Multiplicity in Everett’s interpretation of quantum mechanics

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Abstract

Everett’s interpretation of quantum mechanics was proposed to avoid problems inherent in the prevailing interpretational frame. It assumes that quantum mechanics can be applied to any system and that the state vector always evolves unitarily. It then claims that whenever an observable is measured, all possible results of the measurement exist. This notion of multiplicity has been understood in different ways by proponents of Everett’s theory. In fact the spectrum of opinions on various ontological questions raised by Everett’s approach is rather large, as we attempt to document in this critical review. We conclude that much remains to be done to clarify and specify Everett’s approach.

KEY WORDS: Everett, many worlds, multiplicity, quantum mechanics, interpretation.

1 Introduction

Everett’s ‘relative state formulation of quantum mechanics’ (1957a), also known as ‘the many-worlds interpretation,’ was proposed almost sixty years ago. It remained little more than a curiosity for a couple of decades, but has henceforth attracted sustained attention. Its current status was synthesized and criticized in the remarkable recent monograph by Saunders et al. (2010), while Byrne (2010) uncovered at the same time the fascinating story of its genesis.
Everett’s original motivation was to provide a formulation of quantum mechanics that would avoid problems inherent in the then current interpretational frame, which drew both from the Copenhagen distinction between the quantum and the classical and from the Dirac–von Neumann collapse of the state vector. The main problem comes in so-called measurement situations which, in view of later discussions, we presently formulate on a specific example.

Let $|a_1\rangle$ and $|a_2\rangle$ be an orthonormal basis of a two-dimensional Hilbert space, associated for instance with a spin-$\frac{1}{2}$ particle. Let an apparatus be designed so as to measure an observable $\Sigma_z$ given by

$$\Sigma_z = |a_1\rangle\langle a_1| - |a_2\rangle\langle a_2|.$$  \hspace{1cm} (1)

Matrix elements of $\Sigma_z$ in the above basis are given by the Pauli matrix denoted by $\sigma_z$.

Let $|\alpha_0\rangle$ denote the normalized initial state of the apparatus. In a nondestructive measurement, the interaction between the particle and apparatus is assumed to be effected by a unitary operator such that

$$|a_1\rangle|\alpha_0\rangle \rightarrow |a_1\rangle|\alpha_1\rangle, \quad |a_2\rangle|\alpha_0\rangle \rightarrow |a_2\rangle|\alpha_2\rangle,$$  \hspace{1cm} (2)

where the arrow symbolizes time evolution and $|\alpha_1\rangle$ and $|\alpha_2\rangle$ are orthogonal pointer states. Let $c_1$ and $c_2$ be complex coefficients (satisfying $|c_1|^2 + |c_2|^2 = 1$ for normalization). Because the unitary evolution is linear, we must have

$$(c_1|a_1\rangle + c_2|a_2\rangle)|\alpha_0\rangle \rightarrow c_1|a_1\rangle|\alpha_1\rangle + c_2|a_2\rangle|\alpha_2\rangle.$$  \hspace{1cm} (3)

Thus the interaction has transformed an initial product state into a final entangled state.

If we look carefully at the right-hand side of (3), we see that the apparatus finds itself in a superposition of different pointer states. This is highly counterintuitive. It doesn’t help to introduce an observer $O$ to read the pointer and evolve from a normalized state $|O_0\rangle$ to a state $|O_1\rangle$ if he reads $\alpha_1$, or to a state $|O_2\rangle$ if he reads $\alpha_2$. For if $O$ is treated quantum-mechanically, the combined particle-apparatus-observer system evolves as

$$(c_1|a_1\rangle + c_2|a_2\rangle)|\alpha_0\rangle|O_0\rangle \rightarrow (c_1|a_1\rangle|\alpha_1\rangle + c_2|a_2\rangle|\alpha_2\rangle)|O_0\rangle$$

$$\rightarrow c_1|a_1\rangle|\alpha_1\rangle|O_1\rangle + c_2|a_2\rangle|\alpha_2\rangle|O_2\rangle.$$  \hspace{1cm} (4)
At the end of the process, the observer therefore finds himself in a superposition.

The Copenhagen solution of the measurement problem consists essentially in pointing out that an apparatus is necessarily classical, and therefore cannot be a quantum system as hypothesized before \(^\text{[2]}\). The upshot is that the apparatus registers either \(\alpha_1\) or \(\alpha_2\), but not both. Copenhagen adherents bear the burden of precisely specifying where the quantum-classical boundary lies.\(^\text{[1]}\)

The Dirac–von Neumann solution of the measurement problem consists in introducing a break in the unitary evolution of the state vector. It doesn’t matter whether the break occurs after the system-apparatus coupling or after the system-apparatus-observer coupling. In the former case for instance, the break occurs as

\[
c_1|a_1\rangle|\alpha_1\rangle + c_2|a_2\rangle|\alpha_2\rangle \\
\rightarrow |c_1|^2(|a_1\rangle\langle a_1|)(|\alpha_1\rangle\langle \alpha_1|) + |c_2|^2(|a_2\rangle\langle a_2|)(|\alpha_2\rangle\langle \alpha_2|). \tag{5}
\]

The right-hand side of (5) represents a proper mixture where the pointer shows \(\alpha_1\) with probability \(|c_1|^2\) and \(\alpha_2\) with probability \(|c_2|^2\). Von Neumann (1955) called the break Process 1 (the collapse of the state vector), contrasting it with Process 2, the unitary Schrödinger evolution. Proponents of collapse bear the burden of precisely specifying how and in what circumstances Process 1 occurs.

Everett’s proposal was to take (3) and (4) at face value. This means that, in some sense, all outcomes of a measurement have the same ontological status. The resulting interpretation of quantum mechanics would not require the presence of a classical apparatus or observer external to a quantum system. Quantum mechanics could therefore, in principle, be applied to the whole universe. Moreover, the theory would not require an explicit collapse of the state vector. The state vector would only evolve through Process 2, that is, through Schrödinger’s unitary evolution.

I have argued elsewhere (Marchildon, 2011) that the most important problem related to Everett’s work is the understanding of multiplicity.\(^\text{[2]}\) It is

\(^1\)Or, they have to live with the fact that an apparatus behaves classically if it performs a measurement, and quantum-mechanically if it is itself measured by a super apparatus.

\(^2\)This assessment is not consensual. See for instance the extensive discussion of probability in Saunders et al. (2010), or Schwindt (2012), who argues that the preferred basis problem has a component which is not solved by decoherence.
clear that for Everett, all possible results of a quantum experiment exist. In what sense they do exist, however, was not made precise in Everett’s published work. Perhaps the closest he comes to specifying this is found in the following quote (Everett, 1957a, p. 459):

We thus arrive at the following picture: Throughout all of a sequence of observation processes there is only one physical system representing the observer, yet there is no single unique state of the observer (which follows from the representations of interacting systems). Nevertheless, there is a representation in terms of a superposition, each element of which contains a definite observer state and a corresponding system state. 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 purpose of this paper is provide a fairly exhaustive review of the ways people have tried in subsequent years to understand multiplicity in Everett’s framework. They can be broadly divided into three groups: many worlds, many minds, and decoherent sectors of the wave function. We shall see that these approaches further subdivide, and that they all raise important questions that have not been completely answered. We shall not presume to make any final assessment on Everett’s program, but we shall conclude at least that there is still much to be clarified and specified in it.

2 Many worlds

The phrase ‘many worlds’ evokes the genuine existence of a great number of more or less similar copies of the world we live in. The idea that the world literally splits into a number of (initially) slightly different real copies of itself was first formulated in print by DeWitt. Indeed (DeWitt, 1970, p. 33):

This universe is constantly splitting into a stupendous number of branches, all resulting from the measurementlike interactions

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3 Unless specified otherwise, emphasis is always in the original.
4 Earlier syntheses can be found in Whitaker (1985) and Barrett (1999).
between its myriads of components. Moreover, every quantum transition taking place on every star, in every galaxy, in every remote corner of the universe is splitting our local world on earth into myriads of copies of itself [...]. I still recall vividly the shock I experienced on first encountering this multiworld concept. The idea of $10^{100+}$ slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense.

According to this quote, the split occurs at the atomic, that is, at the microscopic level. Every time an interaction produces entanglement, whether or not macroscopic objects are involved, a split presumably occurs. This goes beyond what we find in Everett, at least in print. There are strong indications (Byrne, 2010; Bell, 1976, p. 95; Deutsch, 1996, p. 223) that Everett, just like DeWitt, had in mind a genuine split. Unlike DeWitt, however, he applied it only in contexts where there is an interaction involving something like a macroscopic apparatus. Moreover, he proposed rather specific conditions under which measurements occur (Everett, 1957b, pp. 10, 53, 55):

[A]ll measurement and observation processes are to be regarded simply as interactions between observer and object-system which produce strong correlations.

[A] measurement is simply a special case of interaction between physical systems—an interaction which has the property of correlating a quantity in one subsystem with a quantity in another.

We shall therefore accept the following definition. An interaction $H$ is a measurement of $A$ in $S_1$ by $B$ in $S_2$ if $H$ does not destroy the marginal information of $A$ (equivalently: if $H$ does not disturb the eigenstates of $A$ in the above sense) and if furthermore the correlation $\{A,B\}$ increases toward its maximum [...] with time.

In other words, a measurement transforms a product state of a quantum system and an apparatus into a maximally-entangled state, in a nondestructive way (i.e. system eigenstates are left invariant).

Already at this stage, we are confronted with two different views of splitting, which give rise to two questions:

$^5$But Osnaghi et al. (2009, p. 107) point out that throughout Everett’s writings, the terms ‘real,’ ‘reality,’ ‘actual,’ ‘branching process’ and ‘branches’ appear systematically in quotes.
1. Does the split occur with all microscopic entanglement-producing interaction, or only in macroscopic measurementlike contexts?

2. Does the split occur in every possible basis in which the entangled state can be expressed, or just in one basis?

With respect to the second question, it seems that it would be impossible to recover appearances if a genuine split occurred along any basis. This would mean real worlds with macroscopic apparatus, and even human observers, in quantum superpositions. We will see, however, that such a conclusion may not hold in other interpretations of Everett’s theory. Butterfield (1995, p. 133) pointed out that branching along arbitrary bases may be coherent, but it presumably implies sacrificing natural meshing conditions between branches of different quantities, in order to avoid no hidden variable theorems.

So it seems that with a genuine split, there must be some preferred basis. Ballantine (1973) pointed out that if the split occurs at the atomic level, there is no natural definition of a branching representation. Note that it doesn’t help to propose that branching occurs along states that are left invariant by the interaction, like \( |a_1 \rangle \) and \( |a_2 \rangle \) in (2). For this nondestructive interaction is very special, and one can easily contemplate entanglement-producing interactions that leave no states invariant. If the split only occurs at a macroscopic level, decoherence no doubt helps in selecting a preferred basis. But following Bell, Everett can be criticized for not making the concept of instrument reading precise (Bell, 1976, pp. 96–97):

\[
[I]f \text{ instrument readings are to be given such a fundamental role should we not be told more exactly what an instrument reading is [...] [F]undamental physical theory should be so formulated that such artificial divisions are manifestly inessential.}
\]

We see that if the split occurs only with macroscopic apparatus, the problem of specifying what an apparatus is looks very much like the problem of clarifying the classical-quantum distinction in the Copenhagen interpretation.

Vaidman (1998, p. 251) envisions a microscopic split in connection with neutron interferometry: “My proposal is that during the period of time the neutron wave function is inside the interferometer there are two neutron worlds[..]” But we will see later that he proposes rather robust conditions for a macroscopic split. Bell (1986, p. 193) had summarized the ambiguity
between microscopic and macroscopic split in the following way: “One is given no idea of how far down towards the atomic scale the splitting of the world into branch worlds penetrates.”

There are several distinct ways to view splitting, even if it is restricted to occur in connection with macroscopic events only.

Healey (1984) considers that splitting occurs upon a measurement-like interaction. According to him, the simplest way to view splitting (say, into \( n \) copies) is that every elementary system splits into \( n \) copies, in usual ordinary space. But this, for Healey, is hardly defensible, for mass-energy would also be multiplied and we would presumably be aware of the overcrowding of space. Accordingly, the split he introduces can become acceptable in two different ways:

1. The physical systems do not split, only their states do.

2. Not only systems, but space itself splits. The resulting systems may be viewed as living in a higher-dimensional space.

Healey develops the first way into lines that anticipate what we shall elaborate in Sect. 4. With respect to the second way, he claims (pp. 598–599) that

within the framework of ordinary non-relativistic quantum mechanics, a version of the many-worlds interpretation according to which space and its constituent quantum systems split on quantum measurement offers no interpretative advantages over a version in which the actual outcome of a measurement is only one of many possible states of the world in space.

Healy then analyses the actual one-world version he has in mind. It turns out to be related to modal interpretations (Vermaas, 1999) and to share some of their problems. Note that in the context of genuine splitting, the relevance of retaining many worlds has often been questioned. Indeed (Kent, 2012, p. 423):

As Bell [...] and (probably many) others [...] have noted, if the branching of worlds were precisely and objectively defined, a many worlds interpretation would seem unnecessarily extravagant. Given a precisely defined branching structure, we can just as easily define a one world interpretation of quantum theory.
Several investigators have proposed reasonably specific definitions of what should be counted as a world. Vaidman (2014) clearly commits to a definition along macroscopic lines. He proposes that the quantum state of a world is given by

\[ |\Psi_{\text{world}}\rangle = |\Psi_{\text{object 1}}\rangle |\Psi_{\text{object 2}}\rangle \cdots |\Psi_{\text{object N}}\rangle |\Phi\rangle, \]

where each ‘object’ is macroscopic and \(|\Phi\rangle\) represents the quantum state of all the particles that do not constitute objects. In the 2002 version of the same Encyclopedia article, he also considered the possibility that only the object states directly perceived by sentient beings appear in (6), with \(|\Phi\rangle\) representing everything else.

Butterfield (1995) had a similar representation, where the \(|\Psi_{\text{object i}}\rangle\) are decohering states of macroscopic objects and \(|\Phi\rangle\) is the overall relative state. Discussing how splitting and multiplicity (or ‘plurality’) can apply to branches, he concludes that decoherence removes the need of physical splitting. In Butterfield (2001), formally similar definitions of worlds are used both for many-worlds and decoherence approaches.

Graham (1973) interprets Everett’s as a world-splitting theory, where there is one world corresponding to each possible result of a measurement. In an attempt to recover the Born rule from Everett’s approach, he applies the split to an observer reading a macroscopic apparatus intended to measure the relative frequency operator on a collection of identically prepared systems. It is not clear if the split also applies to a single measurement of a microscopic observable.

Here again, precision in definitions may reduce the appeal of a many-worlds approach. Indeed (Barrett, 1999, p. 157):

DeWitt and Graham’s world-splitting rule tells us that worlds split whenever a measurement-like interaction occurs, but they never explain precisely what counts as a measurement-like interaction; rather, this is determined by one’s choice of a preferred basis in the theory, which is never made explicit. But note that if we did know what it took to count as a measurement-like interaction here, then one would be able to solve the measurement problem in the standard collapse theory by stipulating that the global wave function collapses whenever precisely that sort of interaction occurs.

The next important question that comes up with genuine splitting is whether the split is irreversible or, equivalently, whether each branch hence-
forth evolves completely independently from the others. In a collective reply
to DeWitt (1970), Gerver points out (Ballantine et al., 1971, p. 40) that

if it is possible for the universe to split into two slightly different
realities by a quantum-mechanical event, then surely it is equally
possible for two slightly different universes to become identical in
the same manner.

DeWitt (1970, p. 35) also believes that in principle the split can be un-
done, “by bringing the apparatus packets back together again.” But Everett
(1957b, pp. 97–98) seems to be more cautious:

There is an essential irreversibility to Process 1 […] The irre-
versibility of the measuring process is therefore, within our frame-
work, simply a subjective manifestation reflecting the fact that
in observation processes the state of the observer is transformed
into a superposition of observer states, each elements of which
describes an observer who is irrevocably cut off from the remain-
ing elements. While it is conceivable that some outside agency
could reverse the total wave function, such a change cannot be
brought about by any observer which is represented by a single
element of a superposition, since he is entirely powerless to have
any influence on any other elements.

It should be pointed out that undoing the split would involve a rather
peculiar process, even if we admit that splitting occurs in purely microscopic
interactions. Suppose that a split has occurred after interaction (3), where
$|\alpha_1\rangle$ and $|\alpha_2\rangle$ represent microscopic states. For a time both terms on the
right-hand side of (3) are different worlds. Now it may happen that $|\alpha_1\rangle$
evolves into $|\alpha_0\rangle$ in world 1, while $|\alpha_2\rangle$ evolves into $|\alpha_0\rangle$ in world 2, with $|a_1\rangle$
and $|a_2\rangle$ unchanged. Then the global state would revert to the left-hand side
of (3). At that moment, world 1 and world 2 would unsplit, or recombine
into just one world. Zeh (1970) points out that someone in a given branch
cannot estimate the probability of inverse branching.

Several authors have pointed out that splitting into completely indepen-
dent worlds is incompatible with Schrödinger dynamics:

Apparent collapse has also been described as ‘world-splitting,’
and, as several authors have warned […] it is tempting to take
world-splitting as a physical process and thus effectively return to the Copenhagen interpretation. (Donald, 1995, p. 532)

If one supposes that the state of a world determines the behaviour of physical systems in that world in so far as their behaviour is determined, then the splitting-worlds theory is incompatible with the usual linear dynamics. (Barrett, 1999, p. 160)

A similar conclusion can be drawn from Albert and Barrett (1995), who consider the measurement of an observable pertaining to an apparatus that has already made a spin measurement.

The difficult problem of recombination can, however, be avoided. Deutsch (1985) suggests that there are infinitely many worlds (he calls them ‘universes’) at any time. There number neither increases nor decreases. In measurement contexts the set of all worlds is partitioned in as many branches as there are possible measurement results, the measure of worlds in each branch corresponding to the probability of the associated observable value. Thus we have bifurcation instead of splitting. To the measured observable Deutsch attempts to associate an interpretation basis in the Hilbert space, within the quantum formalism. Deutsch claims that the probabilistic interpretation is now truly built in, although Butterfield (2001) argues that it is difficult to make sense of probability in Deutsch’s approach.

Note that bifurcation avoids a problem that several people see with splitting, namely, a dramatic increase in mass-energy, in violation with the known conservation laws. No such thing can happen if the number of worlds does not change.

A continuous infinity of worlds is also postulated by Boström (2012), who tries to combine the approaches of Everett and Bohm. Boström considers the configuration space of \( N \) pointlike particles and associates, at a given time, a distinct world with each configuration. However, he identifies worlds which differ only by the permutation of two identical particles. Some may find it hard to believe that two configurations that differ only by slight differences in the coordinates of one particle give rise to entirely different worlds. Note that many worlds along Bohmian lines were also considered by Bell (1976, 1981), Tipler (2006) and Valentini (2010). Boström attempts to answer the criticism that multiplicity in this case is entirely artificial.

In perspicuous early analyses of Everett’s approach, Bell suggested that the real novel element in Everett’s theory is the repudiation of the concept of past:
Everett [...] tries to associate each particular branch at the present time with some particular branch at any past time in a tree-like structure, in such a way that each representative of an observer has actually lived through the particular past that he remembers. [This] attempt does not succeed [...] and is in any case against the spirit of Everett’s emphasis on memory contents as the important thing. We have no access to the past, but only to present memories. (1976, p. 95.)

Keeping the instantaneous configurations, but discarding the trajectory, is the essential (in my opinion) of the theory of Everett. (1981, p. 133.)

Butterfield (1995) also argues that the absence of history tends to support plurality.

If splitting into many worlds is a physical process, several specific questions arise. Thus Lockwood (1989, p. 226) asks “at what point in the von Neumann chain does the split or decomposition occur, and on what spacelike surface?” Tipler (1986, p. 206) had partly answered the second query:

[M]any presentations of the MWI [many-worlds interpretation] have made it appear more counter-intuitive than it really is. For example, many accounts assert that “the entire universe is split by a measurement.” This is not true. Only the observed/observer system splits; only that restricted portion of the universe acted on [by] the measurement operator $M$ splits.

It is not clear where the two physical instances of the apparatus sit if the rest of the universe is not split.

Squires (1988, p. 16) raises the question “what can ‘splitting’ possibly mean in this context—what moves away from what?—and in what ‘space’?” To such interrogations, Tappenden (2000, p. 113) replies:

This all suggests that what is involved in unpacking Everett’s proposal is the addition of a further dimensionality to standard four-dimensional spacetime.]

But Vaidman (2014) claims that the worlds of the many-worlds interpretation “exist in parallel at the same space and time as our own.” We will come back to this in Sect. 4.
In an early discussion of Everett’s and DeWitt’s ideas, Smolin (1984) first introduced what he calls the “minimal relative state interpretation” (MRS). In the MRS, the right-hand side of (3) is not interpreted as the actual state of the composite system, but as the list of contingent statements like ‘If the apparatus reads $\alpha_1$, then the quantum system’s observable $\Sigma_z$ has value +1.’ Smolin then shows that the MRS has several of the advantages that the full-fledged MWI has. In the MWI, the right-hand side of (3) represents the actual, objective state of affairs of the composite system, where all outcomes are actual (p. 445):

[I]f we wish to regard our having observed a particular $a_i$ to be the outcome of the experiment as an actual event in the world then it follows that we must also regard our having observed each of the other possibilities as also being actual events in the world.

But Smolin also expresses caution about splitting (pp. 447–448):

One usually introduces at this point in the discussion the expression that the different statements are all true, but each is true of a different ‘branch’ of the wavefunction […] The disadvantage of using the language of branches is that it suggests that some kind of dynamical mechanism is taking place, in addition to the evolution of the wavefunction, in which, as time goes on and initially isolated systems come together and interact, the universe is ‘splitting’ into more and more ‘branches.’

This makes it more difficult to understand what Smolin has in mind with the actuality of all outcomes, unless it is interpreted as in the next sections.

3 Many minds

The first full-fledged formulation of the idea that the split involves the mind rather than the world seems to be the one of Albert and Loewer (1988). Yet some passages in Everett’s published work can be construed in that way. For instance we read (Everett, 1957b, p. 10) that

after the interaction has taken place there will not, generally, exist a single observer state. There will, however, be a superposition of the composite system states, each element of which contains a
definite observer state and a definite relative object-system state
[...]. Thus, each element of the resulting superposition describes an
observer who perceived a definite and generally different result,
and to whom it appears that the object-system state has been
transformed into the corresponding eigenstate. In this sense the
usual assertions of Process 1 appear to hold on a subjective level
to each observer described by an element of the superposition.

Cooper and van Vechten (1969, pp. 1217–1218), who point out the sim-
ilarity of their views to Everett’s, come rather close to the idea of many
minds:

[O]ur knowledge that our own mind is in some state need not
be reflected in the wave function. Rather, it is expressed in the
way we pose the question. That a system is in the state $U$ is
equivalent to the statement that all coupled ‘good’ systems and
sane minds will agree that the system is in the state $U$ [...]. The
wave function may contain a superposition of $U$ and $L$ but there is
no manifestation of this to anyone—including the mind described
by the wave function—unless interference can occur.

Zeh (1970, 1981) anticipates the many-minds view, and attributes the
idea to Everett. Healey (1984) also suggests that Everett can be understood
along that way, while the general idea is further anticipated in Albert (1986)
and Squires (1987, 1988, 1991).

Albert and Loewer motivate their introduction of many minds by listing
three problems with the splitting-worlds view: (i) the fact that, as they
see it, it entails the nonconservation of mass-energy; (ii) the difficulty to
understand probability within a deterministic theory; and (iii) the choice of
a preferred basis. They then point out that if the Schrödinger equation is
always valid, the brain states of an observer, in a measurement context, can
evolve into a superposition. Belief states, however, are never superposed, for
an observer never believes he is in a superposition of seeing $|\alpha_1\rangle$ and seeing
$|\alpha_2\rangle$. Therefore, belief states cannot be wholly physical. Albert and Loewer
thus commit themselves to some form of dualism.

Albert and Loewer then introduce minds in two different ways, the latter
being their favorite. In the single-mind view (SMV), each observer has one
mind. The state vector after measurement is given by (3), but the observer’s
mind is associated either with $O_1$ or (exclusive) with $O_2$, with probabilities
respectively. Albert and Loewer point out that the nonphysi-
calism in this case is rather acute, for mind states do not even supervene on
physical states. Moreover, the SMV gives rise to what has become known
as the mindless-hulk problem (Albert, 1992). This consists in the fact that
after the split, all brain states but one are mindless. Thus in EPR contexts,
Alice’s single mind and Bob’s single mind can end up in different branches,
unless there are strong nonlocal correlations between minds.

In the many-minds view (MMV), every observer has associated with it
an infinite set of minds. In (4), a fraction \(|c_1|^2\) of minds become associ-
ated with \(O_1\), and a fraction \(|c_2|^2\) with \(O_2\). Minds are associated with brain
states but are not subject to superposition. In spite of this nonphysicalism,
mental states are supervenient on brain states. Although the time evolu-
tion of each mind is probabilistic, the time evolution of the set of all minds
is deterministic. Albert and Loewer claim that the many-minds view is lo-
cal. Although they do not fully commit to it, they favor the transtemporal
identity of individual minds. Since the transtemporal identity of individual
minds has no ground in physical facts, this makes up for a definitely dualistic
view. Saunders (1996b) notes that there is no mindless hulk problem if the
transtemporal identity of minds is rejected.

Barrett (1995) rehabilitates the SMV, provided the mental dynamics is
suitably constrained by the linear physical dynamics.

Squires (1988) also proposed what amounts to the SMV. Later Squires
(1991, p. 285) introduced a concept of universal consciousness, to avoid the
mindless hulk problem (although he didn’t use the term):

The obvious way of satisfying this requirement [that the choices
made by Jack’s and Jill’s conscious minds be correlated] is to
assume some sort of universality of consciousness so that when,
for example, Jack’s conscious mind is aware of the result, then
‘Conscious Mind’ is also aware of it [...] The [alternative] idea [...] is that, associated with Jack’s brain, there are an infinite number
of conscious minds.

Another advocate of many minds is Lockwood, who first presented his
views soon after Albert and Loewer (Lockwood, 1989, p. 226):

According to the relative state view, there is no collapse (or de-
composition) of the wave function, individual or multiple. Rather
than say that, on the relative state view, the observer splits the
universe by carrying out a measurement, it would be closer to the mark to say that it is the universe that splits the observer.

For Lockwood, multiplicity is associated with higher dimensionality (p. 232):

What I am proposing, following Deutsch, is that we interpret the mathematical formalism of quantum mechanics in such a way that the fact of a physical system’s being in a superposition, with respect to some set of basis vectors, is to be understood as the system’s having a dimension in addition to those of time and space.

Lockwood (1996) further developed the many-minds view and neatly summarized it (pp. 170–171):

A many minds theory, as I understand it, is a theory which takes completely at face value the account which unitary quantum mechanics gives of the physical world and its evolution over time. In particular, it allows that, just as in special relativity there is a fundamental democracy of Lorentz frames, so in quantum mechanics there is a fundamental democracy of vector bases in Hilbert space. In short, it has no truck with the idea that the laws of physics prescribe an objectively preferred basis. For a many minds theorist, the appearance of there being a preferred basis, like the appearance of state vector reduction, is to be regarded as an illusion. And both illusions can be explained by appealing to a theory about the way in which conscious mentality relates to the physical world as unitary quantum mechanics describes it […] Finally, a many minds theory, like a many worlds theory, supposes that, associated with a sentient being at any given time, there is a multiplicity of distinct conscious points of view. But a many minds theory holds that it is these conscious points of view or ‘minds,’ rather than ‘worlds,’ that are to be conceived as literally dividing or differentiating over time—or (as is possible in principle, though unlikely in practice) […] fusing or converging.

Lockwood’s ideas can be formalized as follows: There is a subsystem of the brain which he calls ‘Mind’ (capitalized). Within Mind is an infinite number of minds, and each of them can have only a single ‘maximal experience’ at any
time. In the brain’s Hilbert space is a ‘consciousness basis’ of orthonormal vectors $|\phi_n\rangle$, each one corresponding to a given maximal experience type $E_n$.

Let $\rho = \sum_i w_i |\psi_i\rangle \langle \psi_i|$ be the Mind’s density operator. One can write $|\psi_i\rangle = \sum_n c_{in} |\phi_n\rangle$, and therefore

$$\rho = \sum_{m,n} \left( \sum_i w_i c_{im} c_{in}^* \right) |\phi_m\rangle \langle \phi_n|.$$  \hspace{1cm} (7)

Lockwood postulates that in $\rho$, $E_n$ occurs with weight $\sum_i w_i |c_{in}|^2$. He views that numerical weight as a segment in a direction orthogonal to time. Although he rejects the transporal identity of individual minds, he associates segments corresponding to an instant $t_2$ with segments at $t_1$ through evolution of the $|\phi_n\rangle$.

According to Lockwood the Mind, in order to have a single maximal experience, has to be exactly in a $|\phi_n\rangle$. If it is described by a slightly different mixture, it won’t have a slightly different experience, but a small fraction of minds will rather have vastly different experiences. Note that the existence of an infinite number of minds defined on a substrate with a finite number of particles and states (with energy smaller than some value) seems to introduce a dualistic component in the theory.

Lockwood’s ideas elicited a number of comments. Deutsch (1996, p. 224) believes that the split goes beyond the mind:

Lockwood’s preference for the term ‘many minds’ over ‘parallel universes’ risks giving the impression that it is only minds that are multiple, and not the rest of reality. Nothing could be further from the truth, or from Lockwood’s theory [...] The distinctive assertion of many-minds theories is that the universe perceived by any one mind is not an objectively separate ‘layer’ of the multiverse. It is merely the view of the multiverse from the perspective of that mind.

On the other hand, Butterfield (1996, p. 202) pointed out the macroscopic indefiniteness of Lockwood’s view:

[I]t is worth emphasizing [Lockwood’s interpretation’s] radicalism: it allows the unobserved macroscopic world to be very indefinite, even within a branch.
Earlier, Butterfield (1995, p. 151) had already suggested that many minds “should bite the bullet: the unobserved rock may well not be definite for any reasonable familiar quantity.” Note that Barrett (1999, p. 210) claims that “Lockwood’s denial of the transcendental identity of minds [...] makes his theory empirically incoherent.”

Butterfield (1995, p. 134) points out that the preferred basis indefiniteness is less of a problem in many minds than in many worlds:

[M]ost advocates [of many worlds] have assumed a notion of apparatus, i.e. a distinguished set of subsystems of the universe, and a distinguished quantity on such an apparatus, e.g. position of the apparatus’ pointer. Commentators have often criticized these assumptions as at best imprecise, and at worst question-begging (at least as part of a solution to the measurement problem) [...] As we shall see, [many minds] sees itself, with some justice, as improving on this imprecise answer, in effect by picking out as definite those quantities on the brain that correspond to perception of a definite pointer-position.

His view of many minds is rather close to a modal interpretation (1995, pp. 145–146, 148):

[Many minds] is a proposal for how to pick out the subsystems of the universe, and the quantities (bases) on them, that are to define the branches. Roughly speaking, it proposes that the subsystems be brains (considered as quantum systems), and that the quantities be those quantities whose eigenstates are, or underlie, conscious mental states.

Then the proposal is: mind or consciousness picks out a factorization of the universe’s state-space (into the state-space of the brain, and the state-space of the rest of the universe), and then also picks out a basis on the first factor—the basis of those quantum states that are or underlie conscious mental states. A branch is defined by an element of the basis, together with the relative state of the rest of the universe for that element.

Bacciagaluppi (202, p. 109) believes that “[t]he concept of a brain state corresponding to a definite perception [...] should not be thought of as providing a ‘global’ preferred basis for the universe, but a set of ‘local’ preferred bases, one for every observer.”
Page (1996, 1997) proposed an approach related to many minds, which he calls ‘Sensible Quantum Mechanics’ (SQM). In the spirit of Everett, the quantum state never collapses in SQM, but there is a multiplicity of conscious perceptions. Page (1996, p. 585) bases his approach on three axioms:

**Quantum World Axiom:** The unconscious ‘quantum world’ \( Q \) is completely described by an appropriate algebra of operators and by a suitable state \( \sigma \) (a positive linear functional of the operators) giving the expectation value \( \langle O \rangle \equiv \sigma[O] \) of each operator \( O \).

**Conscious World Axiom:** The ‘conscious world’ \( M \), the set of all perceptions \( p \), has a fundamental measure \( \mu(S) \) for each subset \( S \) of \( M \).

**Quantum-Consciousness Connection:** The measure \( \mu(S) \) for each set \( S \) of conscious perceptions is given by the expectation value of a corresponding ‘awareness operator’ \( A(S) \), a positive-operator-valued (POV) measure [...], in the state \( \sigma \) of the quantum world:

\[
\mu(S) = \langle A(S) \rangle \equiv \sigma[A(S)].
\]

In SQM perceptions are basic, and there is no fundamental way to classify them into individual persons or minds. Page leaves it open whether perceptions, whose measure is determined by the quantum state, in turn affect the quantum state. He sees his approach closer to Lockwood’s than to Albert and Loewer’s.

In a series of papers written over a decade, Donald (1990, 1992, 1995, 1997, 1999) has developed a technically very sophisticated theory of many minds. It is impossible to summarize it in a few paragraphs, but some consequences on multiplicity can be briefly extracted.

Donald presents his views of many minds as follows (1990, p. 48):

[T]he universe exists in some fundamental state \( \omega \). At each time \( t \) each observer \( o \) observes the universe, including his own brain, as being in some quantum state \( \sigma_{o,t} \). Observer \( o \) exists in the state \( \sigma_{o,t} \), which is just as ‘real’ as the state \( \omega \). \( \sigma_{o,t} \) is determined by the observations that \( o \) has made and, therefore, by the state of his brain [...]. The a priori probability of an observer existing in state \( \sigma_{o,t} \) is determined by \( \omega \). It is because these a priori probabilities
are predetermined that the laws of physics and biology appear to hold in the universe which we observe. According to the many-worlds theory, there is a huge difference between the world that we appear to experience (described by a series of states like $\sigma_{\alpha,t}$) and the ‘true’ state $\omega$ of the universe. For example, in this theory, ‘collapse’ is observer dependent and does not affect $\omega$. Analysing the appearance of collapse for an observer is one of the major tasks for the interpreter of quantum theory.

Now one can ask (1990, p. 47), “What sort of quantum state describes a brain that is processing definite information [...]?” Donald proposes that the part of the brain relevant to mind can be modeled by a family of switches. An observed phenomenon is then a pattern of switching in a human brain. “[M]ind exists as awareness of brain, but [...] it has no direct physical effect.” (1990, p. 53.) However (1992, p. 1133) “the (objective) physical substrate of consciousness [...] is not just the instantaneous state of a brain but instead involves the history of that brain.”

In Donald’s approach (1992, p. 1149), “collapse is, one might say, a mistake which the observer makes about the state of the world because he is physically incapable of seeing its true state.” The number of worlds is finite, but may be different from one observer to the next. Donald’s approach is formulated so as to be consistent with special relativity and quantum field theory. In the end (1999, p. 19):

Nothing is ‘real’ except the switching structures of individual observers (each considered separately), the initial condition $\omega$, the underlying quantum field theory, and the objective probabilities defined by the hypothesis. Out of these ‘elements of reality,’ each separate observer must construct his experiences and learn to guess at what his future may bring. This is done by the observer being aware of his structure as awareness of an ‘observed world’. How this might be possible is [...] a sophisticated form of the doctrine that one is aware of the external world entirely through being aware of the history of one’s own brain.

I should note that there is sometimes little distinction between many worlds and many minds, as the following quotes from Vaidman (1998, pp. 245, 255, 257–258) illustrate:
The ‘world’ is a subjective concept of a sentient observer.

The basis of the decomposition [...] of the Universe is determined by the requirement that individual terms $|\psi_i\rangle$ correspond to sensible worlds. The consciousness of sentient beings who are attempting to describe the Universe defines this basis.

Every time we encounter a situation in which, according to the standard approach, collapse must take place, there splitting in fact takes place; and the ambiguity connected with the stage at which collapse occurs corresponds to the subjective nature of the concept of world. While this ambiguity represents a very serious difficulty of the collapse theories, it is not a serious problem in the MWI. The collapse as a physical process should not be vaguely defined, while the vagueness of the concept of a conscious being is more of an advantage than a problem.

4 Decoherent sectors

When Everett’s theory is construed as representing a genuine split into many worlds, the split occurs according to a specific decomposition of the total state vector. That decomposition is taken to coincide with states where the apparatus pointer, or more generally any macroscopic object, is well defined. Clearly, nothing in the total state vector singles out such a decomposition. This is the preferred basis problem.

It turns out, however, that this problem is considerably attenuated if dynamics is added to the instantaneous state vector. This is a consequence of decoherence theory (Schlosshauer, 2004), whose detailed consideration lies beyond the scope of this paper. We will nonetheless say a few words about it, since approaches to Everett discussed in this section make essential use of it.

Let us for the moment go back to (4), and take $O$ to represent a general environment instead of a human observer. Let $\rho$ be the reduced density operator obtained by tracing out the environmental degrees of freedom in the final state. We then get

$$
\rho = |c_1|^2(|a_1\rangle\langle a_1|)(|\alpha_1\rangle\langle \alpha_1|) + |c_2|^2(|a_2\rangle\langle a_2|)(|\alpha_2\rangle\langle \alpha_2|)
+ c_1^* c_2^* \langle O_2|O_1\rangle(|a_1\rangle\langle a_2|)(|\alpha_1\rangle\langle \alpha_2|) + c_1^* c_2 \langle O_1|O_2\rangle(|a_2\rangle\langle a_1|)(|\alpha_2\rangle\langle \alpha_1|).
$$

(8)
It has been shown that in a wide variety of models, the environment states $|O_1\rangle$ and $|O_2\rangle$ are nearly orthogonal if $|\alpha_1\rangle$ and $|\alpha_2\rangle$ represent macroscopic states. The off-diagonal terms in $\rho$ therefore vanish for all practical purposes.

The fact that the right-hand side of (8) essentially coincides with the right-hand side of (5) has sometimes been taken as an implementation of the Dirac–von Neumann collapse. In a collapse, however, $\rho$ is a so-called proper mixture, one that represents ignorance of a true state of affairs that is either $(|a_1\rangle\langle a_1|)(|\alpha_1\rangle\langle \alpha_1|)$ or $(|a_2\rangle\langle a_2|)(|\alpha_2\rangle\langle \alpha_2|)$. But $\rho$ in (8) represents an improper mixture, which cannot be interpreted as ignorance.

The theory of decoherence turns out to be an important building block of an approach to Everett different from many worlds and many minds. The first step in that direction was taken by Gell-Mann and Hartle (1990), whose program “is an attempt at extension, clarification, and completion of the Everett interpretation.” (p. 430.) Gell-Mann and Hartle make use of the consistent histories formalism. In the end however, they take only one world to be real.

In a series of papers published in the 1990s, Saunders (1993, 1995, 1996a, 1996b, 1998) has developed an approach to Everett based on decoherence theory. Saunders begins by developing an elaborate analogy between quantum mechanics and special relativity. He points out that most thinkers nowadays view the notion of ‘now,’ or of ‘the present,’ as relational rather than absolute. Indeed Minkowski’s four-dimensional picture of space-time leaves no room for identifying something like ‘now,’ or an absolute past or absolute future. Time is relational: one can say (in a given Lorentz frame for instance) that an instant $t_2$ is earlier than, simultaneous with or later than $t_1$, but not that it lies in some absolute past, present or future.

So it is, according to Saunders, with actuality in quantum mechanics. Actuality is to be viewed as purely relational.

The basic idea of the relational approach is that this is all that is required at the level of the fundamental equations. What is ‘actual,’ just as what is ‘now,’ are to be understood as facts as relations. There is nothing more to be put in; neither the ‘flow’ of time, taking us from one ‘now’ to the next, nor the reduction of state, taking us from one ‘actuality’ to another. (1995, p. 243.)

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6See also Seidewitz (2007).

7A similar analogy was made in Geroch (1984).
Our approach is of Everett type, qualified as follows: there is a plurality of ‘observers’ or ‘classical worlds’ (Everett worlds), but only in the same Pickwickian sense that there exists a plurality of spacelike hypersurfaces (within a fixed spacetime foliation), a plurality of ‘nows.’ (1993, p. 1554.)

The formalism of quantum mechanics is to be based solely on the universal quantum state and its unitary evolution determined by some universal Hamiltonian operator. Suppose that the right-hand side of (4) represents the universal state at some time $t$, where $|O_1\rangle$ and $|O_2\rangle$ are (nearly) orthogonal environment states. Then $|a_1\rangle|\alpha_1\rangle$ is viewed as actual with respect to $|O_1\rangle$, and $|a_2\rangle|\alpha_2\rangle$ is actual with respect to $|O_2\rangle$. Neither the macroscopic pointer state $|\alpha_1\rangle$ nor the state $|\alpha_2\rangle$ are actual in any absolute sense, but both are actual in a relational sense.

Since no basis is singled out in the universal quantum state, the notion of actuality is not restricted to macroscopically well-defined states. Indeed if (4) is written in terms of linear combinations $|O'_1\rangle$ and $|O'_2\rangle$ of $|O_1\rangle$ and $|O_1\rangle$, then the state actual relative to $|O'_1\rangle$, for instance, will be a linear combination of $|a_1\rangle|\alpha_1\rangle$ and $|a_2\rangle|\alpha_2\rangle$.

The fact that organisms like humans perceive macroscopic objects as definite does not give them any enhanced actuality. “The goal is to define a sense in which ‘the classical’ can be understood as an anthropocentric structure within quantum mechanics.” (Saunders, 1993, p. 1560.) Indeed complex structures are taken to have evolved in the universal state through something like Darwinian pressure. It is a selective advantage to perceive definite macroscopic objects, which is why such objects are actual relative to evolved organisms like humans.

Saunders (1993) also rejects the notion of splitting, no more appropriate than the one of a ‘now’ containing different times.

Wallace (2002, 2003) follows Saunders in the analogy between quantum mechanics and special relativity, as well as on decoherence and evolution favoring the emergence of stable structures. He identifies real structures with stable patterns in the universal quantum state (2003, p. 91):

My claim is instead that the emergence of a classical world from quantum mechanics is to be understood in terms of the emergence from the theory of certain sorts of structures and patterns, and that this means that we have no need (as well as no hope!) of the precision which Kent and others here demand.
Going back to (4) once again, there is one apparatus pattern $|\alpha_0\rangle$ in the universal quantum state at the beginning of the experiment. Therefore there is one apparatus. At the end of the experiment, the universal quantum state contains two distinct apparatus patterns $|\alpha_1\rangle$ and $|\alpha_2\rangle$. Therefore there are now two apparatus. According to Wallace (2003, p. 92), this doesn’t cause problems because

If A and B are to be ‘live cat’ and ‘dead cat’ then P and Q will be described by statements about the state vector which (expressed in a position basis) will concern the wave-function’s amplitude in vastly separated regions $R_P$ and $R_Q$ of configuration space, and there will be no contradiction between these statements.

Just like Saunders, Wallace allows that worlds are imprecisely defined:

The problem given rise to by this abstraction is that there exist many choices of consistent history space, but if we follow Everett and keep the state as fundamental there is no problem. Just as our choice of world-decomposition (i.e. fine-grained basis) is made for ease of description rather than more fundamental reasons, so our choice of history space is just made so as to give a convenient description of the quantum universe. (2002, pp. 648–649.)

Another question which at first sight should have a precise answer: if there was one cat before the measurement and two after it, when exactly did the duplication of cats occur? [...] Put another way, the cat description is only useful when answering questions on timescales far longer than [the decoherence timescale] $\tau_D$, so whether or not quantum splitting is occurring, it just doesn’t make sense to ask questions about cats that depend on such short timescales. (2003, pp. 97–98.)

We should point out that the present approach views the evolution of Schrödinger’s cats quite differently than the many-worlds approach. Let $|\text{Live}\rangle$ and $|\text{Dead}\rangle$ represent states of the live and dead cat, and let $|\text{ND}\rangle$ and $|\text{D}\rangle$ represent states of the decayed and nondecayed nucleus. The compound system starts at $t = 0$ in the state $|\text{ND}\rangle|\text{Live}\rangle$. At time $t$, the state vector has become

$$|\psi(t)\rangle = e^{-\alpha t}|\text{ND}\rangle|\text{Live}\rangle + \sqrt{1 - e^{-2\alpha t}}|\text{D}\rangle|\text{Dead}\rangle,$$  \hspace{1cm} (9)
where $\alpha^{-1}\ln 2$ is the nucleus’ half-life. In the present approach, (9) means that the measure of worlds where the cat is dead continuously increases. In the many-worlds approach, there must be a continuous split of the worlds described by the first term on the right-hand side of (9), so as to constantly increase the number of worlds described by the second term.

It can be argued that nonlocality is less of a problem in decoherence than in many-worlds approaches. Referring to EPR-type experiments, Hewitt-Horsman (2009, p. 888) concludes that

the second particle is still correlated with the first in neo-Everett, and at first glance it would seem that some sort of non-local signal is needed, to tell the worlds of the first particle how they join up with the worlds of the second particle. This is indeed necessary in those many world theories that have spatially extended worlds that split instantaneously.

Butterfield (2001, p. 133) has pointed out the rather complex ontology of Saunders’ and Wallace’s approach:

Saunders and Wallace conclude from these difficulties that we should liberally accept resolutions of the universal quantum state $\Psi$ into an arbitrary basis—or at least an arbitrary basis that is a fine-graining of ‘the’ decoherence basis. In Wallace’s terminology of ‘worlds,’ they consider continuously many bases (even if they restrict themselves to bases that fine-grain ‘the’ decoherence basis), and so commit themselves to continuously many worlds [...]

This is certainly a dizzying ontology. After all, each of these continuously many worlds is ‘inhabited.’ Each world is not just a component of a state (where states represent reality) but also has a ‘system’ (albeit not an ordinary object!) actually in it. They would still have continuously many worlds even if for each basis they said—as they do not—that only one world is ‘inhabited.’

Kent (2010, p. 311) argues that the decoherence approach is close to the many-minds approach:

[I]t seems to me [...] that, at various points in their arguments, Saunders, Wallace, Greaves–Myrvold and Papineau tacitly—and, since they reject the many-minds interpretation, illegitimately—appeal to many-minds intuitions. Indeed, at least in the first
three cases, it seems to me that if one fleshed their ideas out into a fully coherent and complete interpretation, one would necessarily arrive either at the many-minds interpretation or something even worse.

But neither Saunders nor Wallace want to interpret multiplicity in terms of many worlds or many minds. How then are they going to interpret it?

Let us first focus on Wallace’s patterns and, for vividness, formulate the question in terms of Schrödinger’s cat. Wallace claims that there is no contradiction in the simultaneous existence of the live cat and the dead cat. The reason is that they both correspond to well-defined patterns in the universal quantum state and that the two patterns are associated with vastly different regions in configuration space. This is also what happens in classical theory, where two different cats will always occupy vastly different regions in configuration space.

But there is a crucial difference between classical patterns and patterns in the universal state vector. In classical theory, two different cats will not only occupy different regions in configuration space, but they will also occupy disjoint regions in three-dimensional space. That is, their projections from configuration space to three-space will not overlap. This is not so with Wallace’s patterns. Projected in three-space, the live cat may not only step on the dead cat’s tail, he may literally get into it. How can one understand such multiplicity?

One way to understand it is to assume that the live cat and the dead cat don’t project to the same three-space. This would mean that there is an added parameter, or another dimension, introduced to distinguish different three-spaces from each others. It is hard to see, however, what difference there is between this scheme and many worlds.

Another way to understand it is to assume that there is only one three-space into which both patterns project but that they are, so to speak, ghost-like to each other. The live cat’s paw indeed gets into the dead cat’s tail, but he is entirely unaware of it. Or, as Allori et al. (2008, 2009) put it:

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8See also Bacciagaluppi (2002, p. 118): “[I]t should be possible to show that the total set of events will not fit into one simple space-time, but into a branching space-time. The branching space-time ought to be reconstructed from the causal structure of the decoherence events.”

9See Wallace (2012, p. 311): “Other branches, then, are located in precisely the same space and time as our own world; it is just that they are dynamically incapable of (significantly) affecting our world, and vice versa.”
Note that, by the linearity of the Schrödinger evolution, the live cat and the dead cat, that is $m_1$ and $m_2$, do not interact with each other, as they correspond to $\psi_1$ and $\psi_2$, which would in the usual quantum theory be regarded as alternative states of the cat. The two cats are, so to speak, reciprocally transparent. (2009, p. 7.)

Metaphorically speaking, the universe according to Sf or Sm resembles the situation of a TV set that is not correctly tuned, so that one always sees a mixture of two channels. (2008, p. 379.)

It is not clear how physics could be modified to allow for such behavior.

To understand quantum superpositions of macroscopic states like Schrödinger’s cats, Wallace (2012, pp. 36–37) makes an analogy with electromagnetic fields. Let $F_1(x,t)$ represent an ultraviolet pulse going from the Earth to the Moon, and let $F_2(x,t)$ represent a similar pulse going from Venus to Mars. According to Wallace, the field $0.5F_1 + 0.5F_2$ represents two different pulses, rather than a single pulse in a weird superposition. So far so good. But if the two fields overlap in a single region of space-time, then at any space-time point it is more appropriate to say that there is only one field, witness its action on a test charge.

If one follows Saunders and accepts that actuality is relational, perhaps then that space itself is relational. Again, this would require new physics, since both in nonrelativistic quantum mechanics and in quantum field theory, the space-time arena is presupposed antecedently. Three-dimensional space cannot be taken as emerging solely from the wave function, since all separable Hilbert spaces are isomorphic.

5 Discussion

After 50 years, there is no well-defined, generally agreed set of assumptions and postulates that together constitute ‘the Everett interpretation of quantum theory.’ (Kent, 2010, p. 307.)

This assessment, I believe, has been substantiated in this paper with respect to multiplicity: Are worlds physically splitting, or does the split happen only in the mind? Do worlds split locally or globally, instantaneously or on some other space-time hypersurface? Are worlds generated upon any entanglement-producing interaction, or only when macroscopic objects or apparatus are involved? Do worlds split or bifurcate? Do they occupy the same space?
physical space-time or do they involve extra dimensions? These and others are all questions on which different investigators disagree, or even questions that have received different answers at different times from the same investigator. This, I should stress, is not meant as a charge of inconsistency, since opinions and points of view naturally evolve in the course of research. But it illustrates how long the road still is to a full clarification of Everett’s interpretation.

I am much attracted by the so-called semantic view of theories which, as far as quantum mechanics is concerned, construes interpretation as answering the question “How can the world be for quantum mechanics to be true?” From such a point of view, dealing with different consistent interpretations of a theory provides clarification and understanding rather than confusion (Marchildon 2004, 2009). There is no doubt that Everett’s relative states approach constitutes a major contribution to the debate on the interpretation of quantum mechanics. Every interpretation of quantum mechanics has its shortcomings, since none has yet rallied general support. But in closing I would like to stress a few problems that are perhaps more specific to Everett’s theory.

The first problem is what has been documented here, that Everett’s theory is not well defined. Such a charge can also be levelled at the Copenhagen interpretation or at the Dirac–von Newmann collapse postulate. This is in sharp contrast with the de Broglie–Bohm approach which, at least in the nonrelativistic case, is precisely defined. I also believe that the more recent approach of Quantum Bayesianism (Fuchs et al., 2014) is well defined, although it has problems of its own (Marchildon, 2015). In all fairness, the de Broglie–Bohm approach also has yet unsolved problems in the relativistic or field-theoretic case.

What I see as the second problem with Everett’s approach may well be viewed as a virtue by its advocates: it is the fact that the approach stands or falls with the exact validity of quantum mechanics. Add the smallest nonlinear term to the Schrödinger equation, and Everett’s many worlds disappear just like rings of smoke. The provisional status of fundamental theories suggests that wide-ranging ontological claims should not depend on such strong assumptions. By contrast, the de Broglie-Bohm approach is highly adaptable to changes in the formalism of quantum mechanics (Valentini, 2010).

Finally, I cannot help comparing Everett’s extraordinary ontology with other such wildly counter-intuitive instances in the history of thought. I have in mind, for instance, Parmenides’ rejection of motion to match a theory of
being, or Berkeley’s rejection of matter to avoid the mind-body problem. In experimental science, Carl Sagan’s motto that “Extraordinary claims require extraordinary evidence” is a good methodological attitude. It has led for instance to extreme caution a few years ago, when an announcement was made that neutrinos might travel faster than light (a claim that was later retracted). It seems to me that much skepticism about Everett’s approach and its many implementations stems from the fact that in spite of valiant attempts (Deutsch, 1997), the strength of arguments in favor of it do not match the scope of its claim.

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