On the End of a Quantum Mechanical Romance

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ABSTRACT: Comparatively recent advances in quantum measurement theory suggest that the decades-old flirtation between quantum mechanics and the philosophy of mind is about to end. Various approaches to what I have elsewhere dubbed 'interactive decoherence' promise to remove the conscious observer from the phenomenon of state vector reduction. The mechanisms whereby decoherence occurs suggest, on the one hand, that consciousness per se has no role in explaining the outcomes of quantum events and, on the other, that perhaps apart from questions about the very lowest level properties of minds' instantiating hardware or wetware, the unique features of quantum mechanics are utterly irrelevant to the philosophy of mind. Here we explore a better account of interactive decoherence than I have offered elsewhere, make explicit the argument for irrelevance, and address some unanswered questions and an interesting objection against the formulation of decoherence on which our discussion is based.

1. Introduction

1.1 Quantum mechanics excites the imagination unlike any classical theory of physics, probably at least in part because peculiarities of the quantum world conflict so spectacularly with the intuitions most of us develop in the course of interacting with our macroscopic, quasi-classical world. Since its earliest days, philosophers trying to understand similarly peculiar and perhaps counter-intuitive properties of minds and of consciousness have turned to the quantum theory as a possible source of explanation. Often philosophers appeal to the apparent indeterminacies of quantum mechanics to supply a foothold for free will in our otherwise seemingly deterministic world, although there are good reasons to think this a red herring. (Grunbaum, 1972; see also the specifically quantum mechanical objection of Fine, 1993, who nonetheless favours Grunbaum's conclusion.) Here, this subtle question does not occupy us; instead, we consider the relationship between physics and philosophy of mind from the perspective of quantum linear superposition and state vector reduction.

1.2 For our purposes, we understand quantum theories of mind or consciousness which do not especially appeal to indeterminacy to fall under two headings. First are those which point to minds as causal factors or determinants in reducing state vector descriptions of material substrates such as brains, while second are those which appeal to linear superposition, nonlocality, or some such to endow material structures with unique information transforming (but not necessarily *computational*, in the recursion theoretic sense--see Section 4) abilities meant to subserve correspondingly unique abilities of minds. I take the psychon theory of Sir John Eccles (1986, 1990; also Popper & Eccles, 1977) as a paradigm example of the former and something like the approach of Roger Penrose (1989) as an example of the latter, with Marcer (1992) combining elements of each. Recently (Mulhauser, 1995, in press) I have tried to apply a new development in quantum measurement theory to questions in philosophy and cognitive science, a development which suggests theories of both these types are misguided. Our task here is to clarify that development and its significance for the philosophy of mind.

1.3 We begin with a look at the standard account of state vector reduction and the theory of interactive decoherence which promises to supplant it. The new theory leads us on to the position that quantum mechanics has little, if any, bearing on philosophy of mind. Finally, we take a moment to defend decoherence theory against an objection raised by Brian Josephson before finishing with some concluding remarks on unsolved problems and broader difficulties in interpreting quantum mechanics.

2. Traditional Measurement: The Ghost of Mechanics Past

2.1 On the standard account of quantum measurement, originally due to John von Neumann (1955/1932), the act of observation discontinuously projects a quantum system into one of the basis states--represented as a set of eigenvectors spanning Hilbert space--for the observable operator in question. We can think of the probability of finding the system in a state corresponding to a given basis vector as proportional to the magnitude of the system's original state vector--the Hilbert space representation of its wavefunction--projected along that basis vector. (Alternatively, the probability is just the square modulus of each basis vector's coefficient in the linear superposition which makes up the state vector.) The set of probabilities returned when we apply the observable operator to the state vector of a system (or 'collapse the wavefunction' or 'reduce the state vector') is that system's reduced density matrix.

2.2 A crucial fact for our discussion is that it makes *no difference* to the statistical predictions of quantum mechanics exactly when in the course of observation state vector reduction occurs, as long as it happens some time before the result of a measurement has entered the conscious mind of an observer. In this sense, the observer is said to *terminate* the so-called von Neumann chain, the sequence of interactions from quantum system up through measuring apparatus(es) and into a mind. But it is on the end of this von Neumann chain that the philosophers' quantum mechanical romance begins. Some suggest that we take consciousness as more than just the terminus of this chain, that we take consciousness itself as the very mechanism which *precipitates* state vector reduction. The view that consciousness actually brings about state vector reduction has very nearly become the standard in mainstream philosophy, and it has even entered popular folklore, figuring centrally in almost every popular account of the 'new physics'. (See, for instance, Capra, 1982, 1984; Talbot, 1980; compare Squires, 1990.) Nor is it remotely foreign to the physics literature. (London & Bauer, 1939; Wheeler, 1977, 1980; Wigner, 1961, 1963, 1967; Jahn, 1981) Since quantum mechanics predicts deterministic unitary evolution for isolated systems and probabilistic state vector reduction for observed systems, it is easy to see how this interpretation might appeal: the difference between the two cases seems to be just the presence of the conscious observer, so we might think it is exactly *that* which turns what von Neumann called the type I process (unitary evolution in accordance with the Schrodinger equation) into the type II process (state vector reduction).

2.3 In the course of my earlier account of decoherence (Mulhauser 1995), I described a range of problems which this view of state vector reduction creates for philosophy of mind and philosophy of science. Without rehearsing those problems here, we can observe in the current context that this view--the view that the consciousness of an observer actually precipitates state vector reduction--lends itself congenially to both types of theories we mentioned above which attempt to apply quantum mechanics to questions of mind (or vice versa, or both). The notion straightforwardly encourages approaches like that of Eccles, who maintains that causally prior mental 'psychons' govern the states of structures at or above the level of cells in the neocortex by collapsing wavefunction descriptions of pre-synaptic vesicular grids. Likewise, the position that state vector reduction doesn't actually take place until the very end of the von Neumann chain allows the possibility of gross biological structures existing in states of linear superposition for extended periods of time (a la Schrodinger's cat) unless or until they are consciously observed. Appeals to such persisting superposed or wavelike states of gross computationally relevant structures are at the heart of those quantum theories of mind which fall under the second heading. (As an aside, note that our arguments explicitly *do not* apply to theories which appeal to *other* apply to theories which appeal to *other* kinds of wavelike properties of gross biological structures, such as that of Zaman (1992), who offers an electromagnetic theory of brain dynamics governed by Maxwell's equations; this particular theory is probably untenable for other reasons, however, not the least of which is that at the relevant EEG and MEG frequencies, electric and magnetic fields are uncoupled.)

2.4 In the next section, we see that quantum measurement theory has outgrown the need for any account which explicitly appeals to the consciousness of an observer. We see how a quasi-classical world may emerge from the laws of quantum mechanics and how this occurs entirely in the absence of the traditional sorts of 'observer'.

3. Decoherence: Traditional Measurement Theory Gives up the Ghost

3.1 The modern description of decoherence derives from the work of a range of physicists including Murray Gell-Mann, Jim Hartle, Stephen Hawking, Erich Joos, Dieter Zeh, Wojciech Zurek, and others. (It is also especially comprehensible within Hugh Everett's 1957 interpretation of quantum mechanics, and it needn't be incompatible with it, as I incorrectly speculated in Mulhauser (1995). It has grown out of the conviction of quantum cosmology that quantum mechanics ought to apply to the entire cosmos throughout all time, with no arbitrary Copenhagen-style line of demarcation between the quantum world and a classical one. (Coleman, et al., 1991, makes an interesting introduction to quantum cosmology.) If this is true, this conviction that we ought to be able to explain with quantum mechanics (and general and special relativity) all observable behaviour in the entire cosmos, then somehow from quantum mechanics we ought to be able to derive laws describing the quasi-classical behaviour we observe around us most of the time.

3.2 To see how something like this might work, it is helpful first to recall that contemporary quantum mechanics understands a system's wavefunction to contain *all* the information there is about that system. But while the wavefunction contains answers to all the questions we could ask about a system, not all those questions can meaningfully be answered simultaneously. More specifically, we cannot obtain a precise value for the state of a system with respect to one observable without obliterating information about the state of the system with respect to all other non-commuting observables. Perhaps the most common illustration of this point is the observation that we cannot ascertain *both* a particle's position and its momentum at the same time. In practice as well as in theory, explaining or predicting the behaviour a quantum system requires extracting from a complete wavefunction certain information about that system while *ignoring* other information about that system or about other systems with correlated states.

3.3 The significant feature of decoherence is that it turns out when we treat the entire cosmos as a quantum system with a wavefunction description, we can ask questions about the behaviour of macroscopic collections of particles and get answers which very closely approximate the answers offered by classical physics. Of course in practice it is impossible actually to formulate the wavefunction description of any but the smallest subsystems of the cosmos, so obviously we can't begin with the wavefunction of the cosmos and then extract information about our chosen subsystem. To get at what we will use instead, let's take an example of some macroscopic object such as a billiard ball. (Such *very* coarse graining is probably inadequate for a proper specification of the quasi-classical domain, but the details do not concern us here.)

3.4 Suppose we'd like to know the physical position of the billiard ball to within some degree of precision. Significantly, in formulating our question about the billiard ball's location, we ignore the quantum state of everything else in the cosmos. We don't ask about the velocity of certain fleas on John Major's dog or about the state of the Russian economy or even about whether there is a collection of particles known as planet Earth (although there being a position for something like a billiard ball might be contingent on there being a planet Earth). Now, subject to a certain condition we'll specify in a moment, we can use the possible positions of the billiard ball, together with our hypothetical wavefunction of the whole cosmos, to *partition* the set of possible states for everything else--everything we're ignoring just now--into equivalence classes with respect to each of which the billiard ball is in a different position (to some rough approximation). There might be myriad possible states in each of the equivalence classes, but within each class every possible state for everything else is compatible with just one (approximate) location of the billiard ball and incompatible with all its other possible locations.

3.5 The proviso which enables this partitioning is that there be a good degree of *correlation* between the state of the billiard ball and the state of everything else. That is, given that the cosmos is in a pure quantum state, we cannot separate off the billiard ball and be left with a billiard ball in a pure state and a rest-of-the-cosmos in a pure state. Each subsystem--the billiard ball and the rest of the cosmos--is in a *mixed* state, and there are nonseparable correlations between the two. In other words, its evironment, the rest of the cosmos, contains *information* about the state of the billiard ball--just as the billiard ball contains information about the state of the rest of the cosmos. At the level of individual particles such as electrons being fired through a couple of slits at a screen, there might be only very little of this environmental record-keeping, but by the time we reach the level of macroscopic collections of particles like billiard balls being fired through slits (or sat on tables, or whatever), correlations between those collections and the environment are widespread and far-reaching.

3.6 As extensive numerical analysis of complex quantum systems with a degree of environmental interaction reveals, the immediate effect of this environmental record-keeping is that the *coherence* of what might otherwise have been a smooth continuous wavefunction description of the billiard ball is destroyed extremely rapidly. (For some technical examples illustrating this process through so-called spontaneous 'dynamical' decoherence or the decoherence functional of the sum over histories formulation, see Albrecht, 1992; DeWitt, 1993; Dowker and Halliwell, 1992; Finkelstein, 1993; Joos & Zeh, 1985; Paz, et al., 1993; Paz and Sinha, 1992; Paz & Zurek, 1992; Zeh, 1993; Zurek, 1991, 1993, 1994.) That is, the buildup of nonseparable correlations between a system such as a billiard ball and its environment--which, in one famous example, could even be as little as cosmic background radiation--causes a very rapid decrease in the possible states of the system *which can be distinguished through their effects on the environment.* This is little more than a restatement of the partitioning process: because of the correlations between the billiard ball and the rest of the cosmos, asking just about the state of the billiard ball effectively partitions the space of possible states for the rest of the cosmos into equivalence classes, and it is only the billiard ball states which pick out non-empty classes which can be distinguished through their effects on the environment.

3.7 As Paz, et al (1993) suggest, this process "results in a negative selection which leads to the emergence of a preferred set of states... which remain least affected by the 'openness' of the system in question". (p. 488) Conveniently and unsurprisingly, the states that emerge from this environment-induced superselection, which I prefer to call 'interactive decoherence' rather than the 'spontaneous decoherence' common in the physics literature, correspond closely to those of the macroscopic observables of the quasi-classical world. (Albrecht, 1992; Paz, et al., 1993) When we ask the right questions of quantum systems large or small, as long as there is a suitable degree of environmental interaction (which, generally speaking, can be extraordinarily minute), the predictions we derive from this process exactly mimic those of traditional state vector reduction. The most significant difference is that the consciousness of an observer plays *no role* in the decoherence story. The process whereby the billiard ball comes determinately to be in my hand, or in the corner pocket, or in geosynchronous orbit around the third planet from the Sun has no need for any supervising consciousness. Quantum measurement has outgrown the conscious observer, and it is getting by just fine without us! As Zurek suggests in a popular rendition,

Conscious observers have lost their monopoly on acquiring and storing information. The environment can also monitor a system, and...such monitoring causes decoherence, which allows the familiar approximation known as classical objective reality--a perception of a selected subset of all conceivable quantum states evolving in a largely predictable manner--to emerge from the quantum substrate. (Zurek, 1991, p. 44)

3.8 Hopefully it is apparent from this discussion of interactive decoherence that the first category of quantum theories of mind we mentioned above, those which appeal to minds as causal factors or determinants in reducing the state vector descriptions of appropriate hardware or wetware, have lost any support they may have enjoyed from more traditional quantum measurement theory. On the modern view, interactive decoherence would occur even if there were not a single conscious observer in the cosmos. (And, likewise, when a conscious observer *is* involved, selection of the basis states takes place because of the nonseparable correlations introduced by the measurement process and *not* because of the consciousness itself.) In the next section we turn the discussion the other way round: if mind is irrelevant to quantum mechanics, is quantum mechanics also irrelevant to mind? In Mulhauser, 1995, I state this side of the discussion without argument--that quantum mechanics simply was utterly irrelevant to philosophy of mind--but here we take up the argument explicitly.

4. Exorcising The Ghost in the Machine

4.1 With this new understanding of interactive decoherence as a process which occurs automatically and independently, without the influence of any conscious observer, and apparently for every body in the cosmos which has any significant degree of interaction with its environment, it is much easier than it might have been before to see that the relevance of quantum mechanics to questions of mind is analogous to the relevance of quantum mechanics to questions of digital computation. This analogy emphatically does *not* rest on any presupposition of functional similarity between digital computation and the dynamics of minds' hardware or wetware; the analogy comes instead from the levels at which we may describe digital computers on the one hand and things like brains on the other.

4.2 Taking the digital computer example first, the peculiarities of quantum mechanics are of course relevant to a proper understanding of the very lowest level behaviour of logic gates in the silicon chips which typically implement digital computers. But the higher level behaviour of a digital computer--and indeed the theory of digital computation itself--requires that influences of quantum deviations from the classical deterministic framework are completely non-existent at or above the level of the gate itself. That is, while the mechanisms which make the gate work the way it does may be quantum in nature, the gate must play its functional role in the computer in an absolutely deterministic, quasi-classical way that is utterly independent of quantum fluctuations. Indeed, the existence of quantum effects at the lowest levels of digital computers is purely an accident of their micron-level implementation in silicon, for they theoretically work just the same way, if more than a little more slowly, implemented with comparatively huge Babbage-style gears and cogs.

4.3 The most important point is that while quantum mechanics is relevant to understanding the very lowest level properties of digital computers, as it is relevant to understanding the very lowest level properties of any material body at all, it is utterly irrelevant to the theory of digital computation--the 'philosophy of digital computation', if you will. Likewise for philosophy of mind. The very nature of a brain or the hardware substrate of an artificial intelligence as a high temperature physical object in *continual strong interaction* with its environment bodes very unfavourably for the possibility of coherent unitary evolution of components at all but the smallest scales. Carrying complex information in the form of correlations between states of physical observables (the preferred 'physicalist' definition of the word 'information'; see Landauer, 1991) appears straightforwardly incompatible with existing in a coherent state of quantum linear superposition. And without adopting any especially strong views about information processing in minds, the incompatibility between being an information-carrier and maintaining quantum coherence makes it difficult to see how any specifically quantum subsystem could play a functionally relevant role in a mind's hardware or wetware or, alternatively, how any functionally relevant subsystem could have specifically quantum behaviour.

4.4 This does *not* of course mean that no specifically quantum events ever occur in brains, for instance, any more than it means quantum events do not occur in digital computers. For example, quantum effects may well be relevant, as Eccles (1986) suggests, at the level of pre-synaptic vesicular grids. We needn't dispute events which are quantum in character here, or in the activations of voltage-gated ion channels, or in many other comparatively low energy sub-cellular mechanisms. We need only dispute the emergence of any consistent relationships *between* such quantum events which could be relevant to understanding minds. Quantum mechanics may be very important for understanding why extremely low level structures in brains and the like work as they do, but interactive decoherence precludes its having anything to say about larger scale properties of such structures or--very probably--of minds. The phenomenon of interactive decoherence suggests that relevant kinds of higher level structures cannot exist in coherent quantum states, and it guarantees that even lower level structure can exist in coherent quantum states only so long as their interaction with their environment is kept to an absolute minimum. (Zurek, 1991, notes that a rough calculation shows coherence of a 1 gm solid mass at room temperature is destroyed in less than 10^-23 seconds. Coherence even for dust grains interacting with cosmic background radiation is still destroyed in nanoseconds; see Joos & Zeh, 1985, also DeWitt, 1993.) We might speculate that the entire range of actual quantum effects in things like brains could simply be treated stochastically, with nothing relevant to philosophical questions about minds lost by giving up specifically quantum mechanical descriptions.

4.5 In short, then, the argument against the relevance of quantum mechanics to philosophy of mind is two-fold. On the one hand, consciousness is irrelevant to the modern formulation of quantum measurement. Theories of the first kind above, those which appeal to minds as causal factors in collapsing state vector descriptions of mind hardware or wetware, lose all theoretical grounding in light of interactive decoherence. On the other hand, interactive decoherence also reveals that only subsystems either very low in total energy or lacking any significant degree of environmental interaction can exist in coherent quantum superpositions. Thus, quantum mechanics cannot comment on any large scale properties of the material substrates associated with minds, and it certainly does not permit coherent superposed evolution of gross functionally relevant information transforming structures. Theories of the second kind, those which appeal to quantum effects to endow hardware or wetware with unique information transforming properties meant to subserve unique abilities of minds, thus also lose their theoretical grounding in light of interactive decoherence. (By 'information transforming' we denote a far broader class of physical structures than those merely 'computational' or 'computable' in the recursion theoretic sense--see, for instance, Pour-El & Richards, 1989.)

4.6 As an aside, it is worth noting that those such as Penrose (1989), who would appeal to quantum mechanics to endow brains with noncomputable (in the recursion theoretic sense) capabilities, thus moving them into a more powerful class than algorithmic Turing machines or cellular automata, need look no further than deterministic chaos. As early as 1992, I predicted on the basis of theoretical considerations (Mulhauser, 1992; see also Mulhauser, 1993, In Press) that systems which are both chaotic *and* analogue may exhibit behaviour which cannot be effectively simulated by a digital computer (thus contradicting the Church-Turing thesis which has rested safely at the centre of theoretical computer science since the 1930s). Notwithstanding attacks from philosophers such as Peter Smith (1993a, 1993b and in press), who seems often to maintain essentially that chaotic systems are covered by exactly the same computational and physical framework as any other kind of deterministic dynamical system, this position has now been vindicated by the recent specification of a chaotic analogue neural network with 'Super-

Turing' capabilities. (Siegelmann, 1995; see also Siegelmann & Sontag, 1994, Sommerer & Ott, 1994; see Blum, et al., 1989, for a more general treatment of computation over the real numbers as opposed to the rationals and Vergis, et al., 1986, for an earlier analysis of specifically analogue computation.)

4.7 In the next section, we address a tempting objection to the formulation of decoherence to which we've been appealing before continuing on to some closing thoughts about decoherence and broader problems in the interpretation of quantum mechanics.

5. Interactive Decoherence: An Afterthought?

5.1 Soon after making available on the International Philosophical Preprint Exchange a preprint of my earlier account of decoherence, Brian Josephson offered some interesting objections which can help us get at one matter at the heart of quantum measurement. Josephson suggests there often seems to be some sleight of hand at work in the decoherence literature (B. D. Josephson, personal communication, November 10, 1993), although he concedes the merit of my own account is that it goes through the argument sufficiently clearly that perhaps we can see where the sleight of hand occurs. With that thought in mind, let's address the objections and make sure we've discharged sleight of hand from any important roles in the story of decoherence--or from any roles at all!

5.2 The objection first emerges in the straightforward question about something like Schrodinger's cat, "how do we go from the mathematical property of decoherence to the assertion that 'the cat is already either alive or dead long before anyone opens the box'?". (B. D. Josephson, personal communication, November 10, 1993, quoting Mulhauser, 1995) As he indicates,

The nub of the matter is that ordinary physics implies a determinisitic correlation between whether the particle decayed and whether the cat is subsequently alive or dead, plus the fact that owing to the linearity of the Schrodinger equation, once a superposition always a superposition. ...Decoherence implies [only] that the two dead/alive components are entangled states [i.e., that the cat is in a mixed state--G.R.M.] rather than simple product states.

5.3 Josephson wonders whether we could have "continued superposition" when coherence has been lost (B. D. Josephson, personal communication, November 11, 1993), and he objects that "the idea that the system is actually *in* one of the...[basis]... states is put in as an ad hoc axiom, justified by its consistency". (B. D. Josephson, personal communication, November 25, 1993) In other words, decoherence may indicate a preferred basis, but it doesn't show why a system must actually be in a state corresponding to an eigenvector in the basis. Is our assumption that a system actually objectively exists in one of the states used to partition the states of everything else in the cosmos just an unargued afterthought? That a system may objectively exist in a superposed state after coherence of the state vector has been destroyed is a possibility with little more than a subtle background influence for those physicists on whose work the present view as we have outlined it is based, but very lately some commentators have begun suggesting the problem of 'interpreting probabilities'--exactly the same problem to which Josephson's objection points--is crucial to a proper understanding of the emergence of quasi-classical eigen*states*. (See, for instance, the more philosophically thorough treatment of Saunders 1995, who seeks an analogy between relational approaches to time and to quantum measurement.) The difficulty is whether to attribute to the mechanisms of decoherence the same kind of power to 'actualise' basis vectors as we have hitherto attributed to state vector reduction. Let's examine the question more closely and see whether it really is an afterthought to suppose a system is actually in one of the interactively decohered states.

5.4 The outline of one possible answer to the problem begins with a consideration of the experimentally verifiable difference between the proposition that a decohered system has actually 'collapsed' into an eigenstate and the proposition that it still exists in a superposed state, except that the superposition is, on account of decoherence, a linear combination of vectors describing only quasi-classical basis states. The first proposition enables us to tell a story about the system's evolution which proceeds through interaction with an environment and ends with a description of the different eigenstates in which the system might be found upon observation, together with a prediction of the probability of finding the system in any particular eigenstate. Crucially, the probabilities describe the chance the system will have *already collapsed* into one of these states, although, until the observation is made, we remain ignorant of which state is objectively real. The second proposition prompts a story of the system which proceeds through interaction with an environment and ends with a description of a superposition of eigenstates into one of which the system may be forced by conscious observation, together with a prediction of the probability of the system entering any particular eigenstate. Crucially, the probabilities describe the chance the system *will collapse* into one of these states, since before the observation is actually made, the state of the system remains a superposition and it is not determinately in any one of the eigenstates.

5.5 In both these cases, of course, the probabilities sum to unity, so the prediction is that the system *will be* found in precisely one of the eigenstates. And thousands or millions of experiments have revealed the unparalleled accuracy of these predictions: in this sense, the enormous body of experimental evidence tends to confirm both accounts equally well. If there doesn't seem to be any experimentally verifiable difference between the two accounts, has the advocate of interactive decoherence succumbed to the afterthought temptation and simply opted for the new view over the established one for no sound reason?

5.6 The story we've told so far now clearly recommends a negative answer to this question. If we start from the standpoint of the traditional quantum measurement theory of more than the last half century, it might seem at first that 'adding in' the proposition that a decohered system is actually objectively *in* an eigenstate before a conscious observation is made is unfairly putting consciousness on the dole. But recall that under the original projection postulate, consciousness *terminated* the von Neumann chain: the observation was merely the latest time by which a wavepacket could collapse, and the predictions of quantum mechanics were no different whether it collapsed at this last instant or at some earlier time in the chain. Interactive decoherence may now offer an account of the actual mechanisms which *precipitate* state vector reduction, independently of any consciousness phenomenon. It is hardly mysterious that we don't actually *know* the outcome of a measurement until the von Neumann chain is terminated, since after all we don't know the outcome of *any* measurement, quantum or classical, until we actually complete an observation. Apparently we now have in decoherence theory an account of the emergence of the basis vectors--as Josephson concedes-- but it is perhaps confusingly obvious that we can't expect to know *which* eigenstate is actual until we observe it. On the account of interactive decoherence offered here, we are left with only the question of whether the system is actually in an eigenstate before observation. But as we have seen there is no experimentally verifiable difference between the two alternatives, and on this view it is the proponent of accepted quantum measurement theory whose "sleight of hand" is adding in a consciousness phenomenon which has *no explanatory value*. Consciousness is redundant. (In Mulhauser, 1995, pp. 210, 215, I offer a simple but difficult to perform 'consciousness detector' experiment which would distinguish between the two accounts of decoherence, provided that we have some independent means of deciding whether a given observer is conscious. This experiment also implies that von Neumann's account of the type II process is wrong that it makes no difference where in the chain state vector reduction takes place. In our context, we proceed as if von Neumann is correct; I believe our account remains convincing enough!)

5.7 This is the simple answer, anyway. In the next section we turn to some problems with this approach and consider broader questions of interpretation in areas of quantum mechanics which even under decoherence theory still await explanation.

6. Quantum Realities: How Many and Which Ones?

6.1 This type of reply to the problem of interpreting probabilities and their reference accepts state vector reduction as an actual physical process, albeit one which *derives from* unitary evolution. This is in the same spirit as Hartle (1993), and it mirrors Griffiths's (1984) early account of decoherence which explicitly rejects the notion that a single individual system may exist in a linear superposition of decohered eigenstates. The problem, of course, is that such an interpretation, appealing only to the theoretical constructs which have emerged from decoherence theory to date, on the face of it requires either an ignorance interpretation or an 'ad hoc' addition (pace Josephson) of the power of decoherence to 'actualise' eigenstates. Our answer *does* still permit us to reject consciousness as a mechanism for precipitating state vector reduction, since along the lines of the above it performs no experimentally verifiable job over and above the standard picture of the von Neumann chain *together with* interactive decoherence. But it does *not* answer fully the problem of interpreting probabilities.

6.2 The problem of probabilities and the project of salvaging all of our reply to Josephson's objection may be approached in at least two different ways. On the one hand, we might simply take the logic of probability as *fundamental* and deny that our account of measurement has to *explain* anything about it at all. Griffiths (1984) and Omnes (1990) adopt this approach in their formulation of the *process* of decoherence itself if not entirely in the *interpretation* of the resultant decohered states (see also Omnes, 1992), while Gell-Mann and Hartle (1990) and Zurek (1991) are at least sympathetic to it.

6.3 My own preference is to 'bite the bullet' on the ignorance approach to Griffiths's explicit rejection of superposition after decoherence, except with a different twist on 'ignorance': I suspect what is hidden might not be some extra set of variables from which the laws of unitary evolution derive, but instead might be some features of the *interaction* of complex quantum subsystems which, due simply to the computational power required to analyse them, haven't been discovered yet. Analsyses of only very simple interacting systems have yet to appear in the literature, and I suspect that with time we may witness the emergence of certain constraints on the evolution of increasingly complex systems.

6.4 That is, we might expect that given an adequately large repertoire of interacting subsystems, certain configurations of states and correlations between them simply become impossible. Indeed, the other outstanding problem in decoherence theory today, apart from interpreting probabilities, is the closely related problem of accounting for the uniqueness of the quasi-classical domain which arises from the processes of decoherence. Could there be more than one non-equivalent way of partitioning states of subsystems, enabling decoherence into more than one possible state of basis vectors? If so, how do we (or Nature) choose between them? Gell-Mann and Hartle (1990) and Gell-Mann (1994) suggest that macroscopic adaptive systems (such as ourselves) may simply have emerged with only the capacity to utilise the probabilities of a particular quasi-classical domain, without denying the possibility of other, equally 'real', non-equivalent domains. Zurek (1994) and Saunders (1993a, 1993b) make other appeals to evolutionary constraints on complex systems, while I suggest a more radical version in Mulhauser (in press).

6.5 This more radical version continues the flirtation with ignorance interpretations of measurement; it is simply the idea that it may turn out that interactions between a sufficiently large number of subsystems not only pares down the possible states in which subsystems may exist (thus yielding the basis vectors), but it may even *determine* which of those states are actualised. This amounts to a more serious 'evolutionary' constraint on the cosmos itself. Hopes like this have been expressed before in the guise of standard 'hidden variables' theories, and while it is not *those* which I am advocating, it is nonetheless instructive in our context to note some features of those accounts as they might bear on the project of ultimately fitting all the pieces of a picture of decoherence into place.

6.6 Most significantly, contrary to popular opinion, quantum mechanics is *not* incompatible with hidden variables theories; experimentally verified violation of Bell's inequalities shows only that quantum mechanics cannot be explained with specifically *local* hidden variables. (Bell, 1964, 1966; for what set it all off, see Einstein, et al., 1935 and Bohr's reply, 1935a, 1935b; on experimental verification see Aspect, 1976, Freedman

& Clauser, 1972, Fry & Thomson, 1976.) Hidden variables of a nonlocal variety are entirely compatible with quantum mechanics, and they are the basis of at least one possible deterministic interpretation of the quantum theory. (Bohm, 1952) Moreover, if Lockwood's (1990/1989; compare Maudlin, in press) argument against the idea that standard stories of nonlocality actually permit propagation of signals faster than light is to be taken at face value, nonlocal hidden variables might not be as bad as they are commonly supposed. (Faster than light signalling is usually supposed to be the harbinger of doom, since special relativity suggests space-like communication would open up no end of possible assaults on causation.)

6.7 In any case, the speculation I would like to offer is that this general approach to nonlocality, together with interactive decoherence theory, points in the direction of a different sort of deterministic interpretation of quantum mechanics. In particular, I wonder if the kind of nonlocality observed in pure quantum systems like the EPR experiment might also figure in the interactions of hidden variables in the so-called 'quantum vacuum', the source of virtual particles? (See Podolny, 1986 for a charming nontechnical introduction to the quantum vacuum as well as a romantic history of science in the former Soviet Union.) If so, I wonder how decoherence theory would bear on questions about the states of these hidden variables? If decoherence theory could explain fluctuations in the quantum vacuum, perhaps it could also offer deterministic predictions about which of several actual states a decohering system might enter. Or, even more optimistically, perhaps decoherence theorists will eventually discover that hidden variables are no longer necessary because the environment, considered in all its complexity, actually determines the state to which a system will collapse.

6.8 This is the initial speculation I offered above; if this approach bears fruit, the problems of probability and of the uniqueness of the quasi-classical domain simply disappear, and the irrelevance of consciousness becomes all the more convincing. Even success of a weaker version of this speculation--one which would give a single quasi-classical domain without necessarily making it deterministic-- would enable the sort of 'softer' approach offered by Saunders (1995, pp. 255-256) wherein decoherence *does* actualise states, but without actual state vector reduction. On his speculative account, we would then have unitary evolution for the entire cosmos, without state vector reduction, and we would have 'actual' states for macroscopic objects, but we would give up 'actual' states for lower-level subsystems which might be part of decohered macroscopic objects.

6.9 It remains to be seen what will become of such speculations as decoherence theory becomes more widely accepted and attracts more attention in the theoretical community. What does seem clear at this early stage, however, is that quantum measurement truly has outgrown the need for a conscious observer. We've undertaken these closing considerations of probability and the uniqueness of the quasi-classical domain only because they remain outstanding problems in decoherence theory; it should now be clear that our original position that consciousness is irrelevant to quantum mechanics and *vice versa* does not depend upon any particular resolution of these questions. However these questions are ultimately answered, the fact remains that the story of quantum measurement can now be told without mention of any specifically conscious observer. This maturation of quantum mechanics demands similar growth in those areas of philosophy of mind which formerly made some appeal to the quantum world. Seemingly bizarre things still happen as a result of quantum mechanics, but for better or worse consciousness does not appear to be one of those things directly affected--or effected--by it. The partnership between quantum mechanics and one area of philosophy is ending, and quantum mechanics grows on without it; philosophy must do the same.

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