introduce a state, $|\text{`}\alpha_2\text{'}\rangle$, of $\mathcal{M}_2$, which acts as a memory state corresponding to $|\alpha_2\rangle$; that is, the states $|\text{`}\alpha_1\text{'}\rangle$ and $|\text{`}\alpha_2\text{'}\rangle$ indicate that the observer has recorded the outcome $A = \alpha_1$ and $A = \alpha_2$, respectively.

Now if the total state of $\mathcal{P}+\mathcal{M}_1+\mathcal{M}_2$ was given by $|+\rangle\,|\text{`}+\text{'}\rangle\,|\text{ready}\rangle$, then a measurement of A by the observer would change this total state, consisting of a single branch, into a

[9] Albert required only that the state we are now calling $|\alpha_1\rangle$ be an eigenstate of A; we are simply specifying A more precisely than Albert did by requiring that it also have $|\alpha_2\rangle$ as an eigenstate. This particular choice of $|\alpha_2\rangle$ is convenient because it allows us to write the states $|+\rangle\,|\text{`}+\text{'}\rangle$ and $|-\rangle\,|\text{`}-\text{'}\rangle$ as linear combinations of just the two eigenstates $|\alpha_1\rangle$ and $|\alpha_2\rangle$, and therefore saves us from having to specify the other eigenstates of A.

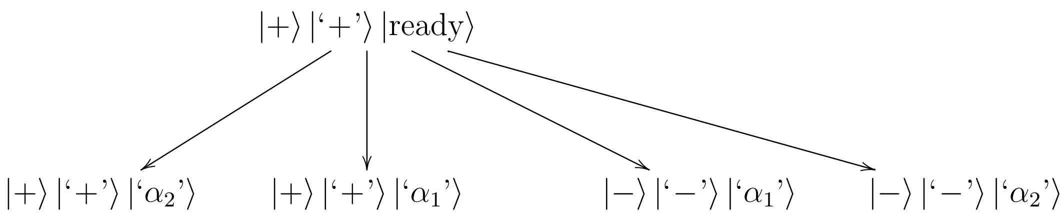

Figure 2: A state that evolves into a superposition of four branches as a result of the measurement of A

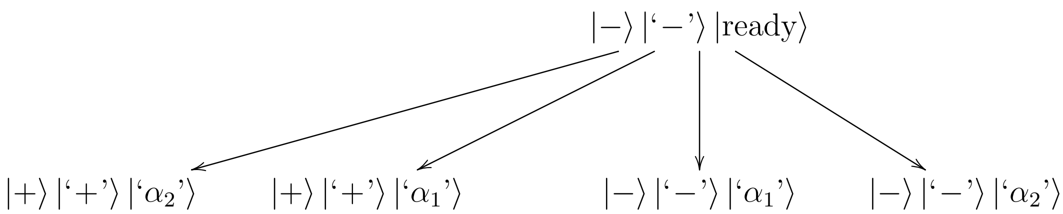

Figure 3: Another state that evolves into a superposition of four branches as a result of the measurement of A

superposition (call it $|\beta_+\rangle$) of four branches.[10] This is depicted diagrammatically in figure 2. And if the total state was $|-\rangle\,|`-'\rangle\,|\text{ready}\rangle$, a measurement of $A$ would likewise change this state, consisting of a single branch, into a superposition (call it $|\beta_-\rangle$) of four branches.[11] This is depicted diagrammatically in figure 3. Clearly the evolution of the states $|\pm\rangle\,|`\pm'\rangle\,|\text{ready}\rangle$ brought about by the measurement of A is more complicated than it seems when one first sees Albert's example. Instead of undergoing the simple transition (2.6), each of these states evolves into a complicated superposition of branches.

[10] The evolution is given by

$$\begin{aligned}
|+\rangle\,|`+'\rangle\,|\text{ready}\rangle &= \big(a^*\,|\alpha_1\rangle + b\,|\alpha_2\rangle\big)\,|\text{ready}\rangle \\
&\to a^*\,|\alpha_1\rangle\,|`\alpha_1'\rangle + b\,|\alpha_2\rangle\,|`\alpha_2'\rangle \\
&= |a|^2\,|+\rangle\,|`+'\rangle\,|`\alpha_1'\rangle + a^*b\,|-\rangle\,|`-'\rangle\,|`\alpha_1'\rangle \\
&\quad + |b|^2\,|+\rangle\,|`+'\rangle\,|`\alpha_2'\rangle - a^*b\,|-\rangle\,|`-'\rangle\,|`\alpha_2'\rangle \\
&= |\beta_+\rangle\,.
\end{aligned}$$

[11] The evolution is given by

$$\begin{aligned}
|-\rangle\,|`-'\rangle\,|\text{ready}\rangle &= \big(b^*\,|\alpha_1\rangle - a\,|\alpha_2\rangle\big)\,|\text{ready}\rangle \\
&\to b^*\,|\alpha_1\rangle\,|`\alpha_1'\rangle - a\,|\alpha_2\rangle\,|`\alpha_2'\rangle \\
&= ab^*\,|+\rangle\,|`+'\rangle\,|`\alpha_1'\rangle + |b|^2\,|-\rangle\,|`-'\rangle\,|`\alpha_1'\rangle \\
&\quad - ab^*\,|+\rangle\,|`+'\rangle\,|`\alpha_2'\rangle + |a|^2\,|-\rangle\,|`-'\rangle\,|`\alpha_2'\rangle \\
&= |\beta_-\rangle\,.
\end{aligned}$$

What is more, the post-measurement states $|\beta_\pm\rangle$ in these two cases are two different superpositions of the *same* four branches. And seeing this is the key to understanding the role of interference between branches in Albert's example. For in this example the total state of $\mathcal{P} + \mathcal{M}_1 + \mathcal{M}_2$ before the measurement of A is

$$|\Psi(t_1)\rangle = a\,|+\rangle\,|`+'\rangle\,|\text{ready}\rangle + b\,|-\rangle\,|`-'\rangle\,|\text{ready}\rangle\,,$$

and the measurement of A induces the evolution

$$|\pm\rangle\,|`\pm'\rangle\,|\text{ready}\rangle \longrightarrow |\beta_\pm\rangle$$

Thus from linearity of the dynamics the total state after the measurement of A is

$$\begin{aligned}|\Psi(t_2)\rangle &= a\,|\beta_+\rangle + b\,|\beta_-\rangle\\ &= a\,|+\rangle\,|`+'\rangle\,|`\alpha'\rangle + b\,|-\rangle\,|`-'\rangle\,|`\alpha'\rangle\,.\end{aligned}$$

Even though each of the two branches of $|\Psi(t_1)\rangle$ evolves into a superposition $|\beta_\pm\rangle$ of *four* distinct branches at t_2, the global state $|\Psi(t_1)\rangle$ itself evolves into a superposition of only *two* distinct branches. The other two branches that occur in the states $|\beta_\pm\rangle$ receive from their parent branches (the two branches of $|\Psi(t_1)\rangle$) contributions which precisely cancel out, eliminating these two would-be branches from $|\Psi(t_2)\rangle$. This is depicted diagrammatically in figure 4.

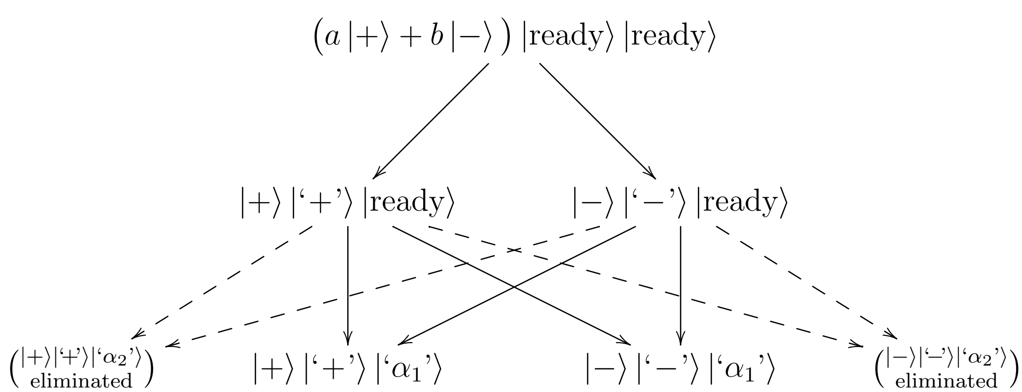

Figure 4: The branching tree diagram for Albert's example. Two terms that would otherwise appear in the final state are eliminated, in the sense that contributions to each of these branches from their two parent branches precisely cancel out, so that both these terms have amplitude 0 in the final state.

This example shows that the linearity of the quantum dynamics does not by itself imply that the future evolution of a branch is indifferent to the presence or absence of other branches. Interference between branches is possible under the linear dynamics, even in an extremely simple model where only ideal measurement interactions are allowed; and when it occurs the interfering branches can no longer be thought of as evolving independently.

2.4 MEMORIES, HISTORIES, AND INTERFERENCE

Albert's example shows that not all measurement schemes consisting of sequences of ideal measurements lead to branching tree structures as well behaved as those Everett used to illustrate his theory. A comparison of the branching tree diagrams for Everett's examples (e.g., figure 1) with that of Albert's example (figure 4) gives a vivid picture of just what good behavior and (one kind of) bad behavior amount to. In Everett's examples, as in Albert's, branches divide upon measurement, so that a single branch can have multiple daughter branches. But in Albert's example we see the converse as well: some branches have multiple parent branches. This section takes up the explanation and the results of the good behavior of Everett-type measurement schemes.

2.4.1 Preserving memories

There is a straightforward reason why all of the branching tree diagrams for measurement schemes like those considered by Everett have the structural feature noted above, namely that all branches have a single parent branch. In the measurement schemes that Everett considers, memories of past measurement outcomes are always preserved. That is, all of the measurement interactions in these schemes leave unchanged the memories of the outcomes of previous measurements. When a given branch present after k measurements is split by the $k+1$st measurement into a superposition of distinct branches, the memories of the first k measurement outcomes already recorded in this branch are inherited by each of its daughter branches.

Such preservation of memories within a measurement scheme is a sufficient condition for a simple branching tree structure in which branches split upon measurement and never recombine. This is a result of the fact that the distinct branches at each time are individuated precisely according to the memory states they assign to the observer. Any two distinct branches B_1 and B_2 in the total state at some time necessarily assign different memory states to the observer. The daughter branches of each branch inherit all memories of past measurement outcomes; thus each daughter branch of B_1 assigns to the observer a memory state different from any assigned by a daughter branch of B_2. Hence the sets of daughter branches of these two branches do not intersect.

When memories are not preserved, that is, when some of the measurement interactions in a given sequence alter memories of previous measurement outcomes, it is possible for some branches to have multiple parent branches. Memories are not preserved in Albert's example, because the eigenstates of the second observable measured, A, are superpositions of the definite memory states $|`\pm'\rangle$ that record the outcome of the first measurement. The second measurement interaction therefore takes a branch in which the observer has recorded in memory the result $\sigma_y = +\frac{1}{2}$, i.e. a branch in which the state of $\mathcal{M}_1$ is $|`+'\rangle$, to a superposition of branches, in some of which the state of $\mathcal{M}_1$ is $|`-'\rangle$. Thus, as we saw above, measurement of A changes the state

$$|+\rangle\,|`+'\rangle\,|\text{ready}\rangle$$

into the superposition

$$\begin{aligned}|\beta_+\rangle = {} & |a|^2\,|+\rangle\,|`+'\rangle\,|`\alpha_1'\rangle + a^*b\,|-\rangle\,|`-'\rangle\,|`\alpha_1'\rangle \\ & + |b|^2\,|+\rangle\,|`+'\rangle\,|`\alpha_2'\rangle - a^*b\,|-\rangle\,|`-'\rangle\,|`\alpha_2'\rangle\,.\end{aligned}$$

The second and fourth terms of this superposition describe observers whose memories of the outcome of the first measurement have been flipped from + to − in the course of the second measurement. This makes it possible for two branches at t_1, branches picked out by distinct memory states, to evolve into overlapping sets of branches at a later time and hence to interfere with each other.

Albert's example shows that if arbitrary measurement interactions are allowed, interference between distinct memory states can occur. Thus it is not merely the linearity of

Schrödinger evolution, as Everett's argument suggests, but a restriction on the particular forms that evolution can take that accounts for the desired independence of branches in his examples. By limiting the kinds of measurements allowed in his examples—and by restricting interactions in his examples to the thus-limited class of measurement interactions—Everett restricts his focus to measurement schemes in which definite memory states are preserved and, as a consequence, interference between distinct memory states does not occur.

2.4.2 Probabilities and Histories

Since all Everett-type measurement schemes preserve memories, they give rise to branching tree structures in which each branch has only one parent branch. This feature in turn entails that there is a one-to-one correspondence between branches and histories. Pick out a branch at any stage of the measurement scheme; it has a unique parent, and this parent branch has a unique parent, and so on, so that tracing back in this way to the initial state (which is assumed to consist of a single branch) we get the unique history connecting the initial state to the chosen branch (figure 5).

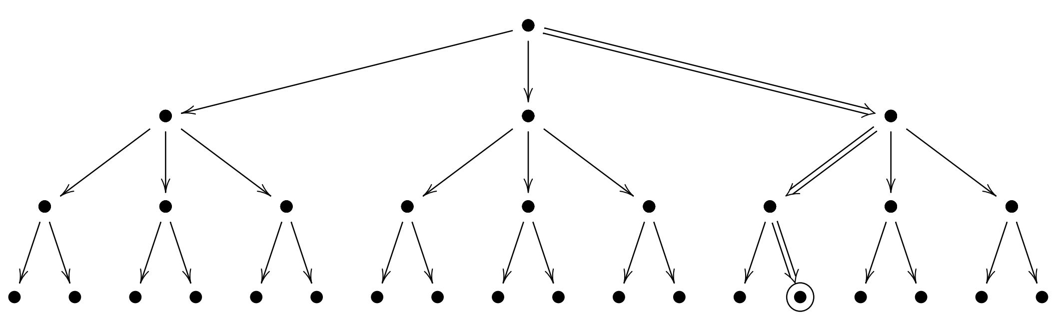

Figure 5: The one-to-one correspondence between branches and histories for Everett-type measurement schemes. For a particular branch at any stage of the measurement scheme, there is only one history leading to that branch from the initial state (the single branch at time t_0). The double-shafted arrows in the diagram trace the unique history terminating in the branch represented by the circled dot.

This one-to-one correspondence between branches and histories in Everett-type measurement schemes provides a natural way to assign probabilities to histories. Everett's interpretation comes equipped with a rule for assigning a probability distribution to the set of *branches* in the total state at each time, namely the usual amplitude-squared probability distribution. With precisely one history associated with each branch, this is also a natural way to assign probabilities to *histories*: Given a particular initial state, set the probability of a particular k-step history (one step for each measurement) equal to the probability of the branch in which this history terminates after the kth measurement. As Everett notes, given the global state after a sequence of measurements, the probability assigned to a given branch in the kinds of schemes he considers can be expressed as a product, where each factor is associated with a particular outcome for one of the measurements in the sequence. The probability of a particular sequence of measurement outcomes indexed by $i, j, \ldots, k, l$ (a sequence consisting of the ith outcome of the first measurement, the jth outcome of the second, etc.) is a product $|\alpha_i|^2 |\beta_{ij}|^2 \cdots |\gamma_{ij\cdots k}|^2 |\delta_{ij\cdots kl}|^2$. Each factor can be associated with the transition from one branch to another: $|\alpha_i|^2$ gives the probability for the transition from the initial state at t_0 to the ith branch at t_1; $|\beta_{ij}|^2$ gives the probability for the transition from the ith branch at t_1 to the branch indexed by i, j at t_2; and so on. (The derivation, which is straightforward, appears in the appendix to this chapter.) Thus from the *single-time* probabilities built into Everett's theory, we can derive *dynamical* probabilities, probabilities for histories and for transitions between branches. The transition probabilities thus derived will be precisely those assigned by collapse quantum mechanics to the same transitions, i.e. those given by the Born rule, or by (what is equivalent in this case) a standard quantum mechanical rule for the probability of a transition from a state $|\Phi_t^i\rangle$ to a state $|\Phi_{t'}^j\rangle$, namely

$$\Pr\left(|\Phi_{t'}^j\rangle / |\Phi_t^i\rangle\right) = \left|\langle\Phi_{t'}^j|\, U(t',t)\, |\Phi_t^i\rangle\right|^2 . \tag{2.7}$$

Two points about these transition probabilities are in order. First, it should be emphasized that these transition probabilities are not built directly into the Everett interpretation. The interpretation only prescribes directly a probability distribution over branches at each time t (given the total state at t); for Everett, diachronic probabilities, relating states or branches at different times, are not basic but are to be somehow inferred from synchronic probabilities. Contrast this with collapse quantum mechanics, in which the basic notion of probability is associated with a *dynamical* occurrence, the transition of a system from one state to another, and also with the consistent histories interpretation, where probabilities are associated with time-ordered sequences of events. For Everett, the basic notion of probability is probability of a branch at a given time—a single-time probability, in contrast to the two-time probabilities (transition probabilities) basic to collapse quantum mechanics or the many-time probabilities (assigned to histories) basic to the consistent histories interpretation. For the kind of measurement scheme Everett considers, in which memories are preserved and hence there is a one-to-one correspondence between branches and histories, the choice to identify the probability of a history specified by a sequence of measurement outcomes with the probability assigned by the Everett interpretation to the last branch in the sequence determines a unique assignment of probabilities to transitions (from one branch to one of its daughter branches) and to histories (sequences of branches).

Second, it is important that the probability (2.7) thus assigned to a particular transition from one branch to another is a function of these two branch states alone, and is *independent of the branch weights* (the coefficients associated with each branch as a term within the global quantum state). This explains why, for the schemes Everett considers, the presence or absence of other branches is undetectable. It turns out that for such schemes, the local state of a branch screens off the two-time probabilities from information about the global quantum state and from information about the past. An observer described by a particular branch can calculate probabilities of measurement outcomes from information about that branch, and the measurement to be performed, without any knowledge of the global state. This is important for the Everett interpretation; for it explains how physicists can make accurate predictions and do meaningful quantum physics without having to know whether other branches might exist—and what these branches and their respective weights are—in the quantum state of the universe.

In fact, the transition probability formula (2.7) is the *only* way to assign transition probabilities that is both (i) independent of branch weights and (ii) consistent with the Everettian probability distribution over branches at a time. For branch-weight independence requires a given transition to be assigned the same probability whether the parent branch $|\Phi_t^i\rangle$ is just one of many branches in the global state, $|\Psi(t)\rangle = \sum_i c_i |\Phi_t^i\rangle$, or the only branch in the global state, $|\Psi(t)\rangle = |\Phi_t^i\rangle$. And in the latter case, the transition probability is just the probability of the daughter branch $|\Phi_{t'}^j\rangle$ given the global state $|\Psi(t')\rangle = U(t', t) |\Phi_t^i\rangle$, and is thus determined directly by the Everettian amplitude-squared rule for branch probabilities:

$$\begin{aligned}
\Pr\left(|\Phi^j_{t'}\rangle / |\Phi^i_t\rangle\right) &= \Pr\left(|\Phi^j_{t'}\rangle / |\Psi(t)\rangle\right) \\
&= \Pr_{|\Psi(t')\rangle}\left(\,|\Phi^j_{t'}\rangle\,\right) \\
&= \left|\langle\Phi^j_{t'}|\Psi(t')\rangle\right|^2 \\
&= \left|\langle\Phi^j_{t'}|U(t',t)|\Phi^i_t\rangle\right|^2 .
\end{aligned}$$

2.4.3 Consistency

We have just seen that a one-to-one correspondence between histories and branches allows for a simple and natural extension of Everettian probability assignments. The key move in making this extension is assigning each history a probability equal to the probability of the branch in which the history terminates. For measurement schemes for which there is no such one-to-one correspondence—those for which some branches have multiple parent branches—this same identification of probabilities is not available. Yet for some of these more general measurement schemes a similar extension of probability assignments is possible.

An example to consider here is the same sequence of two measurements as in Albert's example, but with a slightly different initial state. Instead of $a\,|+\rangle + b\,|-\rangle$, let the initial state of the particle $\mathcal{P}$ be $a\,|+\rangle + \mathrm{i}b\,|-\rangle$; call this example Variation 1 on Albert's example. (There will be a Variation 2 a bit later in the chapter.) The initial, intermediate, and final states for this case are:

$$\begin{aligned}
|\Psi'(t_0)\rangle &= \big(a\,|+\rangle + \mathrm{i}b\,|-\rangle\,\big)\,|\text{ready}\rangle\,|\text{ready}\rangle \\
|\Psi'(t_1)\rangle &= a\,|+\rangle\,|`+'\rangle\,|\text{ready}\rangle + \mathrm{i}b\,|-\rangle\,|`-'\rangle\,|\text{ready}\rangle \\
|\Psi'(t_2)\rangle &= a\big(|a|^2 + \mathrm{i}\,|b|^2\big)\,|+\rangle\,|`+'\rangle\,|`\alpha_1'\rangle + b\big(|a|^2 + \mathrm{i}\,|b|^2\big)\,|-\rangle\,|`-'\rangle\,|`\alpha_1'\rangle \\
&\qquad + a\,|b|^2\,(1-\mathrm{i})\,|+\rangle\,|`+'\rangle\,|`\alpha_2'\rangle + |a|^2\,b(-1+\mathrm{i})\,|-\rangle\,|`-'\rangle\,|`\alpha_2'\rangle\,.
\end{aligned}$$

This is depicted diagrammatically in figure 6. The two branches in the intermediate state in Variation 1 are the same as those in Albert's example, and we have already seen that each of these two branches, considered independently, evolves into a superposition of four branches (as shown in Figures 2 and 3). But the change in relative phase that results from replacing the coefficient b in Albert's example with ib in this example eliminates all

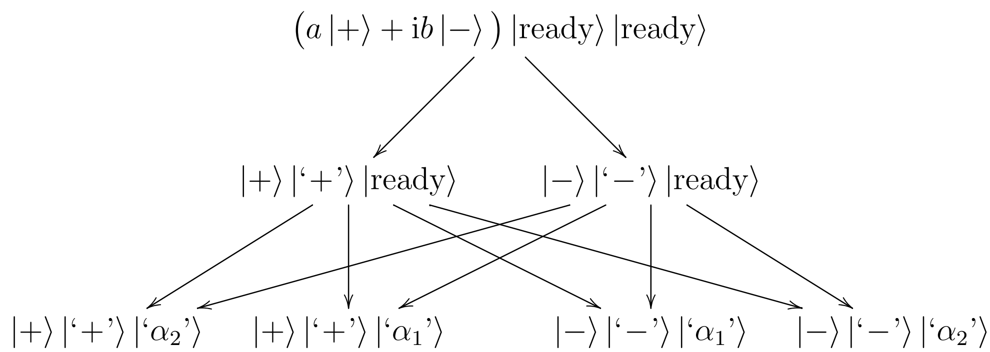

Figure 6: The branching tree diagram for Variation 1

interference and leads to very different final state than in Albert's example. The difference obvious from the diagrams—compare figure 6 to figure 4—is that in Variation 1 four branches are present in the final superposition, whereas in Albert's example only two of these four branches are present in the final state. In Albert's example, the coefficients in the initial state were chosen so that interference completely eliminates two would-be branches from the final state. In Variation 1, on the other hand, the coefficients have been chosen so that there is no interference whatsoever. The two branches in the intermediate state contribute independently to the probability of each branch in the final state, so that the probability of each of the four final branches is just the sum of the contributions from the two parent branches.[12]

The lack of interference makes it possible in this example, as in Everett-type measurement schemes, to assign the standard quantum-mechanical transition probability (2.7) to each transition from parent to daughter branch in a way that is consistent with the amplitude-

[12] The probability of the branch $|+\rangle\,|\text{`}+\text{'}\rangle\,|\text{`}\alpha_1\text{'}\rangle$, for example, is given by its amplitude squared,

$$|a|^2\,(|a|^4 + |b|^4). \tag{2.8}$$

Each parent branch contributes to this probability a quantity equal to the probability of the parent branch itself times the probability of the specified daughter branch given the parent branch. Thus the contribution of the parent branch $|+\rangle\,|\text{`}+\text{'}\rangle\,|\text{ready}\rangle$ to the probability of $|+\rangle\,|\text{`}+\text{'}\rangle\,|\text{`}\alpha_1\text{'}\rangle$ is

$$|a|^2 \times |a|^4\,,$$

and the contribution of the other parent branch, $|-\rangle\,|\text{`}-\text{'}\rangle\,|\text{ready}\rangle$, is

$$|b|^2 \times |a|^2\,|b|^2\,.$$

Summing these contributions from the two parent branches gives the total probability (2.8).

squared probability distribution over branches at each time. As before, the probability of a particular possible history of the observer (a time-ordered sequence of branches, one for each stage of the measurement scheme, where each branch in the sequence is the parent of the next) is given by the product of the probabilities for the transitions constituting this history. Since more than one history may terminate in a particular branch, the probability of a branch is given by the sum of the probabilities contributed to it by each such history. That is, for each branch B,

$$\Pr(B) = \sum_{\substack{\text{histories } H \\ \text{terminating} \\ \text{in } B}} \Pr(H), \tag{2.9}$$

where $\Pr(H)$ is calculated as a product of transition probabilities (2.7) between the (time-ordered) states that make up H.

Condition (2.9) is equivalent, for the simple measurement schemes considered here, to the *consistency condition* of Griffiths (1984), also called the *weak decoherence condition* by Gell-Mann and Hartle (1990). When this condition is satisfied for all branches B at all stages of a measurement scheme, the collection of all histories defined by the measurement scheme is a *consistent* family of histories, in Griffiths' sense. There is no interference between histories in a consistent family—equation (2.9) is just the condition that histories do not interfere. Thus measurement schemes that give rise to a consistent family of histories will not produce any detectable interference effects. In such schemes, then, observers will be unable to detect the presence or absence of other branches, and distinct branches can be thought of as evolving independently.

Consistency or weak decoherence thus provides a more general characterization of the conditions under which distinct branches of the global quantum state can be thought of as "individually obey[ing] the wave equation with complete indifference to the presence or absence ('actuality' or not) of any other elements." Although a consistent set of branch histories may include recombination of distinct branches as well as splitting of individual branches, as in figure 6, recombination does not spoil the effective independence of branch evolution as long as there is no interference between the recombining branches. The components, separately contributed to a single branch by multiple earlier branches, continue to be distinguishable and to evolve independently as long as they do not interfere. Thus decoherence, the absence of interference, as formalized in the consistency or weak decoherence condition, amounts to a criterion for when a preferred decomposition of the evolving global state can be thought of as specifying a set of histories that *branches*, in a generalized sense.

2.5 ENVIRONMENTAL DECOHERENCE

As illustrated by Albert's example, Everett's interpretation implies that interference can occur between distinct branches of the global quantum state and that this interference could be detected if an observer were to measure the appropriate observables. Insofar as Everett's interpretation allows for such detection of interference, its predictions will differ from those of conventional quantum mechanics with the collapse postulate. But of course such interference is never observed: once a measurement has been made and a particular outcome observed, we can make accurate predictions by supposing that no other branches exist. Everett's interpretation owes us some explanation of why the very interference effects that make its predictions different from those of standard collapse quantum mechanics are never observed.

One strategy for providing such an explanation is to argue that it is impossible to measure those observables for which the probabilities generated by the total quantum state differ significantly from the probabilities generated by a typical branch. And such an argument can be given by appealing to environmental decoherence. Environmental decoherence is a process involving the interaction of a macroscopic object with its environment, which includes the microscopic systems that interact with the object, such as air molecules and cosmic radiation. It takes place when the state of the environment becomes coupled to the state of the object in a particular basis (the "decoherence basis"). This coupling results in an entangled state of the object-plus-environment system, which effectively makes it impossible to observe interference effects between distinct states of the decoherence basis, since observing such interference effects would require a measurement of an extremely complicated observable of object-plus-environment. The study of decoherence over the past few decades shows that in any realistic situation this process leads to the decay of interference between elements of the decoherence basis on an astonishingly short timescale.

Consider what happens if we modify Albert's example to include an environment $\mathcal{E}$ that becomes coupled to the states $|`\pm'\rangle$ of the memory system $\mathcal{M}_1$. (Call this modified example Variation 2.) Suppose that the initial state of the entire system $(\mathcal{P} + \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{E})$ is a product state

$$|\Psi''(t_0)\rangle = \big(a\,|+\rangle + b\,|-\rangle\,\big)\,|\text{ready}\rangle\,|\text{ready}\rangle\,|e_0\rangle\,.$$

The measurement of σ_y correlates the state of $\mathcal{M}_1$ with that of $\mathcal{P}$, and then $\mathcal{E}$ very quickly becomes correlated with $\mathcal{M}_1$ so that the total state becomes

$$|\Psi''(t_1)\rangle = a\,|+\rangle\,|`+'\rangle\,|\text{ready}\rangle\,|e_+\rangle + b\,|-\rangle\,|`-'\rangle\,|\text{ready}\rangle\,|e_-\rangle\,, \tag{2.10}$$

where the states $|e_\pm\rangle$ are very nearly orthogonal, $\langle e_+|e_-\rangle \approx 0$. (This is the heart of the decoherence effect: the environment states coupled to distinct states of the object approach orthogonality *extremely* quickly.) As in Albert's example, the global state at this stage has two branches. Finally, it can be shown that after the A measurement the total state is

$$\begin{aligned}|\Psi''(t_2)\rangle = {} & N_1 a\,|+\rangle\,|`+'\rangle\,|`\alpha_1'\rangle\,|e_1\rangle + N_1 b\,|-\rangle\,|`-'\rangle\,|`\alpha_1'\rangle\,|e_1\rangle \\ & + N_2 a\,|b|^2\,|+\rangle\,|`+'\rangle\,|`\alpha_2'\rangle\,|e_2\rangle - N_2\,|a|^2\,b\,|-\rangle\,|`-'\rangle\,|`\alpha_2'\rangle\,|e_2\rangle\,,\end{aligned}$$

where

$$N_1\,|e_1\rangle = |a|^2\,|e_+\rangle + |b|^2\,|e_-\rangle$$
$$N_2\,|e_2\rangle = |e_+\rangle - |e_-\rangle$$

and N_1 and N_2 are normalization constants.[13] This is depicted diagrammatically in figure 7.

The final state $|\Psi''(t_2)\rangle$ has four branches. Consider what this state would look like if the environment was completely insensitive to the difference between the states $|`\pm'\rangle$ of $\mathcal{M}_1$, that is, if $|e_+\rangle = |e_-\rangle = |e_*\rangle$: then $N_1\,|e_1\rangle = |a|^2\,|e_*\rangle + |b|^2\,|e_*\rangle = |e_*\rangle$ and $N_2\,|e_2\rangle = 0$. Interference would occur just as in Albert's example, eliminating the two branches in which the state of $\mathcal{M}_2$ is $|`\alpha_2'\rangle$ (and increasing the probability of the two branches in which it is $|`\alpha_1'\rangle$). But

[13] These normalization constants are:

$$N_1 = \sqrt{|a|^4 + 2\,|a|^2\,|b|^2\,\mathrm{Re}\,\langle e_+|e_-\rangle + |b|^4} \approx \sqrt{|a|^4 + |b|^4}$$
$$N_2 = \sqrt{2 - 2\,\mathrm{Re}\,\langle e_+|e_-\rangle} \approx \sqrt{2}$$

where the approximations hold for $\langle e_+|e_-\rangle \approx 0$.

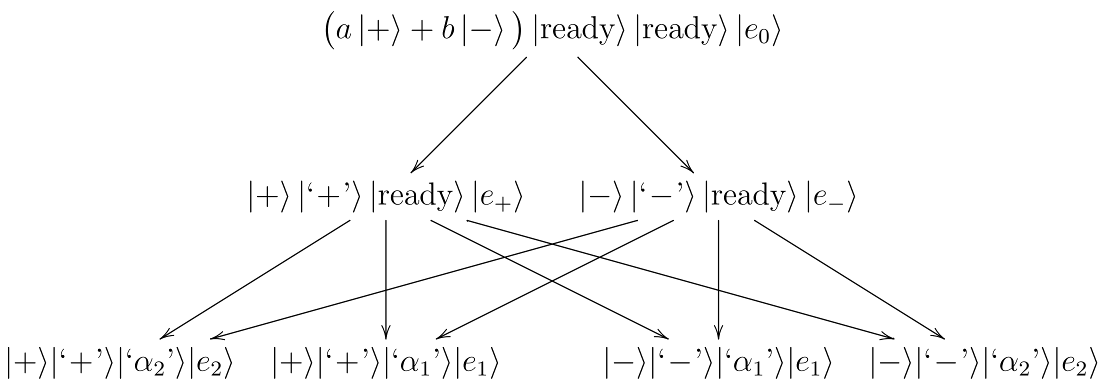

Figure 7: The branching tree diagram for Variation 2 (Albert's measurement scheme with the addition of an environment that becomes coupled to the states $|`\pm'\rangle$ of $\mathcal{M}_1$)

since in this model the states $|e_\pm\rangle$ are very nearly orthogonal to each other, rather than equal, the interference that would arise otherwise is eliminated. All four branches remain.

Furthermore, it turns out that this measurement scheme gives rise to an *approximately* consistent (or decoherent) family of histories. That is, if we assign the standard transition probabilities of equation (2.7) to each transition from parent branch to daughter branch, then the probabilities obtained for histories by multiplying the relevant transition probabilities, *very nearly* mesh (in the sense of condition (2.9)) with the amplitude-squared probabilities Everett's interpretation assigns to branches. In fact we have, for all branches B in Variation 2,

$$\Pr(B) \approx \sum_{\substack{\text{histories } H\\ \text{terminating}\\ \text{in } B}} \Pr(H).$$

Calculation shows that each of the interference terms in the probabilities assigned to the four branches in the final state includes a factor of $\langle e_+|e_-\rangle$—which is to say that these interference terms effectively vanish, since $\langle e_+|e_-\rangle \approx 0$.[14]

So it is clear that environmental decoherence would very quickly wipe out the interference that is at work in Albert's example, the interference between the superposed states $|+\rangle\,|`+'\rangle$ and $|-\rangle\,|`-'\rangle$ that is detected by the measurement of A in Albert's example. Of course, the

[14]The histories in Variation 2 satisfy the *medium decoherence condition* of Gell-Mann & Hartle (1990), which is, as its name suggests, stronger than the weak decoherence condition. The difference (given the assumption of a pure global state) is that the weak decoherence condition requires a vanishing *of the real part* of the inner product of the contributions of any two distinct parent branches to a single daughter branch, while the medium decoherence condition requires that the inner product vanish entirely (i.e. orthogonality of such contributions).

elimination of *interference* between these two states does not imply that either *state* has been eliminated; both still exist in superposition in the global quantum state. Essentially, the superposition

$$a\,|+\rangle\,|`+\text{'}\rangle + b\,|-\rangle\,|`-\text{'}\rangle$$

becomes

$$a\,|+\rangle\,|`+\text{'}\rangle\,|e_+\rangle + b\,|-\rangle\,|`-\text{'}\rangle\,|e_-\rangle$$

(this is what is represented by equation (2.10)), so that interference between the two terms of this superposition cannot any longer be detected by measuring an observable on $\mathcal{P} + \mathcal{M}_1$. If one could measure an appropriate observable on $\mathcal{P} + \mathcal{M}_1 + \mathcal{E}$, one could detect the interference, but this is now beyond the remotest practical possibility. To determine the proper observable to measure, one would first have to know precisely what the (continually evolving!) environment states $|e_\pm\rangle$ are; determining these would require knowing both the precise initial state $|e_0\rangle$ of the vast collection of microscopic degrees of freedom interacting with $\mathcal{M}_1$ and the precise details of the interaction between these microscopic degrees of freedom and $\mathcal{M}_1$. And then, even supposing that one *had* precise knowledge of the (evolving) states $|e_\pm\rangle$, one would have to be able to perform an *exceedingly* complicated measurement on $\mathcal{M}_1$ and its environment, sensitive to minute differences in the states of a vast number of microscopic systems. It is safe to say that performing the required measurement is impossible. Decoherence thus guarantees that interference between branches is impossible to detect.

In fact, this is not quite satisfactory as a statement of the role of decoherence. For saying that environmental decoherence ensures that no detectable interference between branches will occur, presupposes that the environment naturally couples to precisely that preferred basis that specifies how the global state is to be decomposed into branches. The above example does indeed model environmental decoherence by simply assuming that the state of the environment is is coupled to the definite memory states of the observer. A critic of the Everett interpretation could thus object that appealing to decoherence to explain the lack of interference between branches simply adds to the preferred basis problem a new embarrassing question for the interpretation: Why should the state of the environment be correlated with precisely the preferred states of the observer? The natural response for the Everettian is to reverse the order of these questions, and to let the facts about the environmental interaction determine which states are preferred. The environment is as it were continually monitoring or measuring an observer's state, and those particular states of the observer the environment is coupled to are preferred from the point of view of the Everett interpretation, *precisely in the sense that interference between these states is negligible.*

In fact environmental decoherence would seem to provide a way of specifying a preferred basis that avoids any reference to observers and definite memory states at all. For every object subject to decoherence by its environment, some set of states is thereby picked out. And the global quantum state can then be decomposed into branches that are tensor products of these preferred states for every object. Interference between such branches will be effectively nil, so that each branch effectively evolves independently of the others.

2.6 CONCLUSION

Decoherence, in the sense of the absence of interference between branches, is required to explain why observers in an Everettian universe cannot detect the presence of other branches in the universal quantum state. The phenomenon of environmental decoherence provides an explanation for this absence of interference, and also explains why interference between branches cannot be observed even by means of carefully contrived experiments: The speed and effectiveness with which the process of environmental decoherence converts a superposition of observer states into a superposition of states of the observer-plus-environment composite system guarantees that the required measurements would be impossible to carry out.

But decoherence, again in the sense of absence of interference, is actually a much more fundamental notion for the interpretation, since the picture Everett paints of the quantum universe as a collection of continually splitting branches implies the absence of interference between these branches. The absence of interference in fact provides a way of giving content to the notion of branches, and a way of picking out branches—or at least of determining whether a decomposition of the global state *qualifies* as a decomposition into branches. Environmental decoherence, which continually acts to prevent interference between macroscopically distinguishable states of objects, provides a way for Everettians to give an answer to the preferred basis problem: Why should the interpretation privilege a decomposition of the global quantum state into a branches in which familiar macroscopic properties are definite? The Everettian can say that the interpretation privileges decompositions of the global state into branches, i.e. effectively non-interfering states; and environmental decoherence can explain why the requisite non-interfering states should be states in which the familiar macroscopic quantities—but not superpositions of them—are definite.

2.7 APPENDIX: DERIVATION OF TRANSITION PROBABILITIES

This appendix presents the derivation of Born-rule transition probabilities from Everettian probabilities for branches for Everett-type (i.e. memory preserving) measurement schemes. To represent a general Everett-type measurement scheme, let $\mathcal{S}$ be the collection of object systems and $\mathcal{M}$ be the collection of memory systems of the observer or apparatus. The total state of the composite system $S + M$ is represented by a state on $\mathcal{H} = \mathcal{H}_{\mathcal{S}} \oplus \mathcal{H}_{\mathcal{M}}$. At each time, the total state of $S + M$ is expanded in terms of definite memory states $|m_0\rangle$, $|m_i\rangle$, $|m_{ij}\rangle$, etc., of $\mathcal{M}$ and the corresponding relative states of $\mathcal{S}$. (The entire collection of definite memory states is assumed to be pairwise orthogonal; the relative states are in general not pairwise orthogonal.) The initial state of $S + M$ is assumed to be a product state,

$$|\Psi(t_0)\rangle = |s_0\rangle\, |m_0\rangle\, .$$

After the first measurement, the total state is a superposition

$$|\Psi(t_1)\rangle = \sum_i \alpha_i\, |s_i\rangle\, |m_i\rangle\, ,$$

where $\alpha_i = \langle s_i | s_0 \rangle$. After the second measurement the state is

$$|\Psi(t_2)\rangle = \sum_{i,j} \alpha_i \beta_{ij}\, |s_{ij}\rangle\, |m_{ij}\rangle\, ,$$

where $\beta_{ij} = \langle s_{ij}|s_i\rangle$. And in general after r measurements the total state is

$$|\Psi(t_r)\rangle = \sum_{i,j,\ldots,k,l} \alpha_i \beta_{ij} \cdots \gamma_{ij\cdots k} \delta_{ij\cdots kl} \, |s_{ij\cdots kl}\rangle \, |m_{ij\cdots kl}\rangle \, ,$$

where there are r indices $i, j, \ldots, k, l$ and r coefficients $\alpha_i, \beta_{ij}, \ldots, \gamma_{ij\cdots k}$, $\delta_{ij\cdots kl}$, with $\delta_{ij\cdots kl} = \langle s_{ij\cdots kl}|s_{ij\cdots k}\rangle$.

The probability assigned to a given branch is its amplitude squared; for the branch indexed by $(i, j, \ldots, k, l)$ this is

$$\Pr(|s_{ij\cdots kl}\rangle \, |m_{ij\cdots kl}\rangle) = |\alpha_i|^2 \, |\beta_{ij}|^2 \cdots |\gamma_{ij\cdots k}|^2 \, |\delta_{ij\cdots kl}|^2$$

Because of the one-to-one correspondence between branches and histories, we can without ambiguity define the probability of the sequence of measurement outcomes picked out by this sequence $(i, j, \ldots, k, l)$ by assigning it the same probability as this branch. That is, the branch probability is also stipulated to be the joint probability of this set of measurement outcomes:

$$\Pr(i, j, \ldots, k, l) = |\alpha_i|^2 \, |\beta_{ij}|^2 \cdots |\gamma_{ij\cdots k}|^2 \, |\delta_{ij\cdots kl}|^2$$

We are now in a position to determine the probability of a particular outcome for a given measurement conditional on a particular sequence of outcomes for all the previous measurements:

$$\begin{aligned} \Pr(i) &= |\alpha_i|^2 \\ &= |\langle s_i|s_0\rangle|^2 \\ \\ \Pr(j|i) &= \frac{\Pr(i,j)}{\Pr(i)} \\ &= \frac{|\alpha_i|^2 \, |\beta_{ij}|^2}{|\alpha_i|^2} \\ &= |\beta_{ij}|^2 \\ &= |\langle s_{ij}|s_i\rangle|^2 \\ \\ &\vdots \end{aligned}$$

$$
\begin{aligned}
\Pr(l|i, j, \ldots, k) &= \frac{\Pr(i, j, \ldots, k, l)}{\Pr(i, j, \ldots, k)} \\
&= \frac{|\alpha_i|^2 \, |\beta_{ij}|^2 \cdots |\gamma_{ij\cdots k}|^2 \, |\delta_{ij\cdots kl}|^2}{|\alpha_i|^2 \, |\beta_{ij}|^2 \cdots |\gamma_{ij\cdots k}|^2} \\
&= |\delta_{ij\cdots kl}|^2 \\
&= |\langle s_{ij\cdots kl} | s_{ij\cdots k} \rangle|^2
\end{aligned}
$$

These conditional probabilities are effectively transition probabilities giving the probability for an observer within a particular branch to find herself within a particular daughter branch as a result of the next measurement.

3.0 THE MODAL INTERPRETATION AND DECOHERENCE

Environmental decoherence drives the reduced density matrix of a decohering system to a mixture approximately diagonal in the basis of eigenstates of some preferred observable. If the system is a measuring apparatus and the preferred observable is the pointer observable, then decoherence leads to a reduced state of the apparatus that is an (improper) mixture diagonalized by the states of definite pointer readings. It seems that this result could be parlayed into a solution to the measurement problem, given an interpretation of the physical import of the quantum state that allows us to interpret an improper mixture of this form as we would a proper mixture—i.e., as a classical probability distribution over a range of possible physical states, each with a definite value for the preferred observable. The modal interpretation would seem to be an interpretation of just this kind. Hence it seems natural to look to the modal interpretation to make sense of the results of decoherence.

This chapter examines some of the already well-known successes and failures of the alliance between the modal interpretation and decoherence. I argue that the main lesson to be extracted from this examination is that the alliance was from the start misguided. All along, it was decoherence, in an underappreciated dynamical role, that was doing the real interpretive work.

3.1 THE MODAL INTERPRETATION

The modal interpretation of quantum mechanics refers to a family of interpretations sharing one central feature, namely the claim that the quantum state of a system determines only a collection of properties which are *possibly* possessed by the system. This is a clear departure from the orthodox interpretation of the quantum state—the eigenvalue-eigenstate link—which states that the definite properties of a system are uniquely determined by the quantum state. Modal interpretations associate a collection of possible properties with the quantum state, but a system in a given quantum state will actually possess only some subset of these possible properties. The quantum state does not determine which possible properties are actually possessed; there is only a probabilistic relation between quantum state and possessed properties. To put it in terms of observables rather than properties, the quantum state of a system determines a set of observables which have definite values on that system. In general it does not determine the actual values of these observables, but only determines a probability distribution over the various possible values of each observable.

The version of the modal interpretation I shall consider here is a generalization of the closely related proposals of Kochen (1985) and Dieks (1989), along the lines of Vermaas & Dieks (1995) and Bacciagaluppi & Hemmo (1996). It makes use of the fact that every density operator ρ on a Hilbert space $\mathcal{H}$ has a unique spectral resolution

$$\rho = \sum_i w_i \mathbb{P}_i \tag{3.1}$$

where the the coefficients w_i are the distinct, strictly positive eigenvalues of ρ. The corresponding projectors $\mathbb{P}_i$ are pairwise orthogonal, and if we augment the set $\{\mathbb{P}_i\}$ with the projector $\mathbb{P}_0$ onto the 0-eigenspace of ρ (if it exists), then the resulting set $\{\mathbb{P}_0, \mathbb{P}_1, \mathbb{P}_2, \dots\}$ gives a decomposition of $\mathcal{H}$ into orthogonal (but not necessarily one-dimensional) eigenspaces of ρ.

The set of definite properties of a system α with reduced state ρ is determined by the projections $\mathbb{P}_i$ in the spectral resolution of ρ, according to the following rule (Property Ascription Rule for 1 System):

PAR1 Let α be a system with density operator ρ. The set of possible properties of α is generated by the spectral projections $\mathbb{P}_i$ of ρ. The probability that α possesses the possible property $\mathbb{P}_a$ is given by

$$\Pr(\mathbb{P}_a) = \mathrm{Tr}(\rho \mathbb{P}_a) \tag{3.2}$$

The set of possible properties is *generated* by the spectral projections $\mathbb{P}_i$ in the sense that this set is closed under the quantum-logical operations of negation ($\neg\mathbb{P} = \mathbb{I} - \mathbb{P}$), intersection ($\mathbb{P} \vee \mathbb{P}' = \mathbb{P}\mathbb{P}'$), and conjunction ($\mathbb{P} \wedge \mathbb{P}' = \mathbb{P} + \mathbb{P}' - \mathbb{P}\mathbb{P}'$), where the latter two operations are defined for pairs of compatible projections ($\mathbb{P}\mathbb{P}' = \mathbb{P}'\mathbb{P}$). This rule implies in particular that precisely one of the projections $\mathbb{P}_i$ in the spectral resolution (3.1) of ρ is possessed, with probability w_i.

Joint probabilities for properties of subsystems of a composite system simultaneously having certain values are given by a second rule (Property Ascription Rule for an N-Subsystem Compound):

PARN Let ω be a compound system $\omega = \alpha\&\beta\&\cdots\&\kappa$ with density operator ρ^ω. The possible properties of each subsystem are determined by the reduced state of the subsystem according to PAR1. The joint probability that the (disjoint) subsystems of ω simultaneously possess the possible properties $\mathbb{P}^\alpha_a, \mathbb{P}^\beta_b, \ldots, \mathbb{P}^\kappa_k$ is given by[1]

$$\Pr(\mathbb{P}^\alpha_a, \mathbb{P}^\beta_b, \ldots, \mathbb{P}^\kappa_k) \;=\; \mathrm{Tr}(\rho^\omega[\mathbb{P}^\alpha_a \otimes \mathbb{P}^\beta_b \otimes \cdots \otimes \mathbb{P}^\kappa_k]) \tag{3.3}$$

The modal interpretation is sufficient, by itself, for solving the measurement problem for ideal measurements. Consider an ideal measurement on object system $\mathcal{S}$, with associated Hilbert space $\mathcal{H}_\mathcal{S}$, by apparatus system $\mathcal{A}$, with Hilbert space $\mathcal{H}_\mathcal{A}$. Let $\{|o_i\rangle\}$ be the eigenstates of measured observable O, $\{|p_i\rangle\}$ the eigenstates of pointer observable P, and $|p_0\rangle$ the "ready" state of $\mathcal{A}$. If the initial state of $\mathcal{S}$ is a superposition of O eigenstates, then the evolution of the composite state of $\mathcal{S} + \mathcal{A}$ is given by

$$\sum_i c_i\,|o_i\rangle\,|p_0\rangle \to \sum_i c_i\,|o_i\rangle\,|p_i\rangle = |\Psi_f\rangle \tag{3.4}$$

The post-measurement entangled state $|\Psi_f\rangle$ is one in which, according to the eigenvalue-eigenstate link, neither the pointer observable P nor the measured observable O has a definite value. The modal interpretation, on the other, hand, says that both these observables do

[1]One consequence of these property ascription rules is worth mentioning: because this version of the modal interpretation does not privilege any decomposition of a compound system over another, property composition and decomposition fail. There are states ρ of a compound system $\mathcal{X} + \mathcal{Y}$ such that an observable O is definite on $\mathcal{X}$ (as determined by the reduced state $\rho_\mathcal{X}$) but the observable $O \otimes I$ is not definite on $\mathcal{X} + \mathcal{Y}$ (as determined by ρ). Likewise there are states ρ of $\mathcal{X} + \mathcal{Y}$ such that $O \otimes I$ is definite on $\mathcal{X} + \mathcal{Y}$ but O is not definite on $\mathcal{X}$. See Clifton (1996: sec. 2.3) for details.

have definite values in the state $|\Psi_f\rangle$, provided that the set $\{|c_i|^2 : c_i \neq 0\}$ is non-degenerate.[2] The reduced density operators of the measured system $\mathcal{S}$ and the measuring apparatus $\mathcal{A}$ are

$$\begin{aligned} \rho^{\mathcal{S}} &= \sum_i |c_i|^2 \, \mathbb{P}_{|o_i\rangle} \\ \rho^{\mathcal{A}} &= \sum_i |c_i|^2 \, \mathbb{P}_{|p_i\rangle}, \end{aligned} \tag{3.5}$$

where $c_i \neq 0$ and $\sum_i |c_i|^2 = 1$. Then assuming nondegeneracy, equation (3.5) gives the unique spectral resolutions of $\rho^{\mathcal{S}}$ and $\rho^{\mathcal{A}}$. PAR1 entails that precisely one of the eigenprojections $\mathbb{P}_{|p_i\rangle}$ of P is a possessed property of the apparatus, with probability $|c_i|^2$, so the pointer observable P has a definite value. Similarly, one of the eigenprojections $\mathbb{P}_{|o_i\rangle}$ of O is a possessed property of the object system, with property $|c_i|^2$, so O has a definite value. And PAR2 gives the joint probabilities

$$\Pr(\mathbb{P}_{|o_i\rangle}, \mathbb{P}_{|p_i\rangle}) \;=\; \mathrm{Tr}(\rho[\mathbb{P}_{|o_i\rangle} \otimes \mathbb{P}_{|p_j\rangle}]) \;=\; |c_i|^2 \delta_{ij}$$

where the density operator of the $\mathcal{S} + \mathcal{A}$ compound is $\rho = \mathbb{P}_{|\Psi_f\rangle}$. Therefore the modal interpretation predicts perfect correlation between the possessed values of $\mathcal{A}$ and $\mathcal{S}$.

Clearly, the modal interpretation solves the measurement problem for ideal measurements. For the property ascription rules of the modal interpretation entail that a measurement of this type will have a definite outcome: the pointer observable P will have a definite value when the $\mathcal{S} + \mathcal{A}$ compound is in the unitarily-evolved post-measurement state $|\Psi_f\rangle$ (equation (3.4)). Moreover, the modal interpretation says that the probability that this definite value will be the eigenvalue p_i, indicating that the measured observable O has been found to have the value o_i on system $\mathcal{S}$, is the desired (Born rule) probability, $|c_i|^2$.

[2]When the set $\{|c_i|^2 : c_i \neq 0\}$ is degenerate, no maximal observable will be be among the definite observables. In this case, if the pointer observable is a maximal observable, then the modal interpretation does not guarantee that the pointer observable will have a definite value. This is a problem that needs to be addressed by proponents of the modal interpretation, but I will consider only non-degenerate cases in this chapter.

3.2 THE PROBLEM OF NON-IDEAL MEASUREMENTS

3.2.1 The Problem

The measurement problem arises because measurement interactions governed by the unitary dynamics lead to entangled object system-apparatus states that do not correspond to definite pointer values by the lights of the eigenvalue-eigenstate rule. The modal interpretation drops this rule and replaces it with its own rule (PAR1) for property ascription, which picks out as definite observables whose eigenvectors diagonalize the reduced states of a system. This rule succeeds in ascribing definite pointer readings to an apparatus at the end of an ideal measurement interaction. However, this rule does not have the same success when more general models of measurement interactions are considered. For these more general models, this rule typically says that pointer observable is *not* among the definite observables of the apparatus at the conclusion of the measurement.

The general form of the evolution in a measurement interaction between object system $\mathcal{S}$ and apparatus $\mathcal{A}$ (where both measured and pointer observables have discrete spectra) is

$$\sum_i c_i \left|o_i\right\rangle \left|p_0\right\rangle \longrightarrow \sum_{i,j} d_{ij} \left|o_i\right\rangle \left|p_j\right\rangle = \left|\Psi\right\rangle . \tag{3.6}$$

(As before the states $|o_i\rangle$ of $\mathcal{S}$ are the eigenstates of the measured observable O, the states $|p_j\rangle$ of $\mathcal{A}$ the eigenstates of the pointer observable P, and $|p_0\rangle$ the "ready" state of $\mathcal{A}$.) An ideal measurement is a special case, for which the off-diagonal coefficients d_{ij} vanish and the diagonal coefficients are equal to the coefficients associated with the eigenstates of the measured observable in the initial state of the measured system, $d_{ii} = c_i$. These conditions ensure that the post-measurement state is in biorthogonal form when expressed in terms of eigenstates of O and P. Hence the reduced state of the apparatus in particular is diagonalized by the eigenstates of the pointer observable P, ensuring that the modal interpretation ascribes a definite pointer reading to the apparatus.

But for a non-ideal measurement—when $d_{ij} \neq 0$ for some $i \neq j$—the reduced state of $\mathcal{A}$ that results will not generally be diagonal in the pointer basis. The biorthogonal decomposition of the post measurement state will pick out some other states $|\hat{o}_i\rangle$ and $|\hat{p}_i\rangle$ of $\mathcal{S}$ and $\mathcal{A}$,

$$|\Psi\rangle = \sum_i \lambda_i |\hat{o}_i\rangle |\hat{p}_i\rangle , \tag{3.7}$$

and the reduced state of $\mathcal{A}$ will have spectral decomposition

$$\rho^{\mathcal{A}} = \sum_i |\lambda|^2 |\hat{p}_i\rangle \langle \hat{p}_i| \tag{3.8}$$

Thus according to the modal interpretation, some apparatus observable $\hat{P}$, with eigenstates $|\hat{p}_i\rangle$, will have a definite value after measurement. In general this definite observable will be *incompatible* with the pointer observable P, and P itself will *not* have a definite value.

The question then is: do real measurement interactions lead to apparatus states for which the modal interpretation dictates that neither the pointer observable nor a nearby observable is definite? Albert & Loewer (1990; 1993), Elby (1993), Dickson (1994), and Ruetsche (1995) all argue *yes*. Both practical and theoretical limitations on real-life measurement interactions motivate the conclusion that real-life measurements do include measurements that are problematic for the modal interpretation.

3.2.2 Resolution by Appeal to Decoherence

Thus a problem of empirical adequacy looms for the modal interpretation; objectors argue that treating measurements realistically requires models of measurement for which the modal interpretation predicts that pointers will not point. The standard maneuver to defend the modal interpretation against this problem is to invoke environmental decoherence. Taking seriously the insistence that measurements be modeled realistically, modal advocates point out that realistic measurement apparatuses are constantly interacting with their environments. They then show that when this environmental interaction is incorporated into models of measurement, even non-ideal measurement interactions eventuate in a post-measurement reduced state of the apparatus of the right form. Essentially, simple models show that environmental decoherence drives $\rho^{\mathcal{A}}$ toward diagonality in the pointer basis very rapidly, even for general measurement interactions.

Here I consider a general measurement interaction (3.6) with the addition of an environment that monitors the pointer observable of the apparatus, following Bacciagaluppi & Hemmo (1996). Consider first the evolution induced by the interaction of $\mathcal{S} + \mathcal{A}$ alone (ignoring for the moment any interaction with the environment). This has the general form:

$$\sum_i c_i |o_i\rangle |p_0\rangle \longrightarrow \sum_{i,j} d_{ij} |o_i\rangle |p_j\rangle \tag{3.9}$$

This evolution can be rewritten as

$$\sum_i c_i |o_i\rangle |p_0\rangle \longrightarrow \sum_j \mu_j |o_j^*\rangle |p_j\rangle \tag{3.10}$$

where the states $|o_j^*\rangle$ are the (not necessarily orthogonal) states of $\mathcal{S}$ relative to the states $|p_j\rangle$ of $\mathcal{A}$.[3] Suppose now that the pointer observable P is the decohering variable, so that the interaction Hamiltonian $H_{\mathcal{A}\mathcal{E}}$ correlates the state of the environment to the pointer eigenstates $|p_i\rangle$ without disturbing them. That is, suppose that the $\mathcal{A}$-$\mathcal{E}$ interaction alone (now neglecting for the moment the $\mathcal{S}$-$\mathcal{A}$ interaction) is given by

$$|p_j\rangle |e_0\rangle \longrightarrow |p_j\rangle |e_j(t)\rangle \tag{3.11}$$

Then provided that the time scale of the measurement interaction is long with respect to the time scale of decoherence, so that the speed of the evolution given by equation (3.11) is much faster than that given by equation (3.10), then the compound system $\mathcal{S} + \mathcal{A} + \mathcal{E}$ will

[3] These states are defined by

$$\mu_j := \sqrt{\sum_i |d_{ij}|^2} \qquad \text{and} \qquad |o_j^*\rangle := \sum_i \frac{d_{ij}}{\mu_j} |o_i\rangle ,$$

evolve thus[4] (Bacciagaluppi & Hemmo 1996: 258):

$$\sum_i c_i |o_i\rangle |p_0\rangle |e_0\rangle \longrightarrow \sum_j \mu_j |o_j^*\rangle |p_j\rangle |e_j(t)\rangle \,. \tag{3.13}$$

The observables that have definite values for the apparatus $\mathcal{A}$ at time t are determined by the reduced state $\rho^{\mathcal{A}}(t)$, obtained by taking the density operator corresponding to the r.h.s. of (3.13) and taking the partial trace over the systems $\mathcal{S}$ and $\mathcal{E}$. Expressed in the pointer basis $\{|p_i\rangle\}$, the reduced state is (Bacciagaluppi & Hemmo 1996: 260)

$$\rho^{\mathcal{A}}(t) = \begin{pmatrix} |\mu_1(t)|^2 & \cdots & \bar{\mu}_j(t)\mu_i t \langle o_j^*|o_i^*\rangle \langle e_j(t)|e_i(t)\rangle & \cdots \\ & & \ddots & \\ & & & |\mu_n(t)|^2 \end{pmatrix}. \tag{3.14}$$

The environment states rapidly become orthogonal, with $\langle e_j(t)|e_i(t)\rangle \approx 0$ for $t \gg \tau_D$. This implies that the off-diagonal elements of $\mathcal{A}$'s reduced state will approach 0 very quickly, since these contain a factor $\langle e_j(t)|e_i(t)\rangle$. Note that this is true regardless of the size of the inner product $\langle o_j^*|o_i^*\rangle$, i.e., even if these relative states of the measured system are far from orthogonal. So a very short time after the measurement interaction, $\rho^{\mathcal{A}}(t)$ is very nearly diagonal in the pointer basis.

Since $\rho^{\mathcal{A}}(t)$ is not *exactly* diagonal in the pointer basis, the modal interpretation says that the pointer observable P is not a definite observable; P will not, in general, have a definite value. But provided that the Hilbert space $\mathcal{H}_{\mathcal{A}}$ is finite dimensional, and that the eigenvalues of $\rho^{\mathcal{A}}(t)$ are not too close to degeneracy, the *approximate* diagonality of $\rho^{\mathcal{A}}(t)$ in the eigenbasis $\{|p_i\rangle\}$ of P is enough to guarantee that there is a *nearby* observable $\hat{P}_t$ which *is* definite (Ruetsche 1998: 228). To make this precise: let the eigenvectors of $\rho^{\mathcal{A}}(t)$

[4]The evolution of a $\mathcal{S}+\mathcal{A}+\mathcal{E}$ composite like this is sometimes presented as though it were a two-stage process, where first the $\mathcal{S}$-$\mathcal{A}$ interaction (3.10) occurs, followed by the $\mathcal{A}$-$\mathcal{E}$ interaction (3.11):

$$\begin{aligned} \sum_i c_i |o_i\rangle |p_0\rangle |e_0\rangle &\xrightarrow{(1)} \sum_j \mu_j |o_j^*\rangle |p_j\rangle |e_0\rangle \\ &\xrightarrow{(2)} \sum_j \mu_j |o_j^*\rangle |p_j\rangle |e_j(t)\rangle \,. \end{aligned} \tag{3.12}$$

See for example Schlosshauer (2004: 1275). Clearly, though, the environment $\mathcal{E}$ interacts with the apparatus $\mathcal{A}$, even as $\mathcal{A}$ interacts with the measured system $\mathcal{S}$. And given how fast decoherence effects occur, the $\mathcal{A}$-$\mathcal{E}$ interaction will have a non-negligible effect on $\mathcal{E}$ during the course of the $\mathcal{S}$-$\mathcal{A}$ interaction.

be denoted by $|\hat{p}_i^t\rangle$; provided that the eigenvalues of $\rho^{\mathcal{A}}(t)$ are not degenerate, we have (by reordering if necessary) $\langle \hat{p}_i^t | p_j \rangle \to \delta_{ij}$ as $t \to \infty$. Bacciagaluppi & Hemmo (1994) show that the rate at which this inner product converges is closely related to the (extremely fast) rate of convergence for the inner product $\langle e_i(t)|e_j(t)\rangle$ of the environment states. They show that the closer the eigenvalues of $\rho^{\mathcal{A}}(t)$ are to degeneracy, the slower the convergence of $\langle \hat{p}_i^t | p_j \rangle$, but they also show that only in the case of extreme near-degeneracy would the delay be significant in practice. (See Bacciagaluppi & Hemmo (1994) for a numerical measure of near-degeneracy and details about the rate of convergence.) Thus, except in cases of extreme near-degeneracy, we have $\langle \hat{p}_i^t | p_j \rangle \approx \delta_{ij}$ for timescales relevant to measurement. If we define $\hat{P}_t = \sum_i p_i \mathbb{P}_{|\hat{p}_i^t\rangle}$ (where the coefficients p_i are the eigenvalues of $P = \sum_i p_i \mathbb{P}_{|p_i\rangle}$), then $\hat{P}_t$ is a definite observable for the state $\rho^{\mathcal{A}}(t)$, and $\hat{P}_t$ is close to P in the sense that their eigenstates are close in Hilbert space norm and they have the same eigenvalues.

To reiterate, the designated pointer observable P is not a definite observable of the apparatus after the measurement, but an observable $\hat{P}_t$ which is very close to P in the sense just explained *is* definite. This gives a solution to the measurement problem, *provided* that we relax the requirement that the observable P itself have a definite value after measurement and require instead only that an observable *close to P* be definite. Many authors (e.g. Bacciagaluppi & Hemmo (1996), Butterfield (2001)) argue that it is appropriate to relax the requirement of a definite value for the pointer observable in just this way, on account of the vagueness of the property of the apparatus that we need to account for (its indicating a particular measurement result) and the impossibility of distinguishing eigenstates of distinct but close observables by means of measurements. (See Ruetsche (1998) for a critical discussion of relaxing the requirement and of the reasons usually given for doing it.)

If we accept the definiteness of some observable close to the pointer observable as sufficient for the apparatus to qualify as indicating a particular outcome, then the combination of decoherence and the modal interpretation ensures that measurements have outcomes (bracketing only the cases of exact degeneracy and very near degeneracy of the reduced state of the apparatus). For decoherence very rapidly drives the reduced state of the apparatus toward diagonality in the pointer basis, and the modal interpretation then implies that some observable very close to the pointer observable is definite.

One further requirement is to account for the stability of measurement outcomes. Decoherence ensures that the set of definite properties of the measuring apparatus is stably close to the set of designated pointer states $\{|p_i\rangle\}$; thus after a measurement interaction the apparatus effectively has a definite pointer reading $|p_i\rangle$ at each moment, and PAR1 gives the probabilities $|c_i|^2$ for the various possible readings. But as formulated so far, the modal interpretation is silent about correlations between properties a system possesses at different times. It is consistent with the synchronic probabilities dictated by PAR1 and PARN for pointer readings to jump erratically among the $|p_i\rangle$. Modal theorists typically assume that pointer readings do not vary erratically; measurement outcomes are stable. The precise form that this assumption takes, and the reasons given for it, vary: Vermaas (1996; 1999) explicitly assumes stability of measurement outcomes, on the grounds that this assumption is required for empirical adequacy. Healey (1989) simply states a stability condition for systems whose evolving states and possessed properties are characterized by a particular formal condition satisfied for measuring apparatuses; Healey (1995) gives a modified stability condition formulated to apply to measuring apparatuses under environmental decoherence. Bacciagaluppi & Hemmo (1998) assume stability of measurement outcomes in the context of environmental decoherence. Hemmo (1996) gives a stability postulate explicitly formulated in terms of environmental decoherence: if the set of possessed properties of a system are stably close to a fixed decohering variable, then transitions from one possessed property to another are extremely unlikely.[5]

To sum up: decoherence secures definite outcomes for even imperfect measurements in the sense that, barring extreme near-degeneracy of its reduced state, a measuring apparatus will have after a measurement interaction a definite property that is *extremely* close to a definite pointer reading. Under the stability assumption, which can also be motivated by decoherence, the possessed property of the apparatus will furthermore be stably close to a single definite pointer reading. By appealing to decoherence, advocates of the modal interpretation can explain the definiteness and stability of pointer readings. But note that the stability assumption takes us beyond the basic rules of the modal interpretation.

[5] For Hemmo, the stability postulate is a particular case of a more general constraint on how possessed properties vary over time: he proposes "that in cases of decoherence the multi-time probabilities should approximate the probabilities prescribed in the consistent histories formulation" (1996: 24).

3.2.3 Failure: Continuous Models

Bacciagaluppi & Hemmo (1996) and Bacciagaluppi (2000) report that for continuous models of decoherence, however, the modal interpretation seems unable to account for definite measurement outcomes. In this context the preferred states selected by the interaction with the environment are highly localized. On the other hand, "the properties determined by the [property ascription rule PAR1] correspond to wavefunctions that are delocalized over the whole spread of the state" (Bacciagaluppi 2000: 1433). So in models of this kind, the definite properties picked out by the modal interpretation do *not* correspond to the preferred states picked out by decoherence (as they *do* for the finite-dimensional case). And since the definite properties given by the modal interpretation are highly delocalized, there seems to be a marked failure of empirical adequacy; for the modal interpretation apparently predicts highly nonclassical properties for systems whose decohering variables are continuous.

The problem is that in high-dimensional cases, extreme near-degeneracy of the reduced state of the decohering system is typical. This near-degeneracy means states with respect to which the reduced state is nearly diagonal may be quite far from states with respect to which it is exactly diagonal. Thus, although the reduced state of the system is approximately diagonal with respect to position, the eigenstates of the reduced state are not well-localized.

> The upshot of this analysis of the modal interpretation is very startling.... In the present case, a pointer that is initially spread out over a macroscopic distance will be insensitive to the intervening process of decoherence and will remain spread out.
>
> Thus, contrary to initial expectations, the modal interpretation and decoherence theory do not always go hand in hand: there are models of decoherence theory in which application of the Basic Rule of the modal interpretation does not reproduce the results that are suggested by decoherence.... Given the widespread application of continuous models of decoherence, and in particular their use in arguments for the emergence of classical properties and behavior, this result... constitutes a most convincing argument against the physical adequacy of the definite properties as given by the Basic Rule [PAR1] of the modal interpretation. (Bacciagaluppi 2000: 1442)

Note that the failure of the modal interpretation here has nothing to do with measurement; even an apparatus that begins in a pure state and does not interact with a measured system "will not maintain a property corresponding to a localised state" (Bacciagaluppi & Hemmo 1996: 264).

3.3 THE PROBLEM OF PREPARATION

The measurement problem has a less notorious cousin in the problem of preparation. The preparation problem arises because state preparation, like measurement, is effected by an interaction between an object system and a preparing device, an interaction that—given the unitary quantum dynamics—typically eventuates in an entangled state of object + preparing device. Thus far, the preparation problem parallels the measurement problem. But the reason an entangled state is problematic is different in the context of preparation than in the context of measurement. The point of a preparation procedure is that it allows the assignment of a definite known pure state to the prepared system, but such an assignment is incompatible with the entangled state of object + preparing device actually produced.[6] Thus the supposition that preparations unfold unitarily by itself raises an obstacle to supposing that preparations eventuate in the desired prepared state. The measurement problem, by contrast, hinges on an additional interpretive principle:

> The preparation problem is not merely the measurement problem rephrased. The measurement problem rests on two assumptions: assuming that unitary dynamics governs measurement situations and that the eigenvector/eigenvalue link governs the determinate values a system possesses, we encounter post-measurement superpositions of pointer eigenstates we can't interpret as measurement outcomes. The preparation problem rests on just one assumption. If preparation interactions unfold unitarily, entangling the states of object system and preparing device, our attribution of pure states to prepared systems is illegitimate. (Ruetsche 2003: 33)

Textbook treatments of measurement appeal to measurement collapse to account for the definiteness of apparatus pointer observables after measurement interactions. Collapse is often assumed, implicitly or explicitly, to operate in preparation contexts as well, leaving the prepared system in the designated prepared state. Indeed, preparations are sometimes said to be effected by measurements, so that both problems can be dealt with by the assumption of measurement collapse. The modal interpretation, insisting on the universality of unitary

[6] What is essential to a preparation procedure is that it allows the attribution of a definite known state to the prepared system. It is not essential that this state be a pure state. But for some preparation preparation procedures, like the paradigmatic preparation of a spin-$\frac{1}{2}$ particle in a definite spin state by passing it through a Stern-Gerlach magnet, the definite state that putatively results from preparation is a pure state. It is useful to focus on the case when the prepared state is a pure state since in this case the incompatibility between the unitarily evolved entangled state and the state assigned to the object system on the basis of preparation is evident.

evolution of the global quantum state, rejects the collapse approach and handles the measurement problem by abandoning the eigenvalue-eigenstate link. But this maneuver leaves the preparation problem untouched. The modal interpretation is still faced with the task of making sense of the ascription of a pure state to a prepared system, given its assumption that preparations unfold unitarily.

3.3.1 A Standard Response

Ruetsche (2003) outlines a promising line of response to the problem of preparation given the assumption that collapse does not take place. This response admits that the prepared system is not actually prepared in the desired pure state, but maintains that all future measurement outcomes on the prepared system will nevertheless turn out *as if* it were accurately described by this state. That is, the prepared system does not literally end up in the desired pure state, but this pure state can nevertheless be assigned to it as an *effective* state. Probabilities for outcomes of future measurements on the prepared system obtained from this effective state via the Born rule will be identical to probabilities obtained from the uncollapsed entangled state, *conditional* upon the relevant preparation event. Healey (1989) and Wessels (1997) show that for certain examples and classes of preparations, the predictions obtained as described above from the effective state of the prepared system on the one hand and from the entangled state of prepared system + preparing device on the other do in fact agree.

To avail themselves of this standard response, modal theorists would need to assign conditional probabilities, specifically probabilities for measurement outcomes conditional on earlier preparation events. This would require, if not a full dynamics, then at least two-time transition probabilities for possessed properties. But as already noted, the property ascription rules of the modal interpretation dictate only synchronic probability assignments for possessed properties; they do not include an explicit rule for assigning two-time transition probabilities, nor do they uniquely determine such transition probabilities. The standard response to the problem of preparation would thus require modal theorists to incorporate transition probabilities into the modal interpretation. The question then is, how are such transition probabilities to be introduced? Ruetsche (2003) has explored, and has documented the difficulties facing, two natural approaches to introducing the necessary transition probabilities. The first would posit a dynamics for possessed properties, thereby making the modal interpretation into a full-blown hidden-variable theory.[7] This approach faces a problem of plurality: infinitely many possible dynamical schemes are empirically adequate.[8] The second, more minimalist, approach would simply augment the modal interpretation's existing rules for synchronic probabilities with a rule dictating two-time transition probabilities for possessed properties. However, Ruetsche argues that a particularly natural choice for such a rule—a standard rule for quantum conditionalization, which would in preparation contexts give conditional probabilities equivalent to the Born-rule probabilities obtained form the putatively prepared state—is incompatible with the modal interpretation, in the absence of the specification of a more basic dynamics.

In the face of these difficulties facing the project of finding a home for transition probabilities within the modal interpretation, perhaps it is best to try to respond to the preparation problem without them. A strategy that tries to make do with the resources already provided by the modal interpretation, without having to introduce a dynamics or transition probabilities for possessed properties, is what Ruetsche (2003) terms the *joint account of preparation*. This account is a variant of the standard response outlined above; it provides the necessary conditional probabilities not by positing a general rule dictating two-time transition probabilities, but instead by making use of joint probabilities assigned by the modal interpretation to values for simultaneously definite observables, *where the value of one of these observables can be interpreted as a record of the earlier event to be conditioned on.* This is the strategy

[7]Many authors, both advocates and critics of modal interpretations, have argued on independent grounds that the modal interpretation requires a dynamics for possessed properties. They contend that the modal interpretation is *incomplete* without such a dynamics. These authors take the modal interpretation to supplement the theoretical structure of quantum mechanics with additional variables, namely value states encoding possessed properties. According to the modal interpretation thus construed, the theoretical state of a system includes its quantum state and its value state. A dynamics for the theoretical state thus requires a dynamics for the value state. See Ruetsche (2003) for some discussion of this attitude toward the modal interpretation and an alternative view.

[8]One might hope that even if empirical adequacy allows a vast plurality of dynamics, principles of physicality or naturalness, not forced upon us by empirical adequacy, might serve to narrow the field. But Dickson (1998: 173) argues "that reasonable nonempirical principles will rarely, perhaps never entirely remove the plurality of dynamics [and] that there is no uniquely reasonable set of nonempirical principles that will guide that choice of a dynamics."

pursued by Healey (1989), Hemmo (1996), and Bacciagaluppi & Hemmo (1998) in their treatments of the preparation problem.

3.3.2 Preparation in the Modal Interpretation

I summarize here the treatment of Bacciagaluppi & Hemmo (1998). They consider a preparation effected by a non-ideal measurement interaction that entangles the prepared system with a measuring apparatus. The form of the entangled state that results from this interaction, assuming unitary evolution of the system-apparatus compound and neglecting for a moment further entanglement with the environment, is

$$\sum_{ij} \lambda_{ij} \left|\phi_i\right\rangle \left|\psi_j\right\rangle ,$$

where the states $|\phi_i\rangle$ and $|\psi_j\rangle$ form bases for the Hilbert spaces of the system and apparatus, respectively. By summing over the first index i we can rewrite this state as

$$\sum_{j} \mu_j \left|\phi_j^*\right\rangle \left|\psi_j\right\rangle , \tag{3.15}$$

where the states $|\phi_j^*\rangle$ are the (generally non-orthogonal) states of the system relative to the pointer states $|\psi_j\rangle$ of the apparatus.

Now consider how textbook collapse quantum mechanics and the modal interpretation will describe the result of this preparation. Collapse quantum mechanics dictates that a measuring apparatus will not persist in an entangled state like this, but instead the entangled system will collapse to one of the product states $|\phi_j^*\rangle |\psi_j\rangle$ corresponding to a definite pointer reading immediately upon conclusion of the measurement. As a result of this collapse, then, there is a definite preparation "outcome," that is a definite pointer reading $|\psi_j\rangle$, and the state of the prepared system is the corresponding relative state $|\phi_j^*\rangle$. On this account collapse actually prepares the system in a pure state (though of course only by invoking a collapse mysteriously induced by the measurement that effects the preparation).

The modal interpretation on the other hand maintains that the state of the system-apparatus compound is an entangled state. The simple model above makes it seem as though the apparatus will not have a definite pointer reading, as the reduced state of the apparatus obtained from the entangled state (3.15) is not approximately diagonal in the pointer states given the non-orthogonality of the relative system states; but this problem can be resolved, as we have seen, by appeal to decoherence: A more realistic model including an environment that monitors the pointer observable of the apparatus will guarantee that the reduced state of the apparatus is approximately diagonal with respect to the pointer states, so that an observable very close to pointer position will have a definite value. But notice that the addition of an environment coupled to the pointer states of the apparatus will not similarly affect the reduced state of the *prepared system*. With or without a decohering environment, the reduced state of the prepared system will be $\sum_j |\mu_j|^2 |\phi_j^*\rangle \langle\phi_j^*|$. This expression for the reduced state of the system does not represent it in diagonal form, as the $|\phi_j^*\rangle$ are not mutually orthogonal. The spectral decomposition of this reduced state will have the (diagonal) form $\sum_i |\hat{\mu}_i|^2 |\hat{\phi}_i\rangle \langle\hat{\phi}_i|$ for some set of mutually orthogonal states $|\hat{\phi}_i\rangle$ different, in general, from the relative states $|\phi_j^*\rangle$. According to the modal interpretation, therefore, the possessed property of the prepared system will be given by one of the states $|\hat{\phi}_i\rangle$—not one of the relative states $|\phi_j^*\rangle$ corresponding to the preparation outcome, as according to collapse quantum mechanics.

> One can now draw two conclusions: first that the properties assigned to the quantum system by the modal interpretation are generally *different* from the ones assigned by standard quantum mechanics; and second, that the subensembles selected in a selective measurement according to the measurement outcome will be *inhomogeneous* with respect to the properties assigned by the modal interpretation. (Bacciagaluppi & Hemmo 1998: 99–100)

The latter conclusion follows because the sets of coefficients $|\mu_j|^2$ and $|\hat{\mu}_i|^2$ are different; therefore, given an ensemble of identical systems subjected to the preparation interaction, the subsensembles picked out by different relative states $|\phi_j^*\rangle$ will generally be of *different sizes* than the subensembles picked out by different possessed property states $|\hat{\phi}_i\rangle$.

It is obvious from the start that the modal interpretation cannot ascribe different quantum states, simply on the basis of different preparation "outcomes," to systems subjected to identical preparation interactions. The modal interpretation implies that different preparation outcomes can occur for two prepared systems, even given the same post-measurement entangled state of prepared system + apparatus. What is more surprising, perhaps, is that the modal interpretation is also unable to assign uniformly different *possessed properties* to prepared systems on the basis of different preparation outcomes. Identical preparations on two systems that leave these systems with the same (entangled) quantum state but with different possessed properties might nevertheless produce the same pointer readings on the preparing device. Conversely, and even more surprisingly, identical preparations on two systems that result in different preparation outcomes might nevertheless leave these systems in the same (entangled) quantum state and with the same possessed properties. In short, there is no direct correspondence between a preparation outcome and the possessed properties of the prepared system. Since the standard response to the preparation problem aims to reproduce the Born-rule probabilities for measurement outcomes on a prepared systems by means of probabilities for measurement outcomes *conditional on preparation outcomes* this suggests that there could also fail to be any clear correspondence between the possessed properties of a prepared system and the results of any subsequent measurements performed on it.

To show how the modal interpretation *can* duplicate Born-rule probabilities for measurement outcomes on a system ostensibly prepared in a known pure state, Bacciagaluppi and Hemmo consider a preparation effected by a non-ideal measurement interaction, ending at time t_1, that entangles the prepared system $\mathcal{S}$ with apparatus $\mathcal{M}_1$. After the conclusion of the preparation, a measurement is performed on the prepared system $\mathcal{S}$ by means of an interaction with a measuring apparatus $\mathcal{M}_2$. The outcome registers of both $\mathcal{M}_1$ and $\mathcal{M}_2$ are monitored by environment $\mathcal{E}$. The total state of $\mathcal{S} + \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{E}$ at the end of the preparation interaction (time t_1) is

$$|\Psi_1\rangle = \sum_i \mu_i \, |\phi_i^*\rangle \, |\psi_i^1\rangle \, |\psi_0^2\rangle \, |E_{i0}\rangle \, ,$$

where the relative states $|\phi_i^*\rangle$ of $\mathcal{S}$ are in general not orthogonal. Then a measurement interaction takes place, a measurement by $\mathcal{M}_2$ of an observable on $\mathcal{S}$ with eigenstates $|\eta_j\rangle$. Bacciagaluppi and Hemmo consider for simplicity a perfect (but possibly disturbing) measurement, i.e. one that perfectly correlates the post-measurement pointer states of $\mathcal{M}_2$ with the pre-measurement eigenstates $|\eta_j\rangle$ of $\mathcal{S}$. The total state at the end of the measurement interaction (time t_2) is

$$|\Psi_2\rangle = \sum_{ij} \mu_i \, \langle \eta_j | \phi_i^* \rangle \, |\eta_j^*\rangle \, |\psi_i^1\rangle \, |\psi_j^2\rangle \, |E_{ij}\rangle \, .$$

Environmental decoherence, with the pointer observables of both measuring apparatuses as the decohering variables, is represented by the near-orthogonality of the states $|E_{ij}\rangle$ in both indices. As in the treatment of the measurement problem, environmental decoherence plays two roles here. First, it ensures that both the initial preparing measurement and the second measurement will have definite outcomes. After t_1 the reduced state of the preparing apparatus $\mathcal{M}_1$ will be very nearly diagonal with respect to the pointer basis, so that a possessed property $|\hat{\psi}_i^1\rangle$ that is very close to a pointer state $|\psi_i^1\rangle$ will be definite at each moment; similarly, after t_2 apparatus $\mathcal{M}_2$ will have a possessed property $|\hat{\psi}_k^2\rangle$ close to pointer state $|\psi_k^2\rangle$ at each moment. The second role for decoherence is to motivate the assumption of *stability* of these possessed properties. The distinct pointer states of each apparatus are now correlated with states of the environment that are effectively permanently pairwise orthogonal. This means that the distinct pointer states of the apparatus correspond to effectively non-interfering branches of the global quantum state. It is assumed on the basis of this non-interference that the possessed property of the apparatus will have a very low probability of making a transition from (the neighborhood of) one pointer state to (the neighborhood of) another. The assumption of the stability of the possessed property of the preparing apparatus in particular is needed to justify interpreting the preparation outcome indicated at t_2 as a faithful record of the preparation outcome that actually occurred at t_1.

What probability does the modal interpretation assign to measurement outcome $|\hat{\psi}_j^2\rangle$ at t_2, conditional on preparation outcome $|\hat{\psi}_i^1\rangle$ at t_1? The joint account of preparation gives the following answer, assuming stability of the preparation outcome $|\hat{\psi}_i^1\rangle$ (i.e., assuming that the possessed property $|\hat{\psi}_i^1\rangle$ at t_2 is a faithful record of the possessed property of the preparing apparatus at t_1):

$$\begin{aligned} \Pr\left(\hat{\psi}_j^2(t_2)/\hat{\psi}_i^1(t_1)\right) &\approx \Pr\left(\hat{\psi}_j^2(t_2)/\hat{\psi}_i^1(t_2)\right) \\ &= \frac{\Pr\left(\hat{\psi}_j^2(t_2)\,\&\,\hat{\psi}_i^1(t_2)\right)}{\Pr\left(\hat{\psi}_i^1(t_2)\right)} \end{aligned} \tag{3.16}$$

This is now a formula for which the rules of the modal interpretation for synchronic probabilities of possessed properties can be used. PARN gives

$$\Pr\left(\hat{\psi}_j^2(t_2)\,\&\,\hat{\psi}_i^1(t_2)\right) \approx |\mu_i|^2 \left|\langle\eta_j|\phi_i^*\rangle\right|^2,$$

and PAR1 gives

$$\Pr\left(\hat{\psi}_i^1(t_2)\right) \approx |\mu_i|^2 ;$$

both equalities are only approximate, since the possessed properties are very near to, but not exactly identical with, the apparatus pointer states. The conditional probability (3.16) is then

$$\Pr\left(\hat{\psi}_j^2(t_2)/\hat{\psi}_i^1(t_1)\right) \approx |\langle\eta_j|\phi_i^*\rangle|^2 . \tag{3.17}$$

This quantity is the probability dictated by the Born rule for the outcome of a measurement of an observable with eigenstates $|\eta_j\rangle$ on a system in state $|\phi_i^*\rangle$.

This result thus shows that the modal interpretation can duplicate the Born-rule probabilities for measurement outcomes on prepared systems, given decoherence. It shows, in other words, that the modal interpretation can provide a version of the standard response to the preparation problem outlined above: although a preparation does not literally leave the prepared system in the pure state that laboratory practice ascribes to it, the relative state $|\phi_i^*\rangle$, it can nevertheless be assigned this state as an effective description, in the sense that the probabilities for outcomes of subsequent measurements on the prepared system, conditional on the actual preparation outcome and given its actual (entangled) state, coincide with the probabilities obtained by applying the Born rule to this effective state.

3.3.3 Probabilities for Measurement Outcomes and Possessed Properties

It would seem that the possessed properties of a prepared system should play some part in explaining the future behavior of this system and in particular the probabilities for outcomes of measurements performed on it. It is therefore notable that the possessed properties of the prepared system do *not* play a role in the account of preparation just explained. The probabilities for outcomes of subsequent measurements on prepared systems are obtained by conditionalizing on the preparation outcome, or equivalently by conditionalizing on the effective state of the system (since the preparation outcome and effective state are in one-to-one correspondence). But as mentioned above, there is no direct correspondence between the possessed properties and the preparation outcome, hence no direct correspondence between possessed properties and the effective state. The standard quantum mechanical probabilities for outcomes of measurements on prepared systems thus seem not to depend on the possessed properties of prepared systems, according to the modal interpretation. This prompts the question: Are measurement outcomes probabilistically independent of possessed properties in general?

Bacciagaluppi & Hemmo (1998: section 4) answer this question in the negative. They provide a particular example of a preparation such that, they claim, when calculating probabilities of outcomes of subsequent measurements according to the modal interpretation, conditionalizing on the effective state of the prepared system does not screen off dependence on its possessed properties. In their example, a preparation establishes correlations between a composite prepared system $\mathcal{S} = \mathcal{S}_1 + \mathcal{S}_2$ and a preparing device $\mathcal{M}_1$. They suppose that the possessed properties of $\mathcal{S}$ correspond to perfectly correlated product states $|\alpha_i\rangle \otimes |\beta_i\rangle$ on $\mathcal{H}_{\mathcal{S}_1} \otimes \mathcal{H}_{\mathcal{S}_2}$. After the conclusion of the preparation, $\mathcal{S}_1$ evolves freely and a measurement is performed on $\mathcal{S}_2$. Bacciagaluppi and Hemmo show that when calculating probabilities of measurements performed on $\mathcal{S}_2$, conditionalizing on the possessed properties $|\beta_i\rangle$ of $\mathcal{S}_2$ screens off dependence on the effective state of $\mathcal{S}$ (the state indicated by the preparation register $\mathcal{M}_1$).

But I argue that this preparation of $\mathcal{S} = \mathcal{S}_1 + \mathcal{S}_2$ in a very special state actually qualifies as a *twofold preparation, of both the compound system $\mathcal{S}$ and the subsystem $\mathcal{S}_2$, involving two preparing devices (or preparation registers)*—one is the device $\mathcal{M}_1$, which acts as a preparation register for $\mathcal{S}$, and one is the subsystem $\mathcal{S}_1$, which acts as a preparation register for $\mathcal{S}_2$. Both $\mathcal{M}_1$ and $\mathcal{S}_1$ become correlated with the states of their respective prepared systems, and both of them then stably retain their records of the prepared states while $\mathcal{S}_2$ undergoes a second measurement interaction with a measuring device $\mathcal{M}_2$. $\mathcal{S}_2$ thus has an effective state of its own, and since its reduced state is diagonal in terms of the possible effective states, these correspond to the possible possessed properties of $\mathcal{S}_2$. *Conditionalizing on the possessed property of $\mathcal{S}_2$* in this particular example is, I submit, *the very same thing as conditionalizing on the effective state of $\mathcal{S}_2$*. Therefore, I argue that this example does *not* show that conditionalizing on the definite properties ascribed by the modal interpretation to the system $\mathcal{S}$ screens off probabilities for outcomes of measurements on $\mathcal{S}$ from the effective state of $\mathcal{S}$.

Here are the details of the example: A preparation interaction ending at time t_1 entangles prepared system $\mathcal{S} = \mathcal{S}_1 + \mathcal{S}_2$ with preparation device $\mathcal{M}_1$. A measurement device $\mathcal{M}_2$ waits nearby in its ready state. The outcome registers of both $\mathcal{M}_1$ and $\mathcal{M}_2$ are monitored by environment $\mathcal{E}$. The total state of $\mathcal{S} + \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{E}$ at t_1 is

$$|\Psi_1\rangle = \sum_i \mu_i \, |\phi_i^*\rangle \, |\psi_i^1\rangle \, |\psi_0^2\rangle \, |E_{i0}\rangle \, .$$

A crucial assumption is that the possessed properties of $\mathcal{S}$ at t_1 have the form of product states,

$$|\hat{\phi}_i\rangle = |\alpha_i\rangle \otimes |\beta_i\rangle$$

for othonormal sets $\{|\alpha_i\rangle\}$ on $\mathcal{H}_{\mathcal{S}_1}$ and $\{|\beta_i\rangle\}$ on $\mathcal{H}_{\mathcal{S}_2}$—which sets consequently represent the possible properties of $\mathcal{S}_1$ and $\mathcal{S}_2$. The effective states $|\phi_i^*\rangle$ of $\mathcal{S}$ can be expressed in terms of the possessed property states $|\hat{\phi}_j\rangle$, as $|\phi_i^*\rangle = \sum_j \lambda_j^i \, |\hat{\phi}_j\rangle = \sum_j \lambda_j^i \, |\alpha_j\rangle \, |\beta_j\rangle$. Therefore the prepared state at t_1 can be written as a state on $\mathcal{H}_{\mathcal{S}_1} \otimes \mathcal{H}_{\mathcal{S}_2} \otimes \mathcal{H}_{\mathcal{M}_1} \otimes \mathcal{H}_{\mathcal{M}_2} \otimes \mathcal{H}_{\mathcal{E}}$ as

$$|\Psi_1\rangle = \sum_{ij} \mu_i \lambda_j^i \, |\alpha_j\rangle \, |\beta_j\rangle \, |\psi_i^1\rangle \, |\psi_0^2\rangle \, |E_{i0}\rangle \, .$$

Notice that the preparation interaction not only has correlated the states $|\psi_i^1\rangle$ of $\mathcal{M}_1$ with the states $|\phi_i^*\rangle$ of $\mathcal{S}$, but also has correlated the states $|\alpha_j\rangle$ of $\mathcal{S}_1$ with the states $|\beta_j\rangle$ of $\mathcal{S}_2$. It is assumed that, due to decoherence, both the state of $\mathcal{M}_1$ and its possessed properties will remain stable from t_1 onward. It is likewise assumed that $\mathcal{S}_1$ evolves freely after time t_1; according to a result of Vermaas (1996) this entails the deterministic evolution of its possessed properties.[9] From t_1 onward, then, the states of $\mathcal{S}_1$ and of $\mathcal{M}_1$ are guaranteed to preserve their correlations with the original states (at t_1) of $\mathcal{S}_2$ and of $\mathcal{S}$, respectively. Furthermore, the possessed properties of both $\mathcal{S}_1$ and $\mathcal{M}_1$ evolve deterministically from t_1 to t_2, so that they can serve as faithful records at t_2 of the possessed properties these two systems had at t_1—and hence of the corresponding effective states of $\mathcal{S}_2$ and of $\mathcal{S}$. I highlight these

[9]It should be noted that Vermaas' derivation of the deterministic evolution of the possessed properties of a freely evolving system is based on two assumptions: One is the assumption of stability for measurement outcomes (cf. the end of section 3.2.2 above); the other is the assumption that the evolution of possessed properties of a system is dependent solely on the evolution of the reduced state of that system. Thus insofar as any theoretical basis for the assumption of stability for measurement outcomes appeals to decoherence, the theoretical basis for the assumption that freely evolving systems evolve deterministically will be parasitic on a particular assumption about how possessed properties evolve in the context of decoherence.

similarities because the features of $\mathcal{M}_1$ that qualify it as a preparation register that preserves information about the preparation of $\mathcal{S}$, would seem to be features also of $\mathcal{S}_1$ according to which $\mathcal{S}_1$ should likewise qualify as a preparation register that preserves information about the preparation of $\mathcal{S}_2$.

Suppose that a measurement interaction takes place, a measurement by $\mathcal{M}_2$ of an observable on $\mathcal{S}_2$ with eigenvectors $|\eta_k\rangle$. If this is modeled as an ideal measurement for the sake of simplicity (though the same results are obtained even without this simplification) then the total state at the end of the measurement interaction is

$$|\Psi_2\rangle = \sum_{ijk} \mu_i \lambda_j^i \langle \eta_k|\beta_j\rangle |\alpha_j\rangle |\eta_k\rangle |\psi_i^1\rangle |\psi_k^2\rangle |E_{ik}\rangle .$$

Now consider three conditional probabilities for the measurement outcome $|\psi_k^2\rangle$ at t_2, conditional on the preparation "outcome" $|\psi_i^1\rangle$ at t_1, or the possessed property $|\beta_j\rangle$ of $\mathcal{S}_2$ at t_1, or both.[10] The modal interpretation dictates the following conditional probabilities:

$$\Pr(\psi_k^2/\psi_i^1) = \sum_j \left|\lambda_j^i\right|^2 |\langle \eta_k|\beta_j\rangle|^2 \tag{3.18}$$

$$\Pr(\psi_k^2/\psi_i^1 \& \beta_j) = |\langle \eta_k|\beta_j\rangle|^2 \tag{3.19}$$

$$\Pr(\psi_k^2/\beta_j) = |\langle \eta_k|\beta_j\rangle|^2 \tag{3.20}$$

The first of these conditional probabilities (3.18) coincides with the Born-rule probability generated by the state $|\phi_i^*\rangle$ of $\mathcal{S}$ for a measurement of an observable with eigenvectors $|\eta_k\rangle$ on subsystem $\mathcal{S}_2$. This means that conditionalizing upon the preparation outcome $|\psi_i^1\rangle$ and using the rules of the modal interpretation (and the stability and deterministic evolution, respectively, of the possessed properties of $\mathcal{M}_1$ and $\mathcal{S}_1$) generates the same probability for measurement outcome $|\psi_k^2\rangle$ as the Born rule does for a system in state $|\phi_i^*\rangle$. Hence, for the

[10] Actually, the measurement and preparation outcomes are properly represented by the possessed properties $|\hat{\psi}_k^2\rangle$ of $\mathcal{M}_2$ and $|\hat{\psi}_i^1\rangle$ of $\mathcal{M}_1$, rather than the pointer states $|\psi_k^2\rangle$ and $|\psi_i^1\rangle$. But due to decoherence, the possessed properties will be *extremely* close to the pointer states. Assuming that a definite outcome requires only that some observable *close* to the designated pointer observable is definite, and assuming that the reduced states of both devices are far from degeneracy, we can, given our present purposes, safely suppress the difference between the eigenstates of the pointer observable and the (possibly) possessed properties that are extremely close to these eigenstates.

purposes of predicting probabilities of outcomes of measurements performed on $\mathcal{S}$, we can assign to $\mathcal{S}$ the effective state $|\phi_i^*\rangle$ and apply the Born rule.

The question, then, is whether conditionalizing on the possessed properties of $\mathcal{S}$, instead of or in addition to the effective state gives any more information than conditionalizing on the effective state alone. (Conditionalizing on the effective state $|\phi_i^*\rangle$ is the same as conditionalizing upon preparation outcome $|\psi_i^1\rangle$, since they are perfectly correlated.) Bacciagaluppi and Hemmo answer in the negative, on the basis of equations (3.18)–(3.20):

> The example illustrates how in general conditionalizing upon both the possessed property of $\mathcal{S}_2$ and the effective state yields more information than conditionalizing only on the effective state; in this example, further, conditionalizing on the possessed property of $\mathcal{S}_2$ screens off dependence on the effective state, even if it does not determine the result of the measurement with probability 1. (p. 108)

Their assessment clearly depends on the supposition that conditionalizing on the possessed property $|\beta_j\rangle$ of $\mathcal{S}_2$ does not itself amount to conditionalizing on the effective state of $\mathcal{S}_2$. But I submit that conditionalizing upon the possessed property $|\beta_j\rangle$ is in this case equivalent to conditionalizing upon the preparation event (i.e. the possessed property) $|\alpha_j\rangle$, since these properties are perfectly correlated according to the modal interpretation's rule for joint probabilities. And $|\beta_j\rangle$ just *is* the effective state of $\mathcal{S}_2$ given the preparation event $|\alpha_j\rangle$ (since $|\beta_j\rangle$ is the state of $\mathcal{S}_2$ relative to the state $|\alpha_j\rangle$ of $\mathcal{S}_1$). In short, $|\beta_j\rangle$ is the effective state of $\mathcal{S}_2$ given the preparation outcome $|\alpha_j\rangle$. Therefore conditionalizing upon the possessed property $|\beta_j\rangle$ of $\mathcal{S}_2$ is *equivalent* to conditionalizing upon the effective state of $\mathcal{S}_2$. The intended contrast between conditionalizing upon a system's possessed properties and conditionalizing upon its effective state breaks down.

Of course "conditionalizing on the effective state" is *intended* to mean conditionalizing on the effective state $|\phi_i^*\rangle$ of $\mathcal{S}$, or equivalently, conditionalizing on the preparation outcome $|\psi_i^1\rangle$. But then the claim only amounts to saying that conditionalizing upon the effective state $|\phi_i^*\rangle = \sum_j \lambda_j^i |\alpha_j\rangle |\beta_j\rangle$ of $\mathcal{S} = \mathcal{S}_1 + \mathcal{S}_2$ gives less information about probabilities for outcomes of measurements to be performed on $\mathcal{S}_2$ than conditionalizing upon the effective state $|\beta_j\rangle$ of $\mathcal{S}_2$. This is hardly surprising; and in any case it does not show that possessed properties can add to the information about measurement probabilities available via effective states alone.

3.4 DECOHERENCE, DYNAMICS, AND PREFERRED STATES

Advocates of the modal interpretation call upon decoherence to play two distinct roles. One of these roles has to do with the instantaneous form of the reduced state of a decohering system; in this regard advocates of the modal interpretation take decoherence to have a particular kinematical significance. The other has to do with correlations between properties at different times; in this regard advocates of the modal interpretation take decoherence to have a particular dynamical significance. With regard to the kinematical role, it is widely recognized that decoherence does not fulfill the hopes of the modal approach: decoherence effects accomplish less than what modal advocates had claimed. What I want to emphasize in this section is that with regard to the secondary, dynamical role of decoherence, the hopes of the modal approach are, one might say, surpassed: decoherence accomplishes more, dynamically speaking, than modal advocates had claimed. In fact, decoherence does *too much* in the sense that once we recognize what decoherence actually does accomplish, we see that the modal interpretation itself is undercut, not supported, by decoherence.

The primary role of decoherence in the modal interpretation is kinematical in nature: decoherence ensures that the reduced state of a decohering system has a particular form. Decoherence drives the reduced state of a decohering system towards diagonality with respect to the decohering variable. Thus decoherence ensures that a measuring device has at every moment a reduced state that is approximately diagonal with respect to the decohering variable. The modal interpretation, which ascribes particular significance to the states that diagonalize the reduced state of the system, invokes decoherence in the hope that approximate diagonality with respect to the decohering variable will translate into definiteness of a property close to the decohering variable in Hilbert space norm. As the case of a continuous model of decoherence shows, this hope is not in general fulfilled: approximate diagonality of the reduced state with respect to the decohering variable does not guarantee that some observable close to the decohering variable has a definite value. The instability of the spectral decomposition of a density operator near degeneracy points means that for a nearly degenerate reduced state the definite-valued observable assigned by the modal interpretation might be far away—even maximally far away—from the decohering variables. The hope, therefore, that decoherence will in general secure the definiteness of a quantity close to the decohering variable is unfulfilled.

The secondary role of decoherence in the modal interpretation is ensuring the stability of measurement outcomes—ensuring, that is, that the definite property of a measuring apparatus typically does not jump around erratically from one pointer reading to another, but instead remains stably close to a single pointer reading once a measurement interaction has ended. It seems reasonable to invoke decoherence to explain this stability: for under the assumption that the apparatus-environment interaction couples the state of the environment to the pointer observable of the apparatus, states corresponding to distinct pointer readings inhabit effectively non-interfering branches of the global quantum state. These non-interfering branches, and the corresponding apparatus states, therefore effectively evolve independently. It seems reasonable to propose as a constraint on the dynamics of possessed properties that the trajectories of possessed properties close to distinct pointer states would be close to the trajectories of the pointer states themselves, with the effect that after the end of a measurement interaction, the probability for the definite property of an apparatus to make a transition from one (approximate) pointer reading to another typically would be very small. And by making this assumption, in an appropriately generalized form, about the dynamics of the possessed properties of systems subject to environmental decoherence, modal advocates can provide some theoretical basis for the observed stability of pointer readings and ground the joint account of preparation as well.

In fact the assumption can be made even more general, and more plausible, by abstracting from *environmental* decoherence entirely. For certainly the significance of environmental decoherence in this regard is the resulting non-interference of the branches corresponding to distinct pointer readings, or more generally to distinct possible properties. When modal interpreters attribute to environmental decoherence a key role in securing stability of outcomes, this should be understood as a special case of a more general constraint on the dynamics of possessed properties: when the possible properties of a system correspond (approximately) to non-interfering branches of the global quantum state, then the evolution of the possessed properties of the system will follow (approximately) the evolution of the corresponding branch. This generalized version of the stability assumption allows the modal interpretation to account for the stability of measurement outcomes instead of simply postulating this stability in *ad hoc* fashion.

And there are real examples where the generalized stability assumption finds application. Consider the paradigmatic example (discussed in Ruetsche (2003)) of the preparation of a spin-$\frac{1}{2}$ particle in a spin-z eigenstate: the particle is passed through an inhomogeneous magnetic field that entangles its spin degree of freedom with its position. Standard laboratory practice attributes to a particle emerging from the magnetic field along the upper path the pure spin state $|+\rangle$. Provided that the entangled state of the particle is (approximately) biorthogonal in terms of spin-z and position states, $c_+ |+\rangle |\phi_+\rangle + c_- |-\rangle |\phi_-\rangle$, the modal interpretation can account for this attribution of a pure state: in this case the modal interpretation assigns to the particle either the pair of definite properties $|+\rangle |\phi_+\rangle$ (spin up and located in the upper path) or the pair $|-\rangle |\phi_-\rangle$ (spin down and located in the lower path). But standard laboratory practice also attributes to the particle a spin state that is *stable*. In this case the preparing "device" is the position of the single particle, and environmental decoherence clearly cannot be invoked to explain the stability of the preparation "outcome" (upper or lower path), as required by the joint account of preparation (Ruetsche 2003: n. 14). But the generalized stability assumption can: for the possible property pairs $|+\rangle |\phi_+\rangle$ and $|-\rangle |\phi_-\rangle$ correspond to non-interfering branches of the global quantum state, and hence the stability assumption framed in terms of non-interfering branches will apply.

But once non-interference of branches is accorded this more general role in constraining and explaining the dynamics of possessed properties in the modal interpretation, it threatens to account for too much, by modal lights. For in fact the non-interference of branches already plays a role in picking out the possessed properties of systems subject to environmental decoherence: The modal interpretation secures the *right* possessed properties for such systems by ensuring that possessed properties will be very close to properties already preferred by environmental decoherence—which properties therefore pick out effectively non-interfering branches of the global quantum state. This strategy on the part of advocates of the modal interpretation can claim success in picking out the right possessed properties precisely insofar as it succeeds in picking out properties that line up almost exactly with these non-interfering branches. When, as in cases of extreme near-degeneracy, the properties the modal interpretation picks out fail to line up with non-interfering branches, the strategy fails. Tacitly, this strategy recognizes that the "right" set of possible properties of a decohering system is the set of properties corresponding to the non-interfering branches of the global quantum state. The adoption of the generalized stability assumption then admits that not only the specification of these properties at each time but also their evolution is determined by the non-interfering branches to which they correspond. There is little left for distinctively modal interpretational rules to do.

What about systems *not* themselves subject to decoherence? Here again it is non-interference that does the real work. Consider the case of state preparation by measurement, where the pointer observable of the apparatus is subject to environmental decoherence. The general form of the total state of prepared system + apparatus + environment at the conclusion of the preparation is

$$|\Psi_1\rangle = \sum_i \mu_i |\phi_i^*\rangle |\psi_i\rangle |E_i\rangle ,$$

where $|\psi_i\rangle$ are the eigenstates of the pointer observable and the $|\phi_i^*\rangle$ are the corresponding relative states of the prepared system, which are generally not pairwise orthogonal. According to the modal interpretation, the possessed property of the prepared system is one of the eigenstates $|\hat{\phi}_j\rangle$ of its reduced state. The modal interpretation is then left to account for the fact that it is not this modally possessed property but the effective state $|\phi_i^*\rangle$, corresponding to the pointer reading $|\psi_i\rangle$ of the measuring device, that generates correct predictions about subsequent measurements on the prepared system. The joint account of preparation effectively appeals to the fact that the pointer states $|\psi_i\rangle$ pick out non-interfering branches of the total state, so that the pointer reading of the measuring device can be assumed to be stable; but once we see this stability as underwritten by dynamical independence of the branches $|\phi_i^*\rangle |\psi_i\rangle |E_i\rangle$, it is also immediately obvious that the same division into branches privileges the relative states $|\phi_i^*\rangle$ of the prepared system. So non-interference of branches can explain why the relative state $|\phi_i^*\rangle$ corresponding to the pointer reading should be the effective state of the prepared system. The modally possessed property $|\hat{\phi}_j\rangle$ seems superfluous.

3.5 CONCLUSION

I close with two quotations from modal theorists. The first is a quotation from one of the founders of the modal interpretation that shows that the original focus on the biorthogonal decomposition—later generalized to the spectral decomposition—was intended to pick out a decomposition of the global state into "decoherent" states of subsystems:

> The important point is that now there is an objective criterion whether or not a system by itself can be described, on the observational level, by a property related to a single term from a superposition. With reference to [the equation $|\Psi\rangle = \sum_k |\phi_k\rangle |R_k\rangle$], the decisive factor is whether or not the coherence between the various $|\phi_k\rangle$ is broken through the coupling with other systems. The question therefore is whether the "relative states" $|R_k\rangle$ are mutually orthogonal. This is a purely technical physical question, the answer of which depends on the form of the Hamiltonian and the initial state of the total system. The final state is a solution of a Schrodinger-type of equation; when this final state has been calculated it can be ascertained whether or not the states correlated with the $|\phi_k\rangle$ are mutually orthogonal. For a real measurement a further condition must be fulfilled. In this case, there must be a certain permanence in the destruction of coherence between various measurement outcomes. There must be a permanent mark of some kind, that records the result of the measurement. In order to realize this, the measurement interaction must constitute an irreversible process, of the kind familiar from statistical mechanics. Although such processes always leave open the possibility of a reverse evolution into the initial state, the probability of such an occurrence can be neglected in practice. (Dieks 1988: 182)

The second quotation comes from the end of a book-length examination of the modal interpretation, where the author questions the core idea that the reduced state and its evolution specify the possessed properties and their evolution:

> Since the spectral and atomic modal interpretations violate Dynamical Autonomy for composite systems, there does not exist a unique relation between the evolution of the state of a freely evolving composite system and the evolution of the properties of subsystems of that composite. . . . If it is the case that the evolution of the properties of systems is not uniquely related to the evolution of the [reduced] states of those systems, why should it then be the case that the properties themselves are uniquely related to those states? By their violations of Dynamical Autonomy, the spectral and atomic modal interpretations force us to understand the physics of the properties of a quantum system not as being uniquely fixed by the state of that system, but as being dependent on the state of the whole universe. But if this is the case, why then not be brave and also take the properties of a subsystem itself as being dependent on the state of the whole universe? So, the inability of these modal interpretations to satisfy Dynamical Autonomy undermines, in my mind, their very starting point that the properties of a system should be defined from the [reduced] state of the system. (Vermaas 1999: 277–278)

These two quotations highlight my main point: that decoherence undercuts the modal interpretation, rather than supporting it. The modal interpretation, as the first quotation from Dieks makes clear, was all along intended to pick out properties *already characterized by non-interference*. In general, it does not succeed, as the properties determinate by modal lights do not always coincide with properties corresponding to non-interfering branches of the global state. But what seems clear is that regardless of whether the modal interpretation succeeds in latching onto them, one of its founders acknowledges that the "right" properties for an interpretation to pick out are those that correspond to non-interfering branches. This supports my contention that non-interference, or dynamical independence, of branches is the interpretively relevant feature that picks out the possible properties of a system. The second quotation, from Vermaas, highlights one of the reasons for the modal interpretation's failure to secure the right properties: since these properties are tied to non-interfering branches of the global quantum state, identifying and tracking these properties requires attention to features of the *global* state. An interpretation that aims to specify and track the evolution of the definite properties of a system solely on the basis of the reduced state of that system alone seems doomed when these properties are properly characterized in terms of the dynamics of the global state, via non-interference of branches.

4.0 DECOHERENCE AND DEFINITE PROPERTIES

In this chapter I take up arguments given by decoherence theorists for the ability of decoherence to account for the occurrence, or appearance, of definite measurement outcomes, and of observed definite properties of macroscopic objects more generally. I argue that what is required to secure definiteness is the "dynamical decoupling of components" (Zeh 1970) of the global quantum state corresponding to distinct values of familiar macroscopic quantities such as position, and a property ascription rule according to which the resulting dynamically autonomous components represent a collection of possible definite properties. The crucial role of environmental decoherence is to accomplish the required dynamical decoupling between the appropriate staes. But the explanations typical of the decoherence literature obscure this primary role. Discussions of, e.g., diagonality of the reduced density operator and stability of correlations with respect to preferred states, focus on *effects* of this dynamical decoupling accomplished by interaction with the environment. These effects are indeed important to establish insofar as they are characteristic of the familiar states and observables of macroscopic objects; it also seems natural for physicists to be particularly concerned with these effects given their interest in practical matters involving measurement and prediction. But the focus on these effects tends to distract from the underlying cause and to obscure the need to adopt an interpretation of entangled states that relaxes the eigenvalue-eigenstate link—an interpretive move that is implicit in much of the decoherence literature but which decoherence theorists seem unwilling to explicitly acknowledge.

It is widely held that the phenomenon of decoherence is the key to understanding how the classical world of our experience emerges in a fundamentally quantum universe. In particular, decoherence is widely considered to be the key to solving the measurement problem. The literature abounds with statements to the effect that decoherence underwrites a solution to the measurement problem, or explains the collapse of the wave function, or accounts for the appearance of a classical world. Here are three such claims from the literature:

> This interaction, equivalent to "monitoring" of the system by the environment, makes the phase between pointer basis states impossible to observe. Thus, the interaction with the environment forces the system to be in one of the eigenstates of the pointer observable, rather than in some arbitrary superposition of such eigenstates. (Zurek 1982: 1863)

> The last chapter [of a book being reviewed] . . . deals with the quantum measurement problem . . . . My main test, allowing me to bypass the extensive discussion, was a quick, unsuccessful search in the index for the word 'decoherence' which describes the process that used to be called 'collapse of the wave function'. The concept is now experimentally verified by beautiful atomic beam techniques quantifying the whole process. (Anderson 2001: 492)

> For macroscopic systems, the *appearances* are those of a classical world (no interferences, etc.), even in circumstances, such as those occurring in quantum measurements, where quantum effects take place and quantum probabilities intervene. . . . Decoherence explains the just mentioned *appearances* and this is a most important result. . . . As long as we remain within the realm of mere predictions concerning what we shall observe (i.e., what will *appear* to us) . . . no break in the linearity of quantum dynamics is necessary.[1] (d'Espagnat 2001: 136)

Confident claims like these might lead seem to suggest that decoherence *alone* provides a solution to the measurement problem (and related puzzles concerning the quantum/classical correspondence), in the sense that taking the phenomenon of decoherence into account provides orthodox quantum mechanics with the resources needed for a solution. But in fact this is not the case; decoherence, in conjunction with the quantum mechanical formalism and orthodox principles of interpretation, cannot solve the measurement problem. Even when decoherence is taken into consideration, a solution to the measurement problem requires either non-unitary dynamics or some rule for attributing definite properties to quantum systems other than the orthodox eigenvector-eigenvalue link. This is now generally recognized by decoherence theorists. Claims that decoherence *by itself* solves the measurement problem have been strongly criticized for many years, and the lesson seems to have been at least partially absorbed. It is now not uncommon to find decoherence theorists openly

[1] d'Espagnat says this after arguing that the task of science is to "describe human experience, not to describe 'what really is' " (p. 135). That is, science should aim to explain why the world appears to us as it does, but is not required to claim in addition that the world *is* as it appears to be. So in claiming that decoherence can account for the *appearances* of a classical world, he is really claiming that decoherence makes possible as satisfactory a scientific explanation of the classical world as one could reasonably want.

stating that decoherence alone does not solve the measurement problem. Yet the claim that decoherence provides the central piece of the puzzle, or even that decoherence can account for the *appearance* of definiteness, are quite common. So decoherence theorists still maintain that environmental decoherence takes us nearly all the way to a solution.

This chapter aims to uncover the interpretational assumptions, both explicit and implicit, at work in decoherence theorists' attempts to solve the measurement problem. Section 4.1 explains why decoherence seems to promise to bring us close to a solution to the measurement problem. Section 4.2 presents the two central consequences of environmental decoherence, namely the decay of interference terms in the reduced state of the system—the effect specifically known as decoherence—and the selection of a preferred basis of the apparatus. Sections 4.3 and 4.4 take up these effects in turn and consider arguments that each one can account for at least the apparent occurrence of definite measurement outcomes. Section 4.5 considers claims that appeals to consciousness are required as part of a solution to the measurement problem. And section 4.6 sums up what I take to be the crucial lessons of the decoherence program.

4.1 DECOHERENCE AND THE MEASUREMENT PROBLEM

When a measurement is modeled simply as a interaction, governed by the unitary dynamics, between object system $\mathcal{S}$ and apparatus $\mathcal{A}$, the result is an entangled state of $\mathcal{S} + \mathcal{A}$ corresponding to a superposition of measurement outcomes rather than a single definite outcome. Including in the model an environment $\mathcal{E}$ that interacts with the pointer might seem to bring us a long way toward accounting for the definiteness of measurement outcomes. Suppose that the apparatus interacts with an environment consisting of a vast number of microscopic systems, such as air molecules and photons that continually scatter off of the apparatus. The states of the individual systems that interact with the apparatus will be modified by their interaction with it, so that the total state of the environment will become correlated to the pointer states $|p_i\rangle$. Given such an apparatus-environment interaction, the measurement interaction will eventuate in an entangled state over all three subsystems:

$$\sum_i c_i |o_i\rangle |p_0\rangle |e_0\rangle \rightarrow \sum_i c_i |o_i\rangle |p_i\rangle |e_i\rangle = |\Psi\rangle \, . \tag{4.1}$$

At this point there is no pure state description of $\mathcal{S}+\mathcal{A}$; the only available description of it is a description by means of a mixed state known as the reduced state, $\rho^{\mathcal{SA}}$, obtained from the total state $|\Psi\rangle$ by tracing out over the degrees of freedom of the environment; formally, $\rho^{\mathcal{SA}} = \mathrm{Tr}_{\mathcal{E}}(|\Psi\rangle\langle\Psi|)$. If the states of the environment $|e_i\rangle$ correlated with the pointer states the apparatus are pairwise orthogonal, the reduced state of $\mathcal{S}+\mathcal{A}$ will be

$$\rho^{\mathcal{SA}} = \mathrm{Tr}_{\mathcal{E}}\left(|\Psi\rangle\langle\Psi|\right) = \sum_i |c_i|^2 |o_i\rangle\langle o_i| |p_i\rangle\langle p_i| \tag{4.2}$$

This reduced state of $\mathcal{S}+\mathcal{A}$ is thus mathematically equivalent to the mixture that the collapse interpretation posits for ideal measurements.

It is now easy to see why many have thought that taking the environment into consideration might—by itself—solve the measurement problem: the simple model used here results in a final (reduced) state of $\mathcal{S}+\mathcal{A}$ which is *mathematically identical* to the "collapsed state"

$$W = \sum_i |c_i|^2 |o_i\rangle\langle o_i| |p_i\rangle\langle p_i| \tag{4.3}$$

which provides an ensemble description of the state that would result from a measurement if each individual measurement resulted in the collapse of the $\mathcal{S}+\mathcal{A}$ composite system to one of the states $|o_i\rangle |p_i\rangle$, with probability $|c_i|^2$. This collapsed state is consistent (as the pure state $|\Psi\rangle$ is not) with a definite measurement outcome. What is more, a mixed state $\rho^{\mathcal{SA}}$ with the very same mathematical form has been obtained via strictly unitary evolution through the interaction of the apparatus with its environment. It would seem then that taking the environment into consideration results in agreement between predicted and observed measurement results, *without* modifications either to the dynamics or to the property-ascription rule of orthodox quantum mechanics, at least for this simple model. (And decoherence theorists claim that this result can be generalized, in the sense that for realistic models of measurement that include the environment, the post-measurement reduced state of system plus apparatus is, to a very good approximation, a mixture of the desired form.)

However, this is *not* a real solution to the measurement problem. The reduced state $\rho^{\mathcal{SA}}$ is *mathematically equivalent* to the desired mixed state W, but these two mixtures cannot be given the same interpretation. For the state W that orthodox principles of interpretation assign to actual measurement results is a *proper* or *ignorance interpretable* mixture: it is to be understood as representing a system which is in some pure state $|o_i\rangle\,|p_i\rangle$; the actual state is unknown, and only the probability $|c_i|^2$ for each value of i is known. The reduced state $\rho^{\mathcal{SA}}$, by contrast, is an *improper* mixture. We can assign this reduced state to the $\mathcal{S}+\mathcal{A}$ precisely because we know that $\mathcal{S}+\mathcal{A}$ is part of the larger system $\mathcal{S}+\mathcal{A}+\mathcal{E}$ which is in the pure state $|\Psi\rangle = \sum_i c_i\,|o_i\rangle\,|p_i\rangle\,|e_i\rangle$; but this pure state for the larger system shows that the subsystem $\mathcal{S}+\mathcal{A}$ is entangled with $\mathcal{E}$, and so the subsystem $\mathcal{S}+\mathcal{A}$ is definitely not in a pure state. In particular, the eigenvector-eigenvalue link says that the pointer observable P has no definite value for the state $\rho^{\mathcal{SA}}$, because the total state $|\Psi\rangle$ is not an eigenvector of P (to be more precise, of $I_{\mathcal{S}} \otimes P \otimes I_{\mathcal{E}}$). As long as the eigenvector-eigenvalue link is retained, showing that the reduced state $\rho^{\mathcal{SA}}$ is mathematically equivalent to the state W does not amount to predicting a definite measurement outcome, so the measurement problem remains.

If we remain with a pure state description, then environmental decoherence ensures that macroscopic objects always become immediately *entangled* with their environments, via interactions that correlate states of the environment with *states for which the familiar macroscopic quantities are at least approximately definite.* As a result, an object $\mathcal{A}$ subject to decoherence can never exist (except almost instantaneously) in a superposition on $\mathcal{H}_{\mathcal{A}}$ of these states privileged by the environmental interaction. The only possible descriptions by means of a state on $\mathcal{H}_{\mathcal{A}}$ will be one of these pure states, or a mixed state. Decoherence theorists sometimes sum up the result by saying that the environmental interaction destroys superpositions between preferred states and forces a system into one of the states preferred by the environment, or a mixture thereof.

Taking this as a solution to the measurement problem trades on an ambiguity in the phrase "to exist in a superposition," in the question "Why can't decohering objects exist in arbitrary superpositions of the states we observe them in?" If the question is simply, why can't the state of $\mathcal{A}$ be a superposition in $\mathcal{H}_{\mathcal{A}}$ of the states we observe, then the fact that any macroscopic object is constantly becoming entangled with its environment via interactions that correlate states of the environment with states for which the familiar macroscopic quantities are at least approximately definite answers that question: as soon as such a superposition arose, it would immediately become entangled with the environment; the system would not be describable any more by a pure state on $\mathcal{H}_{\mathcal{A}}$, but only by a mixed state. But (and this is the old familiar refrain that decoherence doesn't solve the measurement problem) this does *not* mean that the system is then always described by precisely one of the pure states picked out by the environment; it means that it is described by an entangled state on $\mathcal{H}_{\mathcal{A}} \otimes \mathcal{H}_{\mathcal{E}}$.[2] If the aim is a complete description of the system by exactly one pure state on $\mathcal{H}_{\mathcal{A}}$ that assigns it a definite value for the preferred observables, then entanglement with the environment certainly does not secure this.

From this point of view, it actually looks as though taking interaction with the environment into consideration can only make things *worse* for the measurement problem. For no-collapse interpretations, the measurement problem is just the problem of how to reconcile the entangled post-measurement state of system + apparatus with the occurrence of a definite outcome. Including another degree of entanglement, this time with the environment, should just make this problem more acute. In fact, it should make the problem *much* more serious. In the classic version of the measurement problem, the problem is entanglement, established by a single interaction of limited duration, between the apparatus and a single, isolated system. Adding to the picture an environment, consisting of vast numbers of interacting systems, interacting more or less continually with the apparatus (not to mention the interaction of this environment with other macroscopic objects as well) entails that the problem of entanglement is far more severe than is evident from the classic version. "To put it crudely: if everything is in interaction with everything else, everything is entangled with everything else, and that is a worse problem than the entanglement of measuring apparatuses with the measured probes" (Bacciagaluppi 2008).

[2] Despite what Zurek says: "For now the observer (or the apparatus, or anything effectively classical) is continuously monitored by the rest of the universe. Its state is repeatedly forced into the einselected states, and very well (redundantly) known to the rest of the universe" (Zurek 1993a: 763).

4.2 THE RESULTS OF ENVIRONMENTAL MONITORING

This section presents the two main results attributed to environmental monitoring, namely the selection of a preferred basis and decoherence with respect to that basis.

Very simple models of decoherence look much like the model of measurement *cum* environment in the previous section. In these models, the interaction between a system $\mathcal{A}$ and its environment $\mathcal{E}$ is a measurement-like interaction, in which the environment monitors a preferred observable P, becoming coupled to the eigenstates $|p_i\rangle$ without disturbing these eigenstates. That is, when the initial state of $\mathcal{A}$ is an eigenstate $|p_i\rangle$, the evolution of the composite system $\mathcal{A} + \mathcal{E}$ over time t is given by

$$|p_i\rangle\,|e_0\rangle \longmapsto |p_i\rangle\,|e_i(t)\rangle \tag{4.4}$$

When the initial state of $\mathcal{A}$ is a superposition of eigenstates, $\sum_i c_i\,|p_i\rangle$, the evolution of the composite system is given by

$$\sum_i c_i\,|p_i\rangle\,|e_0\rangle \to \sum_i c_i\,|p_i\rangle\,|e_i(t)\rangle \tag{4.5}$$

The crucial feature of the environment states $|e_i(t)\rangle$ is that they rapidly become orthogonal to each other, i.e.

$$\big|\,\langle e_i(t)|e_j(t)\rangle\,\big| \to 0 \qquad \text{as} \qquad t \to \infty \tag{4.6}$$

for $i \neq j$. The inner product converges as $\exp(-t/\tau_D)$, where the time scale τ_D characterizing the rate of convergence is called the decoherence time. Zurek (1991) reports a typical value of τ_D as 10^{-23} seconds or smaller, for models in which the distinct eigenstates of P correspond to macroscopically different states of the object.

After time t the state of the composite system $\mathcal{A} + \mathcal{E}$ is

$$|\Psi(t)\rangle = \sum_i c_i\,|p_i\rangle\,|e_i(t)\rangle\,; \tag{4.7}$$

for $t \gg \tau_D$, we have $\langle e_i(t)|e_j(t)\rangle \approx \delta_{ij}$. For all practical purposes then, the reduced density operator of $\mathcal{A}$ can be approximated by

$$\begin{aligned}\rho^{\mathcal{A}}(t) &= \mathrm{Tr}_{\mathcal{E}}\left(|\Psi(t)\rangle \langle \Psi(t)| \right) \\ &= \sum_{ij} c_i c_j^* \langle e_i(t)|e_j(t)\rangle |p_i\rangle \langle p_j| \\ &\approx \sum_i |c_i|^2 |p_i\rangle \langle p_i| \quad \text{for} \quad t \gg \tau_D.\end{aligned} \tag{4.8}$$

To sum up: for an arbitrary initial state of $\mathcal{A}$, the $\mathcal{A}+\mathcal{E}$ compound rapidly evolves into an entangled state such that the reduced density operator describing $\mathcal{A}$ is very nearly diagonal in the eigenbasis of the preferred observable P.

One of the central roles claimed for environment-induced decoherence in regard to the measurement problem is the selection of a preferred basis of apparatus states. According to the decoherence program, the interaction of a system with its environment is governed entirely by Schrödinger evolution; hence the aim of the decoherence program is not to predict or explain an actual collapse of an entangled post-measurement superposition to one of its terms. But it is claimed to predict and explain *the menu of states* to which the entangled superposition actually or apparently collapses, by picking out in dynamical terms a preferred basis for systems subject to decoherence, and by extension a preferred decomposition of the global quantum state. In other words, the interaction of a system with its environment is supposed to specify the interpretation basis required to determine the empirical significance of the generally entangled system-environment compound.

Central to this consequence of decoherence is the particular dynamics of the apparatus-environment interaction. If some apparatus observable P commutes with the apparatus-environment Hamiltonian,

$$[P, H_{\mathcal{A}\mathcal{E}}] = 0, \tag{4.9}$$

a condition known as the stability condition, then eigenstates $|p_i\rangle$ of this observable will be unaffected by the interaction with the environment. Thus if the total state of apparatus + environment is at some time a product state of one of these eigenstates, $|p_i\rangle |e_0\rangle$, the interaction will leave it a product state:

$$|p_i\rangle |e_0\rangle \rightarrow |p_i\rangle |e_i\rangle . \tag{4.10}$$

If instead the apparatus is initially in a superposition of eigenstates, then the the apparatus-environment interaction transforms a product state of apparatus + environment into an entangled state:

$$\left(\sum_i c_i |p_i\rangle\right)|e_0\rangle \to \sum_i c_i |p_i\rangle |e_i\rangle . \tag{4.11}$$

The interaction with the environment therefore distinguishes the eigenstates $|p_i\rangle$ from other pure states on $\mathcal{H}_{\mathcal{A}}$ in the sense that only these eigenstates avoid entanglement with the environment.

Preferred Basis: The dynamics of the system-environment interaction picks out a unique set of preferred states $|p_i\rangle$ which do not become entangled with the environment as a result of this interaction. Arbitrary superpositions of these states by contrast become entangled with the environment almost immediately.

A second characterization of the preferred basis arises when we narrow our focus to the state space of $\mathcal{A}$ alone. From this perspective what is special about the preferred basis states is that the interaction with the environment leaves these states pure, while it transforms arbitrary superpositions of them into mixed states.

(Note that the stability condition (4.9) does not generally pick out a *unique* preferred observable, but only a set of compatible observables, and that it does not in general pick out a unique preferred *basis* either, but rather a unique decomposition of $\mathcal{H}_{\mathcal{A}}$ into orthogonal subspaces. In other words, the dynamics can properly be said to pick out a set of preferred subspaces of $\mathcal{H}_{\mathcal{A}}$. I will nevertheless follow the literature in continuing to refer to "the preferred basis" and "the preferred observable.")

The second main consequence of environmental monitoring is the decay of interference effects; it is this consequence that is properly called "decoherence," since that term refers to the elimination of interference:

Decoherence: The interaction of the object with its environment leads to the extremely rapid decay of the interference terms in the reduced density operator $\rho^{\mathcal{A}}$ which correspond to distinct preferred subspaces of $\mathcal{H}_{\mathcal{A}}$. In the limit $t \to \infty$, $\rho^{\mathcal{A}}$ is diagonalized by states belonging to these preferred subspaces. And the decay of the interference terms is so fast that even after an incredibly short time, the interference terms are so small as to be undetectable in practice. Thus, on the timescales relevant for measurement and observation, the reduced state of the object will be indistinguishable for all practical purposes from a proper mixture of the preferred object states.

The upshot: *if* the environment interacts with an object in the right way, i.e., if the state of the environment becomes coupled to some macroscopic observable of the object without disturbing it, and if the corresponding environment states $|e_i(t)\rangle$ rapidly become nearly orthogonal, then the reduced state of the object will evolve incredibly quickly into a mixture that is, for all practical purposes, diagonal in a basis of eigenstates of this observable. To put it another way, the reduced state is for all practical purposes mathematically equivalent to a proper mixture of states which correspond to definite values for the preferred observable. It must be emphasized again that this does not give a solution to the measurement problem: the state of total system (object plus environment) remains a superposition of eigenstates of the preferred observable, and so this observable has no definite value on the object, according to the eigenvector-eigenvalue link. The reduced state of the object is an improper mixture, and so cannot be understood as describing an object which is actually in some (unknown) quantum state for which the preferred observable has a definite value.

Nevertheless, the view is widely shared that taking the process of decoherence into consideration takes us some considerable distance toward a solution of the measurement problem. Butterfield (2001: 14) gives two reasons: First, "the astonishing numbers in these results [describing decoherence rates] liberate us from the traditional aim of getting macrosystems to have definite values for *exactly* the familiar quantities like position." And second, decoherence shows that "orthodox quantum theory on its own brings us close to our goal [i.e. solving the measurement problem]. Roughly speaking, we have only to go a bit further, from an improper mixture to a proper one." That is, we have only to find some some interpretation that will ascribe to an improper mixture the same definite properties that orthodox quantum theory would ascribe to the mathematically identical proper mixture.

4.3 DECOHERENCE, DIAGONALITY, AND DEFINITENESS

The previous section presented the two main results attributed to environmental monitoring, namely the selection of a preferred basis and decoherence with respect to that basis. This section and the one that follows examine claims about the significance of these results, beginning with decoherence.

The most often cited consequence of the process of environmental monitoring is the suppression of interference terms corresponding to macroscopically distinct components of the reduced state of a system. This is the consequence known specifically as decoherence. Decoherence makes the reduced state of the system approximately diagonal in terms of the preferred states. Because of the extreme swiftness with which the off-diagonal terms decay, the mathematical form of the reduced state differs negligibly from a proper mixture of states belonging to the preferred basis (represented by a perfectly diagonal mixture). This formal near-equivalence of the reduced state to an ignorance-interpretable mixture of preferred states brings us tantalizingly close quantitatively to the goal of a description of the apparatus that assigns to it definite value for the preferred observable (see the quotation from Butterfield at the end of the previous section). Not surprisingly, perhaps, decoherence theorists have claimed that this quantitative match with the desired description suffices for at least effective definiteness of the preferred observable.

4.3.1 Diagonality—in Which Basis?

Diagonality with respect to an arbitrary basis cannot be taken to have a fundamental interpretive significance. In general, the reduced state is only *approximately* diagonal in terms of the preferred basis. It will be exactly diagonal with respect to some basis, given by its spectral decomposition. Approximate diagonality will therefore hold for the preferred basis, the eigenbasis of the spectral decomposition, and many other bases. But as we saw in chapter 2, the eigenbasis and the preferred basis are not necessarily close; it is even possible for them to be maximally different. Thus arguments based on diagonality of the reduced state with respect to a particular basis must have some way independent of diagonality of specifying the relevant basis. This could be our interest (as in the Copenhagen interpretation) or the selection of a preferred basis via environmental monitoring (as for Zurek and other decoherence theorists). Zurek emphasizes that instantaneous diagonality or approximate diagonality is not enough; only more or less permanent diagonality with respect to a given basis, and diagonality that occurs for any initial state of the decohering system, will do.

4.3.2 Empirical Indistinguishability

The arguments typically found in the literature concerning the significance of decoherence appeal to the *empirical indistinguishability* of the decohered reduced state from a proper mixture describing an ensemble of identical apparatuses having definite values for the pointer observable.[3] The proper mixture is properly understood as reflecting an ignorance of the actual states (and definite pointer readings) of the individual systems. On the basis of this empirical indistinguishability, the ignorance interpretation is claimed also to be applicable—at least effectively—to the reduced state of the decohered apparatus. In one of his early articles on decoherence Zurek expresses this line of thought in rather strong terms:

> When [the off-diagonal terms] are small, as is usually the case, the density matrix can be thought of as describing the apparatus in a definite state. The probabilities on the diagonal are there because of our (i.e., outside observer's) ignorance about the outcome of the measurement: It is, as yet, unknown to us, but nevertheless it is already definite. . . .
>
> This interaction, equivalent to "monitoring" of the system by the environment, makes the phase between pointer basis states impossible to observe. Thus, the interaction with the environment forces the system to be in one of the eigenstates of the pointer observable, rather than in some arbitrary superposition of such eigenstates. (1982: 1863)

Here Zurek implicitly acknowledges that the apparatus cannot literally be described by a single element of the pointer basis—note his reference to the phase relations between distinct pointer states that are, not nonexistent, but only impossible to observe. In much of the

[3] Janssen (2008) distinguishes between arguments that appeal to statistical equivalence and arguments that adopt an ignorance interpretation of the reduced state of the individual apparatus. In fact I think that these two classes of argument collapse upon examination into a single category. For both arguments purport to establish, on the basis of an (at least implicit) appeal to empirical indistinguishability, the legitimacy of an interpretation of the reduced state licensing the attribution to an individual apparatus of a definite pointer reading. The alleged empirical indistinguishability, if it is not to be based on an assumption of the very definiteness it aims to establish, can only be based on the equivalence with respect to the quantum statistical algorithm between the reduced state and a proper mixture. Thus arguments of both classes ultimately appeal to statistical equivalence.

more recent decoherence literature, this admission is more explicit. The apparatus under consideration is in fact *known* to have no pure state of its own since it is entangled with the environment; the complete description of $\mathcal{S}+\mathcal{A}+\mathcal{E}$ shows the total state to be an entangled superposition that does *not* assign a single pointer state to the apparatus. The interference terms that have disappeared from view given a focus limited to the reduced state of the apparatus come back into view when one steps back to consider the total entangled state.

The notion that the apparatus can nevertheless be "thought of" as "effectively" described by one of the pointer states on the diagonal depends on the equivalence between the reduced state of the apparatus and a proper mixture, with respect to the statistical predictions of quantum mechanics for measurements on $\mathcal{A}$ (or on $\mathcal{S}+\mathcal{A}$) alone. But it is clear that an argument for the conclusion that the apparatus has a definite value for the pointer observable cannot be legitimately based on the quantum statistical algorithm as standardly understood. The statistical predictions of quantum mechanics, given by the Born rule, are standardly understood to be *predictions for the outcomes of measurements*. These predictions *assume* that measurements have definite outcomes—that is, they are predicated on the assumption that measurements give rise to definite pointer readings. In the context of an argument that aims to explain why it is legitimate to attribute a definite pointer reading to a measuring apparatus after a measurement, this assumption implicitly imports an appeal to the very class of facts the argument purports to establish.

Even bracketing this concern about a *petitio principii*, the empirical equivalence argument depends on our inability to measure an observable that would effectively distinguish between the decohered reduced state, with its tiny off-diagonal elements, and the proper mixture, for which all the interference terms are zero. The empirical equivalence argument appeals to the fact that it is effectively impossible to tell the difference via measurement statistics between an ensemble of apparatuses described by a proper mixture of eigenstates of the pointer observable and an ensemble described by a reduced state that is approximately diagonal with respect to the pointer basis. But this does *not* show that an individual apparatus described by a reduced state of this form is actually in an eigenstate of the pointer observable. As long as the eigenvalue-eigenstate link (E-E) is maintained as the principle expressing the relationship between property ascriptions and the quantum state, a definite value for the pointer observable cannot be attributed to an apparatus entangled with its environment. Given their commitment to the ubiquity and significance of such entanglement, it would seem that decoherence theorists can account for the definiteness of pointer readings only if they drop or modify E-E.

The argument from empirical indistinguishability suggests that decoherence theorists are aware of the need for a modified property ascription rule; but it also suggests a strange ambivalence on their part about E-E. On the one hand, the argument is meant to show that the pointer observable has a definite value, at least effectively, despite the fact that the state of the apparatus is *not* an eigenstate. Thus the argument indicates a perceived need to relax or get around the very strict constraint on property attributions imposed by E-E. On the other hand, E-E is a constraint, operating in the background, which decoherence theorists seem to accept: If they were content simply to reject E-E then they could attribute to the apparatus a definite value despite its entangled state, and then the argument from empirical indistinguishability, and the retreat to merely "effective" definiteness, would fall away as unnecessary.[4] The claim to establish only "effective" definiteness seems like a maneuver intended to finesse the issue, allowing decoherence theorists to avoid the implications of E-E for the measurement problem, without having to reject outright this venerable and orthodox principle of interpretation. This seems suspiciously like trying to have it both ways.[5]

4.4 THE PREFERRED BASIS, RECORDS, AND DEFINITENESS

The second main effect of environmental monitoring of an apparatus is the selection of a preferred basis. This preferred basis is selected by the dynamics of the apparatus-environment interaction; it is the basis that is monitored by the environment, i.e., the set of apparatus

[4]Bub expresses a similar thought when he says that the supposition "that a necessary condition for a solution to the measurement problem is the destruction of interference between different pointer-reading states . . . stands and falls with . . . the 'eigenvalue-eigenstate link' " (1997: 221).

[5]I have said that the retreat to "effective" or "apparent" definiteness seems intended to allow decoherence theorists to avoid the implications of E-E for the measurement problem without having to commit themselves to the rejection of E-E. But if they maintain the E-E link and do not posit any new physics (e.g. to induce spontaneous collapse of the quantum state whenever decoherence occurs), then it would be more faithful to their principles to describe the seeming definiteness of pointer readings not as merely effective or apparent but as *illusory*.

states to which the environment becomes coupled. Zurek coined the term "einselection," short for "environment-induced superselection," for this effect. The preferred basis thus picked out is referred to as the preferred basis, the einselected basis, or the pointer basis.

4.4.1 The Pointer Basis and the Possibility of Stable Correlations

Zurek's earliest published work on decoherence (Zurek 1981) opens with a puzzle about the empirical content of a post-measurement entangled state of measured system + apparatus. He emphasizes the freedom one has, mathematically, to expand the post-measurement state in terms of any basis of apparatus states and a set of corresponding relative states of the measured system. Each of these expansions represents correlations between different sets of apparatus states and relative states of the system. All of these expansions are mathematically equivalent, but it seems that only one of them, and only one of the corresponding sets of correlations, could represent the set of possible outcomes for a real measurement—for an experimenter has no corresponding freedom to choose what system-apparatus correlations to consider after a measurement has taken place! Only one particular set of correlations, corresponding to one expansion of the post-measurement state, is available for a given real measurement setup. The puzzle, then, is that it seems impossible to determine, from the post-measurement entangled state alone, just which of the correlations encoded in the post-measurement entangled state will be the correlations actually established. Zurek's central claim is that the puzzle can be solved by considering a model of measurement in which the interaction of the apparatus with an environment is included. The particular dynamics of the interaction between environment and apparatus pick out a unique "pointer basis" of the apparatus. He concludes that the correlations actually established by a measurement are correlations between the apparatus states belonging to the pointer basis, and the corresponding relative states of they measured system. Zurek argues that the resolution of this particular puzzle is directly relevant to a partial solution to the measurement problem as well: "It is the 'monitoring' of the apparatus by the environment which results in the apparent reduction of the wave packet" (1981: 1516). This section examines the details of Zurek's argument.

The puzzle Zurek raises focuses on the fact that a post-measurement entangled state of object system $\mathcal{S}$ and apparatus $\mathcal{A}$ can be expanded in terms of any basis of the apparatus. Suppose that a measurement interaction eventuates in an entangled state in which orthogonal apparatus states $|p_i\rangle$ are perfectly correlated with states $|o_i\rangle$ of the object system:

$$\sum_i c_i \, |o_i\rangle \, |p_i\rangle \, . \tag{4.12}$$

Suppose that the states $|o_i\rangle$ are pairwise orthogonal, so that they are eigenstates of some self-adjoint observable O of $\mathcal{S}$. The above post-measurement state could then be the result of a measurement of O, with the apparatus states $|p_i\rangle$ functioning as pointer states. But the entangled state (4.12) can also be expressed in terms of any other basis $|p'_j\rangle$ of $\mathcal{H}_\mathcal{A}$, as

$$\sum_j c'_j \, |o^*_j\rangle \, |p'_j\rangle \, . \tag{4.13}$$

Here the states $|o^*_j\rangle$ are the states of $\mathcal{S}$ relative to the basis states $|p'_j\rangle$. In general these relative states are non-orthogonal, though they will be pairwise orthogonal in the special case in which all the $|c_i|^2$ of equation (4.12) are equal. In that case, Zurek notes, the correlations represented by expansions of the entangled state in two different bases would correspond to perfect correlations between apparatus states and eigenstates of two non-commuting observables! "Yet we know that quantum mechanics prevents one from measuring simultaneously two noncommuting observables with arbitrary accuracy" (Zurek 1981: 1516).

What determines the proper interpretation of the post-measurement entangled state represented by equations (4.12) and (4.13)? What determines, for example, whether this state actually indicates a perfect correlation between the eigenstates $|o_i\rangle$ and the apparatus states $|p_i\rangle$, or a perfect correlation between the relative states $|o^*_j\rangle$ and the apparatus states $|p'_j\rangle$? The entangled state would seem to encode both these sets of correlations, and infinitely many others; but in real measurements only correlations with a single set of apparatus states seem to be available to the experimentalist. What is the source of this physical restriction that is not encoded in the post-measurement state itself?

Zurek himself formulates the question somewhat differently: He asks, which observable has really been measured on the object system? This way of putting the question is somewhat puzzling, because it amounts to asking how to properly interpret a measurement interaction without specifying the details of the interaction. Zurek points out correctly that the form of the post-measurement entangled state alone does not suffice to determine which observable was measured nor which states of the apparatus are the pointer states corresponding to distinct measurement outcomes. But he ignores the dynamics of the $\mathcal{S}$-$\mathcal{A}$ interaction, which would seem to be essential to the question of what has been measured. Certainly the dynamics of the measurement interaction will suffice to determine whether (4.12) or (4.13) is a more salient expansion of the post-measurement state in the following sense: The dynamics will determine whether the interaction qualifies as an ideal measurement of O, effecting the evolution

$$\sum_i c_i \left|o_i\right\rangle \left|p_0\right\rangle \to \sum_i c_i \left|o_i\right\rangle \left|p_i\right\rangle , \tag{4.14}$$

or (for example) an error-free but disturbing measurement of some other observable Q with eigenstates $|q_j\rangle$, effecting the evolution

$$\sum_j c'_j \left|q_j\right\rangle \left|p_0\right\rangle \to \sum_j c'_j \left|o^*_j\right\rangle \left|p'_j\right\rangle . \tag{4.15}$$

The given post-measurement state (4.12) could be the result of a measurement interaction having either of these forms, or it could be the result of one of many other possible interactions. Zurek's way of formulating the question thus makes it look as though he has left out the information vital to providing the answer.

In fact it seems that Zurek is not really concerned with the question of what has been measured at all, insofar as he is *not* interested in the correlations between the *pre-measurement* state of the measured system and the post-measurement state of the apparatus. He is rather concerned solely with correlations between *post-measurement* states of apparatus and measured system. His question then ought to be not about *measurement* but about *preparation*, since it is *qua* preparation that this interaction establishes correlations between post-measurement states. (An interaction that produces reliable correlations between post-measurement states of apparatus and object system is reliable as a preparation, regardless of whether it also correlates the post-measurement apparatus states with pre-measurement system states. But if it does not do the latter, it is not a reliable measurement interaction.

An ideal measurement interaction produces perfect correlations of both kinds, and so serves as a perfectly reliable means of both preparation and measurement.) Zurek's question could then be posed as: Which expansion of the post-interaction state of $\mathcal{S} + \mathcal{A}$—equation (4.12), or equation (4.13), or some other expansion—specifies the possible results of preparation, and in particular the set of possible prepared states of the object system?

But even this reformulation does not pinpoint Zurek's real concern; he seems to be gesturing at a deeper question. He is concerned with the idea that some way to identify a physically preferred expansion is needed in order to attribute empirical meaning to the entangled post-measurement state. The freedom we have to choose a particular expansion of the post-measurement state seems to be an artifact of the mathematical model that does not reflect a feature of real measurement interactions. For any real measuring apparatus, the range of possible outcomes is fixed, and corresponds to a particular set of definite pointer states that are possible states of the apparatus. An expansion in terms of these pointer states is then salient, while the other mathematically equivalent expansions are not. Zurek's real concern is a general theoretical question about what makes this pointer basis unique. How to account for the fact that a particular pointer basis of the apparatus *is* physically special? Just what is physically special about it?

To resolve the puzzle, Zurek invokes the interaction of the environment with the measuring apparatus. Suppose that after the measurement interaction ends, leaving $\mathcal{S} + \mathcal{A}$ in the entangled state (4.12), the apparatus interacts with its environment $\mathcal{E}$. If the stability condition (4.9) is satisifed for some observable P of $\mathcal{A}$, i.e. if P commutes with the apparatus-environment interaction Hamiltonian $H_{\mathcal{A}\mathcal{E}}$, then this interaction will couple the state of the environment with the eigenstates $|p_i\rangle$ of P while leaving them undisturbed. In that case the environmental interaction will entangle the post-measurement state of $\mathcal{S} + \mathcal{A}$ with the environment, according to

$$\sum_i c_i |o_i\rangle |p_i\rangle |e_0\rangle \rightarrow \sum_i c_i |o_i\rangle |p_i\rangle |e_i\rangle \tag{4.16}$$

In this case then there *is* something mathematically special about a particular expansion. The fact that the environment becomes coupled to the apparatus states $|p_i\rangle$ without disturbing them means that the correlations established by the measurement interaction between these particular apparatus states and the relative states $|o_i\rangle$ of the system are not disturbed; the same correlations between the states $|p_i\rangle$ and $|o_i\rangle$ are represented by the l.h.s. and r.h.s. of equation (4.16). This feature is unique to an expansion in terms of the apparatus states $|p_i\rangle$. In no other expansion are the correlations between the states of $\mathcal{A}$ and $\mathcal{S}$ unaffected by the environmental interaction. Thus for example the l.h.s. of equation (4.16) can be represented in terms of an arbitrary basis of apparatus states $|p'_j\rangle$ and the corresponding relative states $|o^*_j\rangle$ of the object system, but there is no correspondingly simple version of the r.h.s. in terms of states $|p'_j\rangle \neq |p_i\rangle$:

$$\begin{aligned} \sum_j c'_j \, |o^*_j\rangle \, |p'_j\rangle \, |e_0\rangle \rightarrow & \sum_{ij} d_{ij} \, |o^*_j\rangle \, |p_i\rangle \, |e_i\rangle \\ & \neq \sum_j c'_j \, |o^*_j\rangle \, |p'_j\rangle \, |e'_j\rangle \, . \end{aligned} \tag{4.17}$$

The uniqueness of the expansion (4.16) of the entangled state of $\mathcal{S} + \mathcal{A} + \mathcal{E}$ in terms of the pointer basis can be made mathematically precise, for this simple model, via the *tridecompositional uniqueness theorem* of Elby & Bub (1994) (see Bub (1997) for an updated version of the proof). This theorem states that there is at most one expansion of a quantum state on a three-fold tensor product state such as $\mathcal{H}_\mathcal{S} \otimes \mathcal{H}_\mathcal{A} \otimes \mathcal{H}_\mathcal{E}$ that expresses the total state as a tridecomposition, a sum over one index of product states over the three factor spaces. It follows that if a particular basis of apparatus states $|p_i\rangle$ is monitored by the environment according to equation (4.16), then there is no tridecomposition of the total state with respect to any other basis of apparatus states; hence pre-existing correlations between apparatus and environment expressed in terms of other states are destroyed by the interaction with the environment.[6]

[6]The tridecompositional uniqueness theorem provides a clear and immediate proof, in the context of the simple model Zurek considers, that only correlations involving the environmentally monitored states of the apparatus will be preserved under interaction with the environment. But Bub (1997) and Schlosshauer (2004) also appeal directly to this theorem, without reference to stability of correlations, as itself providing a preferred decomposition of the global state and hence a preferred set of apparatus states. They focus on the existence of a unique tridecomposition—or more generally, of an N-decomposition—as a way to eliminate the basis ambiguity Zurek emphasizes in the post-measurement state of an isolated system-apparatus compound. The uniqueness of a tridecomposition or an N-decomposition cannot, however, provide a satisfactory way to specify an interpretation basis. Two reasons are technical reasons regarding tridecompositions (see (Donald 2004)):

- Tridecompositions (and N-decompositions) do not always exist. The theorem states that such a decomposition is unique *if* it exists; but there are states of a threefold compound system for which no

Zurek thus takes the interaction with the environment to pick out a physically preferred basis of the apparatus, the pointer basis, the significance of which is its ability to retain correlations with the measured system despite the interaction with the environment: "The pointer basis of the apparatus $\mathcal{A}$ is chosen by the form of the apparatus-environment interaction: It is this basis which contains a reliable record of the state of the [measured] system $\mathcal{S}$" (1981: 1519). Zurek's focus on the preferred basis, and its significance as the only basis in which correlations are preserved despite interaction with the environment, has remained a consistent thread throughout his writings on environmental decoherence and its significance. (Zurek 1993a; 1998; 2003). No other basis of apparatus states is suitable for recording the state of the measured system—or better, the prepared system—since correlations formed during the $\mathcal{S}$-$\mathcal{A}$ interaction in any other basis are disrupted by the ensuing apparatus-environment interaction.

Also constant throughout his writings is the conviction that by privileging this particular basis, environmental monitoring not only determines which apparatus states can function as records, but also thereby determines which states an apparatus appears to collapse to. From his observation that the pointer basis states *are uniquely suited to serve as records* of the measurement outcome, Zurek apparently concludes that they *do actually so serve*, in the sense that records that result from actual measurements are always instantiated in states belonging to the pointer basis selected by environmental monitoring. In other words, he takes the set of possible outcomes, the set of possible post-measurement (or preparation) states of the apparatus, to correspond to the elements of the pointer basis. Thus in his view environmental monitoring, by specifying the preferred states of the apparatus, solves the puzzle about the empirical content of the post-measurement entangled state: "It is the

tridecomposition exists. There is no reason to expect that for models more realistic than Zurek's, a tridecomposition exists.

- They are also highly unstable—two nearby states of a compound system may have tridecompositions that pick out states on the factor spaces that are far apart. Thus the apparatus states picked out in terms of a tridecomposition could vary wildly as a result of to very small changes in the initial state of the measured system or very small changes in the system-apparatus interaction. Part of the promise of environmental monitoring, by contrast, is that it picks out the same set of preferred states regardless of such variations.

Even apart from these technical considerations, it seems like using the uniqueness of a tridecomposition cannot properly capture what is physically special about states monitored by the environment, since this amounts to using a kinematical criterion to characterize what is really a *dynamical* effect.

'monitoring' of the apparatus by the environment which results in the apparent reduction of the wave packet" (Zurek 1981: 1516).

Schlosshauer (2007) gives a concise summary of Zurek's appeal to the environmental interaction to deal with the interpretational problem of basis ambiguity:

> The stability criterion for pointer states introduced by Zurek means that measurements must be of such a nature as to establish robust records, that is, the system-apparatus correlations ought to be preserved in spite of the inevitable interaction with the surrounding environment . . . . The "user" cannot choose the observables arbitrarily, but must design a measuring device whose interactions with the environment is such as to ensure stable records (which, in turn, defines a measuring device for this observable). In the reading of orthodox quantum mechanics, this can be interpreted as the environment determining the properties of the system. (p. 334)

It is this very last step—the inference from environmentally-induced restrictions on the possibility of stable records to environmentally-determined properties, that requires further scrutiny. Certainly experimenters who want to perform reliable measurements will *want* the definite properties of their apparatuses to coincide with the states stable under environmental monitoring. But why think that nature should grant their wish?

4.4.2 Stability of Correlations as a Constraint on Definiteness

Zurek's account of the way in which environmental monitoring privileges a particular basis of apparatus states in this model, and his characterization of this pointer basis as the only basis in which correlations with the object system are preserved despite the interaction with the environment, are faultless. But his claim that *environmental monitoring results in apparent collapse*—he clearly means an apparent collapse to one of the states in the pointer basis—does not follow. There is a serious gap in his argument here.

What his argument actually establishes is that the environmental interaction selects a unique pointer basis, and hence a unique expansion of the total state. This expansion is special because it is the only expansion in which the original, pre-environmental interaction correlations are preserved. But some additional argument or explanation is needed why this preservation of correlations should have the implication or the result that the terms in this expansion correspond to the empirically possible results of measurement. In other words, an argument is needed that the uniquely selected pointer observable will have a definite value after the measurement. That these preferred basis states are the only states for which correlations with the measured system are preserved under environmental monitoring of the apparatus does not obviously imply that these preferred basis states should correspond to the possible post-measurement physical states of the apparatus. An explanation of (the appearance of) collapse requires an explanation for why the measuring apparatus should (appear to) end up in one of a particular set of alternative states.

The only justification Zurek gives in his earliest papers (1981, 1982) is an appeal to the diagonality of the reduced state with respect to the preferred states. Due to entanglement with the environment, the only available description of the $\mathcal{S}+\mathcal{A}$ compound is by means of a reduced state diagonal in terms of the preferred states of the apparatus and the corresponding relative states of the system:

$$\rho^{\mathcal{S}\mathcal{A}} = \sum_i |c_i|^2 \left|o_i\right\rangle \left\langle o_i\right| \left|p_i\right\rangle \left\langle p_i\right| . \tag{4.18}$$

But as discussed above (section 4.3) such diagonality is not sufficient to show that the states on the diagonal correspond to the possible definite outcomes of the measurement interaction.

Bub (1997: ch. 5) gives a better account of the relevance of Zurek's pointer basis to definite measurement outcomes. Bub agrees that the environmental monitoring described by Zurek picks out a unique observable of the apparatus, and that the eigenstates of this observable are uniquely suited to function as records or indicators of measurement results. Bub also agrees that we have compelling reasons to think that for real-world measuring apparatuses, the observables picked out by the environment in Zurek's sense do in fact coincide with the actually determinate observables of the apparatuses.[7] Bub thus agrees with Zurek that the physical pointer basis of a real-world apparatus can be characterized as the set of states that preserve correlations with the measured system in spite of interaction with the environment. What Bub specifically *rejects* is Zurek's claim that environmental monitoring "results in the apparent reduction of the wave packet"; in other words, Bub denies that environmental monitoring can explain why the preferred observable has a definite value.

[7]Bub actually says that the determinate observable could be either the environmentally preferred observable R "or an observable in terms of which R is defined by coarse-graining" (1997: 160) To simplify the discussion I ignore the latter possibility in the main text.

Instead, the fact that we can construct measuring devices that reliably indicate the state of a measured system shows that the definite observables of real-world apparatuses *do* in fact coincide with Zurek's environmentally-privileged observables. If they did not—if the apparatus observables monitored by the environment did not correspond to definite observables—then reliable measurements would be impossible since correlations between measured system and apparatus would immediately be disrupted by the apparatus-environment interaction. But on Bub's view, the fact that determinate observables do coincide with Zurek's environmentally privileged observables is just a convenient contingent fact about our world:

> What we require for an interpretation of quantum mechanics is the stipulation of a *suitable* preferred determinate observable or set of observables that will yield an interpretation of the processes we regard as measurements in terms of the distributions of pointer readings. The sort of environmental monitoring that happens to occur in our universe guarantees the existence of such preferred determinate observables, and also narrows the range of possible choices. So it is a contingent matter that measurements are possible in our quantum world. But environmental monitoring cannot make an indeterminate observable determinate through the process of decoherence. (Bub 1997: 159)

If one is going to stipulate a determinate observable, an observable that all measurement outcomes are recorded in, then the fact that we can (in some cases) establish perfect correlations between states of a measured system and a record observable, narrows the choice of the determinate observable (for an apparatus at least) to the environmentally preferred observable (or a fine-graining of it).

Thus Bub argues that decoherence serves to provide a constraint on interpretations of quantum mechanics: to be empirically adequate, an interpretation must declare environmentally monitored observables to be determinate. This is a clear and well-motivated role for decoherence with respect to interpretation, but it seems to fall rather short of the role that decoherence theorists like Zurek ascribe to decoherence. For Bub, the task of interpreting quantum mechanics involves putting in definiteness in by hand, by *stipulation*; decoherence theorists typically claim that (at least apparent) definiteness can be *explained* by appeal to decoherence, on the basis of the quantum formalism alone. One consideration that might nurse their conviction is that on Bub's view, the coincidence between environmentally monitored observables and determinate observables is just that—a coincidence, a lucky break for physicists who want to establish reliable correlations between measured systems and apparatus pointers. One could simply accept this coincidence as a contingent fact about the world, as Bub does; but one could also insist that the accord between definiteness and stability cannot simply be a cosmic coincidence, and cherish the conviction that it indicates a deeper connection between definiteness and the preferred basis.

Zurek and other decoherence theorists are convinced that there *is* a deeper connection between definiteness and the preferred basis selected by environmental monitoring. The question remains, however, just what this connection is. Bub represents one extreme: There is no intrinsic connection between definiteness and preferredness; they merely happen to coincide. Considerations of empirical adequacy force us to recognize the definite observables (at least on real-world apparatuses) do in fact coincide with the preferred observables, but this is just an accident of our world. The opposite extreme would take definiteness to be a direct *consequence* of preferredness. The view suggested by the writings of Zurek and other decoherence theorists seems to be that at least *apparent* definiteness is a consequence of preferredness. The next section turns to a consideration of Zurek's argument for this claim, based on the restrictions placed on records by environmental monitoring.

4.4.3 Environmental Monitoring, Records, and Observers

Zurek sees definiteness of certain properties as something to be extracted from the formalism of quantum mechanics and the phenomenon of environment-induced decoherence, rather than something to be added to the formalism by stipulation, as on Bub's view. A prominent strand in Zurek's writings about the significance of decoherence is a broadly Everettian approach, according to which the question of which properties are definite is to be answered by appeal to the appearances available to observers who are themselves quantum systems. A recurring theme in Zurek's writings is that it is only appropriate to seek to account for the way the world appears by seeking to understand the view of the quantum world from inside:

> The perception of unique events can be accounted for naturally from within the framework of decoherence. All of the arguments against decoherence . . . express dissatisfaction with it because it does not force all of the wavefunction of the universe into a unique state corresponding directly to our experience. Rather, it explicitly assumes that the observers are an integral part of the universe and analyzes the measurement-like processes through which perception of the familiar classical reality comes about, thus showing why one can be aware of only one alternative. . . .

> In the quantum setting the observer must be demoted from an all-powerful external experimenter dealing *from without* with one more physical system (the universe) to a subsystem of that universe, with all of the limitations arising from such a confinement to *within* the physical entity he or she is supposed to monitor. Correlation—between the memory of the observer and the outcomes (records) of the past observations—emerges as a central concept. (Zurek 1993b: 88)

In the specific context of the measurement problem, this Everettian approach requires the adoption of a reversed perspective when asking why certain states of a measuring apparatus are privileged; instead of their special role with respect to the measured system, this approach prompts a focus on their special role with respect to the observer. But there is also a close relationship between the approach pursed in the context of the relationship between measured system and apparatus, and the relationship between apparatus and observer. For in both cases Zurek takes the existence of stable correlations to be central, and so the restrictions imposed by environmental monitoring on the possibility of stable correlations will again take center stage.

Zurek's point about the limitations imposed by environmental monitoring on the possibility of stable correlations between measuring apparatus and measured system can be generalized. When any system is subject to environmental monitoring, the only correlations with other systems that can be stably maintained are correlations between the states monitored by the environment and states of the other system. To see this, let $\mathcal{A}$ be a system subject to decoherence and $\mathcal{B}$ a system it interacts with. Let $|a_i\rangle$ be the states of $\mathcal{A}$ monitored by the environment. Suppose that at some moment the joint state of these two systems is an entangled pure state,

$$|\Psi\rangle = \sum_i c_i \, |a_i\rangle \, |b_i\rangle = \sum_i c'_i \, |a'_i\rangle \, |b'_i\rangle \,, \tag{4.19}$$

where the states $|b_i\rangle$ and $|b'_i\rangle$ are relative states of $\mathcal{B}$. Then the interaction between $\mathcal{A}$ and its environment $\mathcal{E}$ will almost immediately lead to an entangled state of $\mathcal{A}+\mathcal{B}+\mathcal{E}$ of the form

$$\begin{aligned} |\Psi\rangle &= \sum_i c_i \, |a_i\rangle \, |b_i\rangle \, |e_i\rangle \\ &\neq \sum_i c'_i \, |a'_i\rangle \, |b'_i\rangle \, |e'_i\rangle \,. \end{aligned} \tag{4.20}$$

Therefore the only correlations between $\mathcal{A}$ and $\mathcal{B}$ that are preserved in spite of environmental monitoring are correlations between the particular states of $\mathcal{A}$ monitored by the environment and the corresponding states of $\mathcal{B}$. Quite generally, then, the only stable correlations between a system $\mathcal{A}$ subject to environmental decoherence and other systems will be correlations involving the states of $\mathcal{A}$ that are monitored by the environment.

In the special case in which $\mathcal{A}$ is a measuring apparatus and the correlations of interest are correlations with a measured system, then this general conclusion becomes the conclusion of Zurek (1981) discussed above in section 4.4.1: stable correlations between measured system and apparatus are only possible if these are correlations involving the apparatus states monitored by the environment. If on the other hand $\mathcal{A}$ is some (perhaps macroscopic) system on which a measurement is performed, and the correlations of interest are correlations between the measured system $\mathcal{A}$ and the measuring apparatus, then we see that the same restriction on stable correlations applies to the states of a measured system if it is subject to decoherence: stable correlations between measured system and apparatus are possible only if these are correlations involving the states of the measured system that are already monitored by the environment. If both measured system and measuring apparatus are subject to decoherence, then only correlations between the environmentally monitored states of both systems can be stable under the interaction with the environment.

To derive consequences for appearances from this restriction imposed by the environment on the possibility of correlations between measured system and measuring apparatus, Zurek considers the case when an observer takes the place of the measuring apparatus. He asks what information observers can acquire about decohering quantum systems, by modeling observers as record-keeping quantum systems themselves subject to decoherence, and considering the consequences that environmentally-induced restrictions on stable correlations will have for the records that represent observers' experiences and memories. The observer possesses a record of the state of some observed object insofar as the state of the observer (more precisely, the state of the subsystem that functions as the observer's memory) is correlated with the state of the object. This makes the restrictions on stable correlations imposed by environmental monitoring immediately relevant. If both the observer's memory and the system observed are subject to decoherence, then only correlations between the environmentally monitored states of both systems can be stable under the interaction with the environment.

A brief comment on Zurek's focus on *correlations* as opposed to *states*: Zurek says that the restriction on stable correlations that results from environmental monitoring encapsulates the significance of the preferred states of a decohering system. He goes so far as to elevate this restriction to the status of a definition of the set of preferred states: "The ability to retain correlations is the defining characteristic of the preferred 'pointer' basis of the apparatus" (Zurek 1998: 1798). He even says that his own discussion of the significance of the preferred states of a system should properly be framed in terms of correlations, rather than states: "We shall use a shorthand, talking about states, while the real story is played out at the level of multipartite correlations. We assume the reader will continue to translate the shorthand into the 'full version'" (Zurek 1998: 1808). But, tellingly, Zurek does not, to my knowledge, himself actually give the "full version," and frame the discussion strictly in terms of correlations, in any of his writings. His discussions always emphasize as well the stability of environmentally monitored *states* under the interaction with the environment; the unique ability of these preferred states to remain stably *correlated* with states of other systems can then be quite naturally explained in terms of the unique stability of these states themselves. So despite his repeated insistence that it is the possibility of stable correlations that is of primary interpretive significance, I will here follow Zurek's example in focusing on the stability of the preferred states of a decohering system, as well as on stable correlations.

The primary thing to focus on here is the differential effect of environmental monitoring on preferred states $|p_i\rangle$ of a decohering system $\mathcal{A}$ as compared to superpositions of preferred states. The preferred states, the ones the environment monitors in the sense that its state becomes coupled to them, do not become entangled with the environment under this monitoring. These states are then unaffected by the environmental monitoring:

$$|p_i\rangle\,|e_0\rangle \rightarrow |p_i\rangle\,|e_i\rangle\,. \tag{4.21}$$

Arbitrary superpositions in $\mathcal{H}_{\mathcal{A}}$ of preferred states, on the other hand, are immediately transformed into entangled superpositions in $\mathcal{H}_{\mathcal{A}} \otimes \mathcal{H}_{\mathcal{E}}$:

$$\sum_i c_i\,|p_i\rangle\,|e_0\rangle \rightarrow \sum_i c_i\,|p_i\rangle\,|e_i\rangle\,. \tag{4.22}$$

One way of expressing this difference is to say that for a system $\mathcal{A}$ subject to decoherence, superpositions of preferred states of a decohering system do not persist *as states in* $\mathcal{H}_\mathcal{A}$ for times longer than the decoherence timescale.

This has immediate consequences for the question of how an observation of a decohering system can be represented. The first obvious consequence is a restriction on the states of the observer's memory that can serve as records: Records cannot persist for times longer than the decoherence timescale unless they are stored in preferred states, so a record of the state of an observed system must take the form of correlations between the observed system and the preferred states of the memory of the observer. This has consequences for perceptions as well as for long-term memories, as superpositions of preferred states are too short-lived even to represent perceptions:

> Only states that can continue to define both the observers and the state of their knowledge for prolonged periods (at least as long as the characteristic information processing time scale of the observer's own nervous system—which, for us, is more than a millisecond, orders of magnitude longer than a macroscopic open system typically takes to decohere—will correspond to perceptions. (Zurek 1993b: 88)

A second consequence is a restriction on the states of the object the observer can maintain records of. Consider a decohering system $\mathcal{A}$ and an observer $\mathcal{O}$, who observes $\mathcal{A}$ via a measurement-like interaction. What states of $\mathcal{A}$ can $\mathcal{O}$ record? A number of decoherence-related considerations strongly suggest that an observer will only be able to record the preferred states of $\mathcal{A}$:

- Only the preferred states of $\mathcal{A}$ persist as states in $\mathcal{H}_\mathcal{A}$; superpositions of preferred states are immediately re-prepared, i.e. transformed into entangled superpositions in $\mathcal{H}_\mathcal{A} \otimes \mathcal{H}_\mathcal{E}$, on timescales much shorter than those required for a macroscopic observer to form a record of the state of $\mathcal{A}$. So only preferred states persist long enough for observer to form a record of them.
- Observers' interactions with measured systems are presumably limited to a relatively small set of possible interaction Hamiltonians, sensitive to the same quantities monitored by the environment; for both kinds of interactions are governed by the fundamental laws of physics, in which particular quantities—notably position—play a distinctive role. Hence even if a superposition of preferred states did persist in $\mathcal{H}_\mathcal{A}$ for long enough to

be observed, it seems that an observer would still be unable to record the presence of such a superposition. (Even if an object did exist in a superposition of states of macroscopically distinct positions, for example, how would that be directly recorded? Even in the laboratory, complicated superpositions of distinct position states are not detected directly by measuring an observable with such complicated superpositions as eigenstates. Instead, such superpositions are inferred from statistics showing interference effects that are gathered via repeated position measurements.)

- Much of the information an observer acquires about a macroscopic system is acquired by intercepting a portion of the environment and reading off the information it carries about the state of the system. This is how vision works, for example. This method only allows the observer to get information about the monitored observables because information about superpositions thereof is not recorded in the environment—in particular not in small pieces of the environment—but only in the system-environment superposition. (Zurek uses the phrase "environment as a witness" to refer to this role of the environment.)

These considerations rely at least implicitly on the fact that the observer's observations are *local*, in the sense that the observer's interaction with the rest of the universe is limited to interactions with states in restricted parts of Hilbert space. The observer can perform measurements on macroscopic systems such as $\mathcal{A}$, or on small parts of the environment, but cannot perform the kind of measurements on the entire $\mathcal{A} + \mathcal{E}$ compound required for recoherence between distinct preferred states of $\mathcal{A}$.

Thus, when an observer $\mathcal{O}$ records the state of a decohering system $\mathcal{A}$, it seems that the only states that the observer's records can become correlated with are the preferred states $|p_i\rangle$ of $\mathcal{A}$:

$$\left(\sum_i c_i \, |p_i\rangle \, |e_i\rangle\right) |o_0\rangle \to \sum_i c_i \, |p_i\rangle \, |e_i\rangle \, |o_i\rangle \, . \tag{4.23}$$

It is here, at last, that the primary significance of decoherence-imposed restrictions on the states available to a system can be found: the environmentally preferred states of a system are the only states that can be recorded by an observer. It is noteworthy that this consequence follows from the conjunction of two related but distinct limitations. One is a limitation, imposed by environmental monitoring, on the pure states that can exist within $\mathcal{H}_{\mathcal{A}}$: Only the preferred states of $\mathcal{A}$ can persist for longer than the decoherence timescale without becoming re-prepared by the environment. The other is a limitation on the interactions by which the coupling between $\mathcal{A}$ and $\mathcal{O}$ can be established: Because the measurement-like interaction by which the observer forms a record of the state of $\mathcal{A}$ is slow compared to the decoherence timescale; because it depends on the same laws of physics governing environmental monitoring and hence will be sensitive to the same quantities; and because it may even be mediated by the environment's role in broadcasting the monitored states of the system, the observer can only record the preferred states of $\mathcal{A}$.

As a consequence of these limitations, imposed by environmental monitoring, an observer's records (where these include memories stored in parts of the brain that encode memories as well as records stored in inanimate systems like notes on paper or in computer files) can only contain information about preferred states of other systems subject to decoherence, not about superpositions of preferred states. These limitations on observers' physical records imply limitations on what observers can perceive, since an observer's perceptions of the physical world are mediated by the observer's physical state, specifically the state of the observer's sensory and neural systems. And so, the argument goes, an observer can never perceive any macroscopic object in a superposition of preferred states. Only the states monitored by the environment are states accessible to observers. These states will be extremely well localized in position, since due to the nature of the fundamental forces involved in the system-environment interaction, the environment will always be extremely sensitive to the position of a macroscopic system. And thus, by considering the possible correlations between observers and decohering systems, we can see why preferred states of a system should, as a consequence of environmental monitoring, appear to be definite: these are the only states that can "appear" to observers at all.

4.5 OBSERVERS AND (APPARENT) DEFINITENESS

Decoherence theorists thus appeal to environmentally-imposed limitations on correlations between observers' records and decohering systems to explain why environmental monitoring of a given set of states of a macroscopic system should result in the *apparent* definiteness of the monitored states. This ultimate appeal to what observers will see, as the origin of apparent definiteness, prompts a question about the role of the observer, and in particular the role of consciousness, in the explanation. Does the appeal to what observers will perceive imply that consciousness is playing a crucial interpretive role in the explanation? To ask the same question in another way, can decoherence account for apparent definiteness without appealing to consciousness? Many authors, both advocates and critics of decoherence-based solutions of the measurement problem, say that appeals to consciousness are essential to any such solution.[8] I will argue here that this is incorrect.

A standard version of the view that an appeal to consciousness is essential to an interpretation of quantum mechanics (see, e.g. Lockwood (1996), who presents a very clear version of the view, albeit one in which decoherence plays a relatively small role) says that as long as universal Schrödinger evolution is insisted upon, the systems that appear to us to have definite states—apparatuses that seem to have definite pointer readings, tables and chairs that seem to have definite positions in space—are always entangled with their environments. They do not have pure states of their own and *a fortiori* they do not occupy eigenstates of the particular observables for which they appear to have definite values. Hence they cannot accurately be said to possess definite values for the observables that nevertheless appear definite. Definiteness arises only as an appearance in the mind of an observer whose state becomes correlated with the state of the system. Typically the introduction of the mind or consciousness is fleshed out in terms of a multiplicity of minds or conscious experiences for each physical observer; one mind (or experience) is associated with each element of a particular basis of brain states, so that even when an observer's brain is described—as it will inevitably be—by a complex entangled superposition of states associated with distinct

[8] Zeh (2000) is a prominent advocate of the decoherence approach who says that a many-minds interpretation of quantum mechanics is the the only interpretation consistent with the assumption of universal Schrödinger evolution. Leggett (2002) and Landsman (2009) are critics who express the same thought.

conscious experiences, a distinct mind is separately conscious of each one corresponding experiences. Decoherence, or rather environmental monitoring, enters the story essentially as discussed above in section 4.4.3: it imposes restrictions on which states of the brain can correspond to conscious perceptions and on the states of external objects that can be recorded by these brain states.

My view, in brief, is that if this is not merely to be a case of *obscurum per obscurius*—In this context, I mean for example an explanation of perceived definiteness (as in Lockwood (1996)) by the mere claim that there is *some* (unspecified, unknown) basis of brain states that corresponds to the consciousness basis—then there must be some reason for saying that the distinct conscious states of the observer must be environmentally monitored states. The reason typically invoked: *these evolve autonomously*, and so are suited to serve as alternative evolving descriptions of an observer's conscious state. But to make this move is either to postulate some kind of dualism—which again qualifies, in this context at least, as a case of *obscurum per obscurius*—or to claim that there is an exception to the standard line above, insofar as an observer can have a definite conscious experience (or many alternative experiences, in many different minds) even when the global quantum state is a superposition of brain states associated with different experiences. To put it another way, even when the global state is an entangled superposition, an observer can have a conscious experience associated with an (autonomously evolving) brain state within a single branch. This is essentially adopting the branch-relativity of property ascriptions for brain states, at least with respect to this individual property. But if autonomously evolving branches justify the adoption of this non-standard interpretational maxim with respect to (certain properties of) brain states, it seems that the same autonomous evolution of branches will justify applying the maxim more generally. But then there is room to say that e.g. measuring devices actually *possess* definite pointer readings, they don't just *appear* to possess them. The appeal to consciousness will then be unnecessary; branch-relativity of property ascriptions allows us to say that objects *appear* to have definite properties (within a given branch) because they *do*.

In short: the appeal to consciousness is either an appeal to something outside the realm of physics, in which case this amounts to a tacit admission that physics can't solve the problem of definiteness, with or without decoherence, or the appeal to consciousness involves a tacit relaxation of E-E (accepting instead an Everettian branch-relative property ascription rule—though perhaps not necessarily a rule according to which all branches are equally real). But if one is prepared to relax E-E in this way—as one *must* be, if a a solution to the measurement problem in a no-collapse interpretation is to be possible—then one can simply apply the relaxed rule more generally, thus securing the actual, and not merely apparent definiteness of properties.

A similar conclusion can be reached by considering the interaction between any two macroscopic objects. The way an object appears to an observer depends crucially on the ways that an observer can interact with, and hence become entangled with, an object. Decoherence imposes severe restrictions on the particular interaction and the possible resulting correlations. But the same goes for any interaction between one object subject to decoherence and another—the state of the one will only be able to become correlated with the preferred states of the other. Thus distinct preferred states of a single system both evolve independently of each other and affect the states of other systems differently. Thinking of these states as representing the real physical states—taking them to pick out a preferred basis—no longer seems like an arbitrary choice or one made just to get the right answer. The environmentally monitored states of a system are physically preferred in the sense that the future evolution of a system, and the ways in which it will affect the evolution of other systems it interacts with, are determined by the evolution of these states. Unlike an arbitrarily chosen pure state, these preferred states are dynamically autonomous; they have trajectories; they are states which can be thought of as having physical significance in their own right.

I take this dynamical independence of distinct environmentally monitored states to be the core, the fundamental effect of environmental monitoring. It is remarkable how seldom it is mentioned in the decoherence literature. One can find clear statements of it, but they arise most often in discussions of consciousness, specifically as part of Everett's argument that the independent evolution of distinct states of the observer—where the relevant observer states are here taken to be picked out by, and their independent evolution a result of, environmental decoherence—prevents the observer described by one of them from becoming aware of the existence of the other. In most of the decoherence literature, more emphasis is placed on *effects* of this dynamical autonomy of environmentally preferred states—approximate diagonality of the reduced state of a system with respect to macroscopic observables, preservation of correlations, the impossibility of detecting superpositions of preferred states—than on the dynamical autonomy itself.

> Each time the system of interest (or the memory of an apparatus, computer or nervous system) is forced into a superposition that violates environment-induced superselection rules, it will decohere on a time scale that is nearly instantaneous when the options are macroscopically distinguishable. This onset of decoherence is the apparent "collapse of the wavepacket." Thereafter each of the alternatives becomes a 'matter of fact' to the observer who has recorded it: *It will evolve on its own, with negligible chances of interference with the other alternatives*, but with the correlation of the records with all the relevant states of the measured observables intact. (Zurek 1993b: 90, emphasis added)

4.6 WHAT DOES DECOHERENCE ACCOMPLISH?

There are three fundamental lessons to be drawn from an examination of decoherence and its role in securing definite measurement outcomes, and more generally, the observed definite properties of macroscopic systems. First, the set of possible "effective" states of a system described by a (possibly entangled) superposition is determined by the dynamics governing that system. *Evolving independently* of other components, in the sense of non-interference, is what characterizes one component of a superposition as a physically meaningful state—an evolving state of the system in its own right, whether this is understood to mean that such a state is actual, effective, or merely possible. The physics of macroscopic objects in our world is described by an Everettian branch (though it is always possible for the evolution of states of these objects to be affected by the presence of other branches in the global quantum state in the very unlikely event of interference between branches). What is required then for the definiteness of a particular quantity is the "dynamical decoupling of components"(Zeh 1970) of the global quantum state representing different values of that quantity. And securing the dynamical decoupling of the appropriate components is what decoherence accomplishes—*this* is its role in contributing to a solution of the measurement problem.

Second, accounting for the definiteness of familiar properties requires a modification of the E-E link, in the form of an Everettian interpretation of quantum mechanics (the branch-relativity of property ascriptions). Tentative adherence to a modified property ascription rule of this form is already implicit in much of what decoherence theorists have to say.

Third, nature places severe restrictions on the way systems can interact; only a limited variety of interaction Hamiltonians are achievable. Contrast this with classical philosophical discussions of measurement problem that often assume any observable can be measured.

These three insights alone already make it possible to explain why observers—and indeed other objects!—don't 'observe' macroscopic objects in complicated superpositions of position, and even why objects can have definite properties despite entanglement with other systems. There is no essential reference to the environment in these insights. Specifying these central ideas without reference to environment, helps to make clear what the role of the environment really is; it clears the way for *showing* that environmental monitoring will be absolutely crucial to e.g. definiteness of properties, without having simply to *stipulate* that definiteness is directly tied to what the environment happens to monitor.

What makes the environment of a macroscopic system special with regard to effecting the relevant dynamical decoupling is first, the *speed and effectiveness* of its coupling to a macroscopic system, which entails that a superposition of environmentally-preferred states almost instantaneously becomes entangled with the environment. The second relevant feature is its vast *complexity*. The vast size of the environment makes it exceedingly likely that a randomly distributed set of states will be, and will remain practically forever, almost orthogonal to each other. This entails that environmentally selected states evolve independently of each other, i.e. interference between them is negligible, and that the entanglement is effectively irreversible ('recoherence' is impossible). The result: an Everettian branching tree structure (branching with no recombination.) Third, the *continuous* nature of the environment's interaction with the system means that the independent evolution of preferred states is enforced at all times, and not merely at a discrete set of observation times as in Everett's picture.

5.0 CONCLUSION

I have argued in the preceding chapters that the significance of environmental decoherence for the emergence of definite properties is properly understood in terms of the dynamical independence of components of the global quantum state. The interaction between a macroscopic system and its environment results in the dynamical decoupling of components of the global quantum state corresponding to distinct values of the environmentally monitored observable of the macroscopic system. Henceforth these components of the global quantum state are dynamically independent of one another; interference between them is negligible, so that each one can be considered to evolve autonomously. That effecting this dynamical decoupling is the crucial role of the environment in the emergence of a classical world is not a new suggestion; indeed, the terminology of "dynamical decoupling" comes from Zeh (1970), which is often cited as the earliest paper belong to the literature on the modern notion of decoherence. But it is an idea that has been neglected, de-emphasized, and obscured in a great deal of the decoherence literature.

This neglect can be explained in part by the historical facts about how the decoherence program became widely known: Zeh's writings in the 1970's on what would later come to be called decoherence attracted little interest. Only in the 1980's, after two pioneering papers by Zurek (1981, 1982), did the study of decoherence and its relevance for the measurement problem begin to receive serious attention from a number of physicists. Zurek also played the primary role in bringing decoherence to the attention of the wider physics community, through his 1991 article in *Physics Today*. Unlike Zeh, Zurek does not emphasize the dynamical independence of components of the global quantum state. As discussed in chapter 4, his explanations of the significance of decoherence for the observed definiteness of familiar macroscopic observables characteristically focus on the diagonality of the reduced state of a decohering system and especially on the stability of correlations with respect to the environmentally monitored states. This difference in focus is probably responsible, in part, for the difference between the initial receptions of their views: Zeh's writings on decoherence, which emphasize interpretational issues and insist that the only no-collapse interpretation compatible with decoherence is an Everettian many-minds interpretation, did not attract the interest of the physics community at large as much as Zurek's writings, which by contrast emphasize the "operational" significance of decoherence and are much less committal on questions of interpretation.[1]

Although I agree with Zeh that the significance of decoherence is properly understood in terms of the dynamical independence of certain components of the global quantum state, I disagree with his contention that the only way to account for the definiteness of familiar observables without positing collapse is via a many-minds interpretation. I explained in chapter 3 why an appeal to consciousness to account for the appearance of definiteness is unnecessary: Zeh says that "Superposed world components describing the registration of different macroscopic properties by the 'same' observer are dynamically entirely independent of one another: they describe *different* observers" (Zeh 1993: 191). But the same dynamical independence holds already for the superposed world components describing different macroscopic properties of any object subject to decoherence. If we are willing to adopt an interpretive principle according to which the dynamical independence of a particular component allows us to say that this component can describe a real observer, who has definite conscious experiences, despite the fact that the global quantum state is an entangled state of observer and the rest of the world, then the same interpretive principle should be applied also to physical systems other than observers and properties other than consciousness.

As for the thesis, common to many-minds and many-worlds interpretations, that all components of the global quantum state are equally real, this also seems unnecessary as far as accounting for the definiteness of familiar observables is concerned. If we take the dynamically independent components of the global state to be the physically relevant ones, to hold this thesis is to say that there are as many actually existing "versions" of an object

[1]For a detailed study of the parts of Zeh and Zurek in the rise of the decoherence program, and discussion of their views regarding interpretation, see Camilleri (2009).

as there are dynamically independent components of the global state representing different properties of that object. On this view an object can have definite properties, even if the global state is an entangled superposition of object + environment. But even on this view, the properties possessed by (a particular version of) an actual object are entirely determined by the single component of the global state that describes it—hence its having definite properties does not depend on the thesis that alternate versions of that object represented by other components of the global state are equally real. As far as definiteness is concerned, it suffices to hold instead that only *one* of the dynamically independent components describing different macroscopic properties of an object characterizes an *actual* object, with all the rest representing merely *possible* objects. What distinguishes such an interpretation from a collapse interpretation is that it maintains at all times the unitarily evolving global state, so that interference between the actual (or inhabited) component and other components is possible. The interpretation I am suggesting is in effect a modal interpretation, according to which the set of possible value states of a given system are given by the set of dynamically independent components of the global quantum state.

It may be helpful here to draw an analogy between the interaction of a macroscopic object with its environment and a preparation interaction. The interaction between object and environment couples the state of the environment to certain components $|p_i\rangle$ of the object's initial state $\sum_i c_i |p_i\rangle$, resulting an entangled state $\sum_i c_i |p_i\rangle |e_i\rangle$ in which the components corresponding to distinct values of i can no longer interfere with each other—the states $|p_i\rangle$ monitored by the environment have become dynamically independent as a result of their entanglement with the environment. This is analogous to the preparation of a spin-$\frac{1}{2}$ particle by passing it through a Stern-Gerlach magnet. If the magnetic field is inhomogeneous along the z axis, the particle's passage through it couples its position with the components $|+\rangle$ and $|-\rangle$, corresponding to eigenstates of spin-z, of its initial spin state $c_+ |+\rangle + c_- |-\rangle$. The result is the entangled state $c_+ |+\rangle |\phi_+\rangle + c_- |-\rangle |\phi_-\rangle$, where $|\phi_+\rangle$ and $|\phi_-\rangle$ are approximately orthogonal states representing the position of a particle exiting the magnetic field along an upper path and a lower path, respectively. As a result of this entanglement, the two spin states $|+\rangle$ and $|-\rangle$ can no longer interfere with each other; they are dynamically independent unless and until the position states coupled to them evolve so as to have significant overlap.

Standard laboratory practice attributes to a particle emerging from the magnetic field along the upper path the pure spin state $|+\rangle$. Implicit in this practice is *the supposition that the particle does follow one path or the other*, in other words, the supposition that the particle has a well-defined position—even though its state is an entangled superposition of states representing widely separated positions. The interpretation that I am suggesting would declare this supposition legitimate: the two dynamically independent components of the entangled state, $|+\rangle|\phi_+\rangle$ and $|-\rangle|\phi_-\rangle$, represent the two distinct possible value states of the system; their probabilities are given by the squares of their respective amplitudes, $|c_+|^2$ and $|c_-|^2$. In the same way, for a decohering system entangled with its environment, the dynamically independent components $|p_i\rangle|e_i\rangle$ of the entangled state represent the distinct possible value states of system + environment; the probability of each possible value state is the square of the corresponding amplitude, $|c_i|^2$.

The modal-dynamical interpretation I am suggesting here is an attempt to accord environmental decoherence interpretive significance by embedding it in a more general interpretive framework. An advantage of this general framework is that, as just outlined, it would allow definite properties to be attributed to isolated microscopic systems in some cases, such as the preparation situation discussed, on the basis of the same general principles allowing definite properties to be attributed to macroscopic systems subject to decoherence. I think we should expect any acceptable account of the role of decoherence in the emergence of definite properties to have an impact in a similar way on how we conceive of superpositions and entanglement even in the microscopic realm.

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