frontiers in Physics

PERSPECTIVE
published: 06 February 2018
doi: 10.3389/fphy.2018.00004

Is the Quilted Multiverse Consistent with a Thermodynamic Arrow of Time?

Yakir Aharonov [1,2], *Eliahu Cohen* [3]* and *Tomer Shushi* [4]

[1] School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel, [2] Schmid College of Science, Chapman University, Orange, CA, United States, [3] H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom, [4] Department of Physics, Ben-Gurion University of the Negev, Beersheba, Israel

Theoretical achievements, as well as much controversy, surround multiverse theory. Various types of multiverses, with an increasing amount of complexity, were suggested and thoroughly discussed in literature by now. While these types are very different, they all share the same basic idea: our physical reality consists of more than just one universe. Each universe within a possibly huge multiverse might be slightly or even very different from the others. The quilted multiverse is one of these types, whose uniqueness arises from the postulate that every possible event will occur infinitely many times in infinitely many universes. In this paper we show that the quilted multiverse is not self-consistent due to the instability of entropy decrease under small perturbations. We therefore propose a modified version of the quilted multiverse which might overcome this shortcoming. It includes only those universes where the minimal entropy occurs at the same instant of (cosmological) time. Only these universes whose initial conditions are fine-tuned within a small phase-space region would evolve consistently to form their "close" states at present. A final boundary condition on the multiverse may further lower the amount of possible, consistent universes. Finally, some related observations regarding the many-worlds interpretation of quantum mechanics and the emergence of classicality are discussed.

Keywords: quantum cosmology, multiverse theory, arrow of time, many-worlds interpretation, stability
PACS numbers: 05.70.-a, 98.80.Qc, 03.65.Ta

Edited by:
Ignazio Licata,
ISEM-Institute for Scientific Methodology, Italy

Reviewed by:
Ovidiu Cristinel Stoica,
Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Romania
Daniel Sheehan,
University of San Diego, United States

***Correspondence:**
Eliahu Cohen
eli17c@gmail.com

Specialty section:
This article was submitted to Interdisciplinary Physics, a section of the journal Frontiers in Physics

Received: *03 November 2017*
Accepted: *19 January 2018*
Published: *06 February 2018*

Citation:
Aharonov Y, Cohen E and Shushi T (2018) Is the Quilted Multiverse Consistent with a Thermodynamic Arrow of Time? Front. Phys. 6:4. doi: 10.3389/fphy.2018.00004

1. INTRODUCTION

Multiverse theory (also known as Meta universe theory) is a group of models assuming that our physical reality encompasses more than one universe, i.e., there exists at least one more universe other than ours. Several types of such multiverses are known in literature [1–12].

Some of these models suggest that our physical reality comprises of infinitely many universes[1], while others postulate that we live in a multiverse with a finite number of universes. Most multiverse theories imply that universes might not be uniquely identified through their macroscopic state at present or past, i.e., their macrostates could be quite similar during long and even infinite time intervals. The ultimate multiverse model (also known as the mathematical multiverse) [13] satisfies this property and postulates that every possible state is in one-to-one correspondence with each universe from the multiverse horizon.

[1] In the context of this work we shall assume a discrete phase-space, meaning that all infinities are countable.

One of the most common explanations of the big-bang is given by quantum fluctuation theory, which suggests that our universe began from a quantum fluctuation, and if so, it is natural to deduce that in our physical reality these fluctuations are taking place in all of our space and time dimensions (see [8] for instance). Therefore, an infinite number of such fluctuations implies a vast multiverse of infinite number of universes.

The multiverse type that we shall focus on is the quilted multiverse [11], whose infinite space and time dimensions presumably contain infinite number of universes. In Greene's words [11]: "At any moment in time, the expanse of space contains an infinite number of separate realms-constituents of what I'll call the Quilted Multiverse-with our observable universe, all we see in the vast night sky, being but one member. Canvassing this infinite collection of separate realms, we find that particle arrangements necessarily repeat infinitely many times. The reality that holds in any given universe, including ours, is thus replicated in an infinite number of other universes across the Quilted Multiverse."

The quilted multiverse provides a theoretical probabilistic approach for the existence of events before the event horizon in our physical reality. Within the quilted multiverse, the event horizon includes events that occur infinitely many times, duplicated in infinitely many universes, which might be finite or infinite. From the characterization above we deduce that there are universes within the quilted multiverse that are not only "close" at a given time (e.g., at present), that is, similar in a sense that will be defined below, but have been very "close" for a substantially large time interval. In terms of Tegmark's hierarchy [12], the quilted multiverse we shall study corresponds to a level 1 multiverse. This type of multiverse postulates that every universe in the multiverse shares the same physical constants (e.g., the Planck constant $\hbar$ and the speed of light c), while other types of multiverses suggest that the physical constants and even physical laws are different within different universes (e.g., string theory landscape [14]). The main argument for this kind of multiverse with different physical constants is that for different universe we would have different spontaneous symmetry breaking and thus different physics. Since there are already several arguments against this type of multiverse (see [15] for instance), we will focus in this paper on the quilted multiverse where parallel universes share the same physical constants and same physical laws. We also emphasize that the quilted multiverse differs from the inflationary multiverse. The former emerges if the extent of space is infinite, while the latter's variety emerges from eternal inflationary expansion. We would assume that the multiple universes within the quilted multiverse can be coarse-grained in a countable manner, they have the same common cosmological features and same local laws, and they do not interact with each other.

We claim in this work (based on our preprint [16]) that the quilted multiverse is not consistent with basic thermodynamic assumptions. In the following section we discuss a thermodynamic arrow of time defined by the stability of entropy increase. In section 3 we present an inconsistency of the quilted multiverse and the proposed thermodynamic arrow of time. Section 4 discusses an upper bound to the number of parallel universes in the quilted multiverse, and section 5 attempts to broaden these results toward other kinds of multiverse when adding to the analysis a final boundary condition. Section 6 concludes the paper.

2. A SUBTLE THERMODYNAMIC ARROW OF TIME

Time seems to incessantly "flow" in one direction, raising the ancient question: Why? This intensively discussed question can be answered in several ways by introducing seemingly different time arrows: thermodynamic, cosmological, gravitational, radiative, particle physics (weak), quantum, and others [17, 18]. We employ in this paper the cosmological arrow of time, which points in the direction of the universe's expansion. This choice implies that parallel universes with the same macrostate will have the same time. Our main argument, however, will rely on thermodynamic stability under small perturbations which allows to define another crucial arrow of time— *the macroscopic behavior of a large system is stable against perturbations as far as its future is concerned, but for most cases is very unstable as far as its past is concerned.* [19, 20]. The positive direction of time is thus determined according the system's stability under small perturbations. Indeed, performing a slight microscopic change (not to mention a large macroscopic change) in the system's past will not change, in general, its macrostate at future times, i.e., the system will end up its time evolution with the same high entropy macrostate. However, when propagating backwards in time, such a slight change in the system's future will have far-reaching consequences on its past [19, 20]. This is the key observation we shall utilize next, akin to the thermodynamic arrow of time which relays on the second law of thermodynamic (although some subtle challenges are known in literature [21, 22]). The difference in terms of stability between future and past stems from the fact that any perturbation of a microstate will tend to make it more typical of its macrostate and thus small perturbations will not interfere with (forward in time) typical evolution. Backwards in time, however, the microstate will propagate toward a smaller phase space volume which is untypical of the macrostate. This difference in Lyapunov stability was rigorously quantified, e.g., in Hoover and Posch [23] and Sarman et al. [24].

In this perspective paper we will formally treat a universe parallel to ours, having at present time a similar macrostate or even the same macrostate, yet with a slightly different microstate as a perturbation. Then we will try to apply the above thermodynamic reasoning.

3. INCONSISTENCY OF THE QUILTED MULTIVERSE

Before we claim that the quilted multiverse is inconsistent with the instability of entropy decrease discussed in section 2, let us define some mathematical symbols which will be useful later on. First, suppose that we have an infinite (yet countable) number of universes, denoted by

$$\mathcal{U} = \{\mathcal{U}_1, \mathcal{U}_2, \ldots\}, \tag{1}$$

where each universe $\mathcal{U}_j$ has the (quantum) microstate $\Psi_j(t)$, and t is the cosmological time.

Further, let us define in phase space a distance measure Δ, which quantifies the difference between the microstate of the $j-$th universe, $\Psi_j(t)$, and the microstate of the $i-$th universe, $\Psi_i(t)$, at some time $t_i = t_j = t$

$$\Delta(\Psi_j(t), \Psi_i(t)) > 0, \tag{2}$$

for $i \neq j$. We hereby define $0 \leq \Delta \leq 1$ to be the ratio between the number of particles whose (possibly entangled) states are orthogonal and the total number of particles. This definition might not be unique (or the most robust) but it captures our intuition as to microscopic proximity of similar/identical macroscopic states. According to this definition and Greene's description of the quilted multiverse, for every $\varepsilon > 0$ there exist at least two universes such that

$$\Delta(\Psi_j(t), \Psi_i(t)) \leq \varepsilon, \ \forall t \in T, \tag{3}$$

where $T = [t_0, t_f]$ is some long time interval comparable with the age of the universes.

Moreover, from the above description of the quilted multiverse, we deduce that every possible event will occur an infinite (countable) number of times. Therefore, this model suggests that there should exist a set W such that

$$W = \{(i,j) | \Delta(\Psi_j(t), \Psi_i(t)) \leq \varepsilon, \forall t \in T\}, |W| = \aleph_0 \tag{4}$$

where ε is some threshold below which we may say that the universes are "close", and W is the set of all possible pairs of universes from the infinite multiverse (Equation 1) that are "close" for a period of time comparable with their age.

We now show that Equation (4) is not consistent with the thermodynamic arrow of time defined in section 2 (it will be implicitly assumed that the universe is in a non-equilibrium state). First, notice that if we have a thermodynamic system $\mathcal{V}$ with the macroscopic state $M_{\mathcal{V}}(t)$ at the cosmological time t, there exist more than one possible quantum state $\Psi_{\mathcal{V}}(t_0)$ (for every $0 < t_0 < t$) that will produce $M_{\mathcal{V}}(t)$ in time t, i.e., there is some volume in the past phase space of (quantum) microscopic states that could reproduce the present macroscopic state. However, a slightly different universe at present (analogous to a small perturbation of the first) would correspond in general to a very different volume in the past phase space [19, 20], which would in turn correspond to a markedly different macroscopic state for all times. Therefore, the backwards evolution in time (presumably dictated by the same dynamical rules) of two very close universes at present will result in two very far universes at the past (see **Figure 1**), thus negating (Equation 4).

There is only a negligible probability that two close universes at present, will evolve backwards in time to two close universes in the past (see also [25]).

Also, it is inconsistent to assume that any arbitrary change to our current universe is a valid parallel universe having the same historical source in phase space or having the same point in time of minimum entropy.

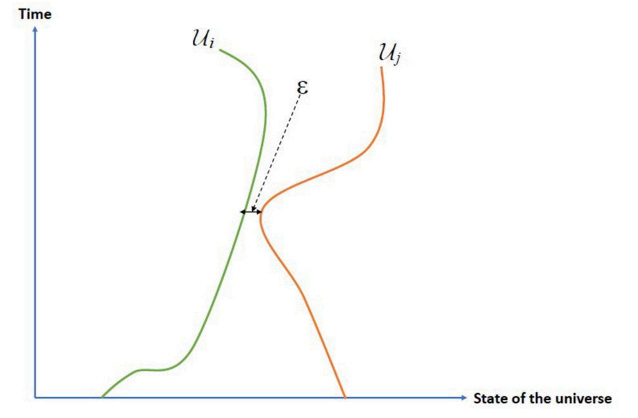


FIGURE 1 | Two "close" universes at present time were most likely "far" in the past.

The number of possible universes can be represented by the Boltzmann relation between entropy S and the set Ω of possible microstates corresponding to the same macrostate,

$$S = k_B \ln |\Omega|, \tag{5}$$

where k_B is the Boltzmann constant.

Then, given the entropy of the i-th universe, $S_{\mathcal{U}_i}$, $|\Omega_{\mathcal{U}_i}|$ is

$$|\Omega_{\mathcal{U}_i}| = e^{S_{\mathcal{U}_i}/k_B}. \tag{6}$$

Assuming that during its 13.8 billion years of history the universe has reached a very large entropy $S_{\mathcal{U}_i} \gg k_B$, we have a huge set of possible microstates $\Omega_{\mathcal{U}_i}$. Let us examine a pair of universes having at t' close states, i.e., $\Delta(\Psi_i(t'), \Psi_j(t')) \simeq 0$, where $\Psi_i \in \Omega_{\mathcal{U}_i}$, $\Psi_j \in \Omega_{\mathcal{U}_j}$ and $|\Omega_{\mathcal{U}_i}| = |\Omega_{\mathcal{U}_j}|$. We claim that at arbitrary time $t'' \ll t'$ they will most likely have $|\Omega_{\mathcal{U}_i}| \neq |\Omega_{\mathcal{U}_j}|$, and the probability that $\Delta(\Psi_i(t''), \Psi_j(t'')) \simeq 0$ will be close to zero. This follows from the fact that $\Omega_{\mathcal{U}_k}(t'')$ is now the backward-in-time evolution of $\Omega_{\mathcal{U}k}(t')$, $k = i, j$, which is a set with very large number of possibilities, so that the probability

$$\Pr\left(|\Omega_{\mathcal{U}_i}(t'')| \simeq |\Omega_{\mathcal{U}_j}(t'')| \mid |\Omega_{\mathcal{U}_i}(t')| \simeq |\Omega_{\mathcal{U}_j}(t')|\right), \tag{7}$$

will be zero.

Another way to see this inconsistency is to consider the point of minimal entropy during the lifetime of our universe. When picking at random another hypothetical universe having at present the same macrostate as our universe, it is most likely to have its minimal entropy at some other time different from ours (most likely after ours). Hence, the histories of the two universes cannot be the same, unless we focus at present only on the zero measure of macrostates having their minimal entropy at exactly the same time as ours.

4. UPPER BOUND TO THE NUMBER OF PARALLEL UNIVERSES IN THE QUILTED MULTIVERSE

We shall try to approach the problem from a different perspective now, beginning with some qualitative considerations. One should note two extreme distance scales between universes in a multiverse. When two universes are extremely close (that is, different but virtually indistinguishable so that $0 < \Delta \ll 1$) at some point in time, they may have a non-negligible probability evolving backwards to extremely close initial states, thereby creating no inconsistency. However, having infinitely many universes which are identical to ours for all practical purposes is not too interesting. On the other hand, if two universes are far apart right now, stability (which corresponds to small perturbation) again plays no role. But this is not the case we wish to rule out.

Between these two contingent cases, lie the problematic distances to which instability considerations can be applied. This may pose a constraint on the distribution of universes within a multiverse—there might be infinitely many universes which are very far from each other and an infinite number of universes which are extremely close, but we do not expect too many universes to be intermediately close when we demand consistency over long times.

Let us examine now for concreteness a $6N$-dimensional quantum phase space. Let us suppose for simplicity that the phase space is discrete and focus on some large yet finite part of it. We can therefore think about this sector as a hypercube with a fine grid. A universe j within this sector is represented e.g., by a Wigner quasi-distribution $W\left(X_j, P_j\right)$ on the grid, where X_j/P_j encapsulates the three position/momentum vectors, respectively, of each particle in this universe. We now start to gradually fill the hypercube with more and more distributions. We begin with those having a slight overlap (or no overlap at all) with the original one and with each other, thus corresponding to universes which are very different. As this process continues, we will have to fill the finite phase space with more and more distributions, closer to each other, until a point (let us denote it by $\Delta = D$) when they become very close, such that distance between the universes characterizes a small perturbation. We would thus unavoidably create at least two universes that are too close to each other. Too close, in the sense that one can be thought of as a small perturbation to the other, and then upon backward evolution in time, they would most likely reach inconsistent states.

We now apply similar arguments to those appearing at the end of the previous section. It seems that in a countably infinite phase space (allowing a countably infinite number of parallel universes) and a finite point in time t, there might be only a finite number of consistent parallel universes whose Δ separation is very close until time $t = 0$, but we leave this as a conjecture. In any case, we would like to point out that an infinite number of parallel universes might be ruled out this way just as a result of thermodynamic considerations.

To resolve this apparent shortcoming of the quilted multiverse we must pose a condition on the possible distance between the universes, and eventually on their density. In case that

$$\Delta\left(\Psi_i, \Psi_j\right) \geq D,\ \forall\, i, j \tag{8}$$

for some threshold $0 < D < 1$, we potentially find a consistent multiverse that does not violate the aforementioned notion of stability. To this microscopic condition we add the macroscopic demand that despite the distance, the various universe would still describe the same macrostate at all times, and in particular would have their minimal entropy state at the same cosmological time. Of course, this multiverse is different from the quilted multiverse, and hence we call it the "Modified quilted multiverse."As opposed to the ordinary quilted multiverse, it might coexist with thermodynamic laws, yet may still violate other basic requirements like Occam's razor[2].

5. GENERALIZATIONS EMPLOYING A FINAL BOUNDARY CONDITION

It could be interesting to apply the above considerations to other kinds of multiverses. However, when the values of physical constants, and moreover, physical laws themselves, in other universes become different from those we know now in our universe, the distance between our universe and others might be very large at present (and furthermore vary with time). Therefore, it is not obvious how to apply stability considerations to these kinds of multiverse.

On the other side of the multiverse scale, there is the many worlds interpretation of quantum mechanics (also known as the quantum multiverse). In previous works [26–28], two of us have employed a final boundary condition on the universe which is of special kind. This unique boundary condition allowed us to overcome some conceptual difficulties appearing in the many worlds interpretation. In particular, we suggested a model for a macroscopically reversible universe without the need of employing infinitely many parallel universes. Furthermore, we were able to devise an effective collapse mechanism in this single-branched "modest" multiverse structure. Finally, our proposed two-time decoherence scheme allowed to draw the boundary between the classical and quantum regimes.

These past results hint that the multitude of universes proposed by the many-worlds interpretation may not be needed in order to account for our empirical observations in a time-symmetric manner. Other kinds of multiverse can be handled the same way, and indeed, posing both initial and final boundary conditions on a multiverse should dramatically lower the measure of possible universes within it: Regardless of the dynamics, when the final state of the multiverse is evolved backwards in time, it must be compatible with any earlier state. As noted in Aharonov and Reznik B [29], some final boundary conditions give rise to the Born rule, and are hence preferable

[2]In the quilted multltiverse, the number (or commonness) of universes does not correspond to probability/Born rule, but in contrast, for the many-worlds-type multiverse we would have to employ a different logic as presented in section 5.

over others. Further conditions on the final state may even isolate a unique set of final boundary conditions with a higher explanatory power. These include our proposal for a quantum universe having a natural notion of classicality emerging from the requirement to store microscopic information in a redundant manner [26–28]. A recently analyzed feature of this time-symmetric universe is a top-down logical structure [30], which could further shed light on the subtle relations between micro and macro scales.

6. CONCLUSIONS

Multiverse theory has various models that describe different structures of the physical reality. One of these models is the quilted multiverse, which postulates that every possible event is occurring infinitely many times in nature, thus there are infinitely many universes resembling ours. At first glance, this model seems to be self-consistent. However, we have shown that this model negates basic thermodynamic principles. The difference between microstates in two "close" universes cannot be ϵ small at each point in time, or even along a finite, sufficiently large time interval. Therefore, any possible type of multiverse would better not assume such a relation between two universes. Moreover, every universe must have its unique past and future in the sense that there is no other universe with the same, or even very close, state over a substantial part of its life time. We therefore have to limit ourselves only to those universes whose macrostates at present time evolve backwards to the same point in time of minimal entropy such as ours. These obviously reside in a very small fraction of phase space and may evolve in a consistent way. Further constraints on the number of possible universes may arise when augmenting this analysis with a final boundary condition on the multiverse.

These findings corroborate previous ones of our group [26–28], suggesting that in addition to apparent inconsistencies and various conceptual problems, the overwhelming multitude exhibited by multiverse theory in general, and the quilted mutliverse/many worlds interpretation in particular, might not be needed in order to satisfactorily account for our observations in the classical and quantum realms using a single, unique universe.

AUTHOR CONTRIBUTIONS

YA: Initiated the work; YA, EC, and TS: Developed the presented ideas; EC and TS: Wrote the manuscript with comments from YA.

ACKNOWLEDGMENTS

We wish to thank Avshalom C. Elitzur and Daniel Rohrlich for helpful comments. YA acknowledges support of the Israel Science Foundation Grant No. 1311/14, of the ICORE Excellence Center "Circle of Light" and of DIP, the German-Israeli Project cooperation. EC was supported by ERC AdG NLST. TS thanks the John Templeton Foundation (Project ID 43297) and from the Israel Science Foundation (grant no. 1190/13). The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of any of these supporting foundations. A earlier version of this work is available as an arXiv preprint [16] (under arXiv.org perpetual, non-exclusive license to distribute this article).

REFERENCES

1. Albrecht A, Sorbo L. Can the universe afford inflation? *Phys Rev D* (2004) **70**:063528. doi: 10.1103/PhysRevD.70.063528
2. Carr B. *Universe or Multiverse?* Cambridge: Cambridge University Press (2007).
3. Czech B. Grainy multiverse. *Phys Rev D* (2011) **84**:064021. doi: 10.1103/PhysRevD.84.064021
4. Johnson MC, Lehners JL. Cycles in the multiverse. *Phys Rev D* (2012) **85**:103509. doi: 10.1103/PhysRevD.85.103509
5. Robles-Perez S, González-Díaz PF. Quantum state of the multiverse. *Phys Rev D* (2010) **81**:083529. doi: 10.1103/PhysRevD.81.083529
6. Wallace D. *The Emergent Multiverse: Quantum Theory According to the Everett Interpretation*. Oxford: Oxford University Press (2012).
7. Weinberg S. Living in the multiverse. In: Carr B, editor. *Universe or Multiverse?* Cambridge: Cambridge University Press (2007). p. 29–42.
8. Garriga J, Vilenkin A. Many worlds in one. *Phys Rev D* (2001) **64**:043511. doi: 10.1103/PhysRevD.64.043511
9. Garriga J, Schwartz-Perlov D, Vilenkin A, Winitzki S. Probabilities in the inflationary multiverse. *J Cosmol Astropart P* (2006) **2006.01**:017. doi: 10.1088/1475-7516/2006/01/017
10. Garriga J, Vilenkin A. Holographic multiverse. *J Cosmol Astropart P* (2009) **2009.01**:021. doi: 10.1088/1475-7516/2009/01/021
11. Greene B. *The Hidden Reality: Parallel Universes and the Deep Laws of the Cosmos*. New York, NY: Vintage (2011).
12. Tegmark M. The multiverse hierarchy. In: Carr B, editor. *Universe or Multiverse?* Cambridge: Cambridge University Press (2007). p. 99–126.
13. Tegmark M. The mathematical universe. *Found Phys.* (2008) **38**:101–50. doi: 10.1007/s10701-007-9186-9
14. Susskind L. The anthropic landscape of string theory. In: Carr B, editor. *Universe or Multiverse?* Cambridge: Cambridge University Press (2007). p. 247–66.
15. Weinberg S. Physics: what we do and don't know. *The New York Review of Books*. (2007).
16. Aharonov Y, Cohen E, Shushi T. Is the quilted multiverse consistent with a thermodynamic arrow of time? *arXiv:1608.08798*. (2016).
17. Savitt SF. *Time's Arrow Today*. Cambridge: Cambridge University Press (1995).
18. Zeh HD. *The Physical Basis of the Direction of Time*. Heidelberg:Springer (2001).
19. Lebowitz JL. Macroscopic laws, microscopic dynamics, time's arrow and Boltzmann's entropy. *Phys A* (1993) **194**:1–27.
20. Lebowitz JL. Statistical mechanics: a selective review of two central issues. *Rev Mod Phys.* (1999) **71**:S346.
21. Cápek V, Sheehan DP. *Challenges to the Second Law of Thermodynamics*. Dordrecht: Springer (2005).
22. Sheehan DP. Quantum limits to the second law. *Entropy* (2003) **4**:183. doi: 10.3390/e4060183
23. Hoover WG, Posch HA. Second-law irreversibility and phase-space dimensionality loss from time-reversible nonequilibrium steady-state Lyapunov spectra. *Phys Rev E* (1994) **49**:1913.

24. Sarman S, Evans DJ, Morriss GP. Conjugate-pairing rule and thermal-transport coefficients. *Phys Rev A* (1992) **45**:2233.
25. Aharonov Y, Brout R, Englert F. La notion de temps. In: Gevenois PA, editor. *Le vieillissement*. Brussels: Les Editions De L'universite De Bruxelles (1997) 13.
26. Aharonov Y, Cohen E, Gruss E, Landsberger T. Measurement and collapse within the two-state vector formalism. *Quant Stud Math Found.* (2014) **1**:133–46. doi: 10.1007/s40509-014-0011-9
27. Cohen E, Aharonov Y. Quantum to classical transitions via weak measurements and postselection. In: Kastner R, Jeknic-Dugic J, Jaroszkiewicz G, editors. *Quantum Structural Studies: Classical Emergence from the Quantum Level*. Singapore: World Scientific Publishing (2017). p. 401–25.
28. Aharonov Y, Cohen E, Landsberger T. The two-time interpretation and macroscopic time-reversibility. *Entropy* (2017) **19**:111. doi: 10.3390/e19030111
29. Aharonov Y, Reznik B. How macroscopic properties dictate microscopic probabilities. *Phys Rev A* (2002) **65**:052116. doi: 10.1103/PhysRevA.65.052116
30. Aharonov Y, Cohen E, Tollaksen J. A completely top-down hierarchical structure in quantum mechanics. *arXiv:1709.07052*. (2017).

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

quantum reports

MDPI

Article

Everett's Multiverse and the World as Wavefunction

Tappenden Paul

44 bd. Nungesser, 13014 Marseille, France; paulpagetappenden@gmail.com

Received: 1 September 2019; Accepted: 9 September 2019; Published: 12 September 2019

Abstract: Everett suggested that there's no such thing as wavefunction collapse. He hypothesized that for an idealized spin measurement the apparatus evolves into a superposition on the pointer basis of two apparatuses, each displaying one of the two outcomes which are standardly thought of as alternatives. As a result, the observer 'splits' into two observers, each perceiving a different outcome. There have been problems. Why the pointer basis? Decoherence is generally accepted by Everettian theorists to be the key to the right answer there. Also, in what sense is probability involved, when all possible outcomes occur? Everett's response to that problem was inadequate. A first attempt to find a different route to probability was introduce by Neil Graham in 1973 and the path from there has led to two distinct models of branching. I describe how the ideas have evolved and their relation to the concepts of uncertainty and objective probability. Then I describe the further problem of wavefunction monism, emphasized by Maudlin, and make a suggestion as to how it might be resolved.

Keywords: everett interpretation; many worlds interpretation; everettian quantum mechanics; quantum probability; wavefunction realism

---

There may be a way to maintain a monistic wavefunction ontology, but it is certainly not trivial to see what that way is [1], p. 129 and original emphasis.

1. Two Concepts of Branching

There are two ways to model branching, both of which can be illustrated by the waters of a river being distributed into the streams of an estuary. If water is thought of as a continuous substance, as many physicists still believed not much more than a century ago, the river splits into lesser streams. However, if water is composed of particles, each particle follows a linear trajectory taking it on a unique path to the sea; no particle splits. It was clearly the former analogy which Hugh Everett III had in mind when he proposed what he called the relative state formulation of quantum mechanics. He wrote of observers splitting in quantum measurement contexts [2].

An observer about to make an idealized z-spin measurement on an x-spin-up particle is to be thought of as splitting into an observer perceiving the outcome U (z-spin-up) and an observer perceiving the outcome D (z-spin-down). On a stochastic interpretation of quantum mechanics, where exclusively one or the other outcome is thought to occur, the pre-measurement observer assigns probabilities for the later occurrence of U and D according the Born rule, where the probability of U plus the probability of D is equal to 1 for the idealized case. However, how can an observer who expects to split assign probabilities to future observations? Jeffrey Barrett argues that it was dissatisfaction with Everett's attempted response to this problem which led Neill Graham to propose an alternative structure to the branching process [3].

I shall use the analogy of a bifurcating road to make the change of perspective vivid. For the idealized measurement there are just two branches, one for the outcome U and the other for the outcome D. Each branch has a quantum amplitude whose absolute square is commonly called the branch weight (W) where $W_U + W_D = 1$. For the road analogy W can be imagined as corresponding to width. Everett thought in terms of a road of unit width bifurcating into two roads of lesser widths which sum to unity. The observer can be thought of as travelling along the unit road and splitting in an amoeba-like way at the junction into an observer on the *U* road and an observer on the *D* road. Everett himself used the analogy of an amoeba in an unpublished manuscript [4]. As Barrett explains, Everett thought of an observer conducting a series of such measurements as repeatedly splitting and attempted to analyze the statistical recordings for the resulting set of observers in terms of a notion of typicality which would do the work of a standard probabilistic assessment of statistical evidence.

Graham sought to bring a probability more directly into the picture by modifying the concept of branching. Instead of our road bifurcating into two roads it bifurcates into two *sets* of roads in such a way that the *measure* of the *U* set of roads is W_U and the measure of *D* set is W_D. We can now imagine that on making the measurement the observer splits into some number N (W_U) of observers observing *U* and N (W_D) of observers observing *D* [5]. The idea is blatantly ad hoc but that's not the only problem.

As Barrett points out, there's an implicit assumption of a principle of indifference: The idea that the original observer is equally likely to find themself on any one of the plethora of post-measurement branches [3]. It's also puzzling why *the* pre-measurement observer should somehow expect to find themself on any one of the post-measurement branches. In what sense can any one of the downstream observers be identified with the upstream observer? An attempt to meet the latter problem was made by David Deutsch when he wrote: "I propose a slight change in the Everett interpretation: Axiom 8. The world consists of a continuously infinite-measured set of universes. By a 'measured set' I mean a set together with a measure on that set [6]".

He continued as follows (by substituting {2} for Deutsch's term I have adapted the citation to make 'model measurement' refer to our idealized spin measurement): "Each of these subsets [of the original set of universes], which I shall call a branch, consists of a continuous infinity of identical universes. During the model measurement, the world has initially only one branch and is partitioned into {2} branches. The branches play the same role as individual universes do in Everett's original version, but the probabilistic interpretation is now truly 'built in' [6], original italics".

To continue with the road analogy, we now have a continuous infinity of roads running parallel, on each of which are isomorphic observers about to make 'identical' measurements. Like the particles of water which never split, no road bifurcates but when the parallel measurements occur each road does a dogleg turn so that the original set of roads partitions into a subset which constitutes the *U* branch, measure W_U, and a subset which constitutes the *D* branch, measure W_D.

In each of Deutsch's identical universes the result of the target measurement is destined to be either *U* or *D* but an observer is in principle unable to determine in advance whether s/he inhabits a universe where the result will be *U* or a universe where the result will be *D*. Although he doesn't explicitly say so, Deutsch thus appeals to a notion of self-location ignorance to introduce pre-measurement uncertainty. Prior to the measurement an observer doesn't know which sort of identical universe s/he inhabits, one in which *U* will occur or one in which *D* will occur. That's why Deutsch sees his proposal as making a probabilistic interpretation of the branching process 'built in'. (Deutsch has confirmed that he was indeed thinking in terms of self-location uncertainty at the time. Private communication.)

Hilary Greaves interpreted Deutsch's proposal in this way, writing: "David Deutsch suggests that, to solve the incoherence problem, the ontology of the many-worlds interpretation needs to be supplemented. In addition to the quantum state of the universe, we are to postulate a continuously infinite set of universes, together with a preferred measure on that set. The measure is such that, when a measurement occurs, the proportion of universes in the original branch that end up on a given branch is given by the mod-squared measure of that branch. Observers can then be uncertain about which outcome will occur in the universe they are in [7], §1.2, original emphasis".

Strictly speaking the term 'proportion' doesn't apply to Deutsch's infinite set of identical universe but Greaves here recognizes that Deutsch has attempted to resolve what she called the *incoherence problem* for Everettian theory, though she didn't embrace the proposal. What Greaves refers to as the incoherence problem is, as she put it: "How can it make sense to talk of probabilities (other than 0 and 1) at all, since all 'possible' outcomes actually occur? [7], §1.1".

Prior to measurement, Deutsch's observer is ignorant as to which sort of identical universe s/he inhabits but, on the basis of knowing the upcoming branch weights, assigns a subjective probability equal to W_U to being in a universe where the measurement outcome will be U and a subjective probability equal to W_D to being in a universe where the measurement outcome will be D. Axiom 8 can be seen as a modification of Graham's proposal in order to introduce pre-measurement uncertainty via self-location ignorance and assumes that measures on an infinite set can be taken as a guide to subjective probability assignments. As with Graham's proposal, choice of measure, which Greaves refers to above as 'a preferred measure' is *ad hoc*, simply chosen to make probability assignments conform to the born rule and there is also an implicit appeal to a principle of indifference.

Responding to this problem about the choice of a preferred measure led Deutsch to be the first to introduce decision theory to deriving the Born rule for an interpretation of quantum mechanics which takes processes such as our idealized measurement as involving branching rather than stochasticity [8] (Deutsch has said that it was Brice DeWitt who brought his attention to the necessity of tackling the measure problem. Private communication). David Wallace has since done considerable further work on Deutsch's original idea so that the line of reasoning has come to be known as the Deutsch-Wallace argument [9], pp. 160–189. Tim Maudlin forcefully rejects it and there have been several other challenges [10].

The Deutsch-Wallace argument claims to show that a well-informed observer pre-measurement should assign subjective probabilities equal to what they take the post-measurement branch weights to be. Note that this effectively makes Deutsch's Axiom 8 redundant; if the argument is good it applies just as well to Everett's original conception of branching as like the bifurcation of a road. It might be objected that for that original conception, where the observer must expect to split, there is no available concept of pre-measurement uncertainty but it's controversial whether such uncertainty is required for the Deutsch-Wallace argument to go through. Greaves has argued against any need for uncertainty in Everettian theory [11].

2. Vaidmanian Uncertainty

Even if there's some controversy as whether a notion of uncertainty needs to be associated with the concept of probability nobody would deny that intuitively things look more difficult for Everettian theory if any appeal to uncertainty is absent. We have also seen that a quest for a role for uncertainty seems to have motivated the first departures from Everett's idea that for our idealized measurement observers split in two. The departure from Everett's original amoebal concept of branching is nascent in Graham's proposal and blatant for Deutsch's Axiom 8.

Lev Vaidman was the first to notice that there's a way to associate uncertainty with Everett's original concept of splitting. He suggested considering the situation of an observer post-measurement, pre-observation [12]. Like Deutsch, Vaidman used the concept of self-location uncertainty. For our idealized spin measurement setup, the well-informed post-measurement, pre-observation observer is interpreted by Vaidman as being uncertain as whether s/he's on the U branch or the D branch. In such a situation Vaidman presumed that the observer should assign a subjective probability equal to W_U to being on the U branch and W_D to being on the D branch, an assumption which I later called the Born-Vaidman rule [13], p. 104.

David Albert objected that Vaidmanian uncertainty 'comes too late, if it comes at all' [14]. Here, it's worth considering what role post-measurement, pre-observation uncertainty plays in *stochastic* theory. From that point of view, our idealized spin measurement would normally be performed by an observer who perceives the outcome as soon as it occurs. Also, since the notion of pre-measurement uncertainty seems unproblematic for stochastic theory there's no motivation to consider what the subjective probability assignments of a post-measurement observer would be if s/he were ignorant of the outcome.

If the pre-measurement observer were offered a wager on outcomes it would seem unproblematic that s/he should make judgments as to how to bet on the basis of pre-measurement uncertainty.

However, clearly in the stochastic case it's possible for an observer to be ignorant of the outcome post-measurement and, equally clearly, in such a situation the observer would make exactly the same judgments as to how to bet post-measurement as they would have done pre-measurement. So, if the post-measurement, pre-observation observer were offered the same wager but told that stakes had to be laid before measurement they would clearly regret not having laid a stake beforehand if they had not done so. Knowing that in advance, the pre-measurement observer would have reason to lay a stake pre-measurement. The implication is that in the stochastic case minimizing possible future regret is just as good a reason to act as is maximizing possible future gain. The same argument applies in the Vaidmanian case, as I pointed out [13], p. 116. Albert's objection is thus fully met. The mere possibility of post-measurement, pre-observation uncertainty is enough to give good reason to act pre-measurement. That hasn't been noticed for stochastic theory but is true there too.

Prior to my argument, Vaidman suggested a different way to explain pre-measurement betting in splitting scenarios. He argued that the pre-measurement observer should 'care' about the weights of post-measurement branches in a way which would explain rational betting behavior [15]. Greaves later developed the idea at some length independently [11], §2.3. My argument effectively demonstrates that what the pre-measurement observer should care about is the gambling judgment of a possible post-measurement, pre-observation observer.

A further problem has remained for the traditional Everettian concept of branching as splitting. For our idealized spin measurement, the Vaidmanian observer clearly must assign subjective probabilities to going on to observe U and D equal to W_U and W_D just as an observer applying stochastic theory must assign subjective probabilities equal to the objective probabilities for the outcomes U and D. Yet on the splitting model, unmodified either *à la* Graham or *à la* Deutsch, there are just two post-measurement, pre-observation observers according to Vaidman, one on the U branch and one on the D branch. In which case each would seem to have to think that they are either the observer on the U branch or the observer on the D branch and can't tell which so either is just as likely as the other. So, each post-measurement, pre-observation observer should assign subjective probabilities of 0.5 to each possibility, irrespective of the values of W_U and $W_{D.}$ In other words, the probability judgments of the Vaidmanian observer should be ruled by a principle of indifference, which makes no sense at all for Everettian theory. There are currently two arguments that the principle of indifference should be overruled by the post-measurement, pre-observation observer which I shall not attempt to assess here [16,17]. They are currently the last word for the Vaidmanian approach to Everettian splitting. Let's now go on to the last word for the alternative model of branching introduced by Deutsch.

3. Parallel Universes Again

Deutsch has not given up on his interpretation of branching as the partitioning of a set of identical universes but has recognized that if multiple universes prior to partitioning are thought of as being qualitatively identical the question naturally arises as to why partitioning should arise at all. What could bring about differences between qualitatively identical universes other than stochastic processes taking place within each of them? Invoking stochastic processes here would make the whole scheme pointless since that was exactly what Everett was trying to do without. Deutsch has attempted to address this problem by using the concept of fungibility. He writes: "It *is* consistent for two identical entities to become different under deterministic and symmetrical laws. But, for that to happen, they must be more than just exact images of each other: They must be fungible [18], p. 265, original emphasis". He continues: "It is not that they [identical universes] coincide *in* anything, such as an external space: They are not in space. An instance of space is part of each of them. That they 'coincide' means only that they are not separate in any way. It is hard to imagine perfectly identical things coinciding. For instance, as soon as you imagine just one of them, your imagination has already violated their fungibility. But, although imagination may baulk, reason does not [18], p. 269, original emphasis".

The suggestion is that thinking of identical universes as like proverbial peas in a pod is too simplistic and they should rather be thought of as like euros. There is no sense in asking the bank to return the very same euros which one deposited. The coins are *not* fungible but the euros are. However, this suggestion seems to create a problem because an observer can presumably indexically refer to the spin measurement device s/he is about to activate. The idea is supposed to be that the observer is ignorant as to which one of an infinite set of devices it is. It is either a device which is destined to show U or a device which is destined to show D. However, it's impossible to indexically refer to a particular one of a set of objects which are fungible. I can point to the coin which I deposit at the bank but not to the euro which is thereby added to my account. So, Deutsch's introduction of the concept of fungibility seems to undermine the idea that one can point to a device which has a determinate future which it is in principle impossible to know in advance. That suggests that if it's assumed that an observer can indexically refer to a spin measurement device, something generally taken for granted, then either the device operates stochastically or it splits in the way Everett suggested. If indexical reference isn't available then the device cannot have a predetermined future which the observer is in principle unable to determine in advance, given total knowledge of the universe which they inhabit. The problem of indexical reference has also arisen for an alternative view of branching which bears some similarity to Deutsch's idea of a partitioning set of parallel universes.

4. Overlap

Independently of Deutsch, Simon Saunders and David Wallace have also sought to introduce pre-measurement uncertainty to Everettian theory via a concept of self-location ignorance [19]. Their proposal is based on David Lewis's analysis of personal fission scenarios introduced to philosophical discussion of personal identity, independent of concerns about physics [20]. In describing Lewis's work Saunders and Wallace write: "The trick was to suppose in the face of branching, say into two, that there are two persons present all along–persons who initially overlap or coincide. This is equivalent to the stipulation that by 'person', roughly speaking, we mean a unique cradle-to-grave continuant, specifically a unique spacetime worm. As for the meaning of 'overlapping', there are plenty of homely analogies: The Chester A. Arthur Parkway, [Lewis] observed, overlaps with Route 137 for a brief stretch, but still there are two roads [19], pp. 294–295, original emphasis".

Two different roads can have a strip of tarmac in common. Likewise, two distinct persons can have 'temporal parts' of their bodies in common. Transposed to the context of the idealized spin measurement, there are two observers present all along, observer$_U$ who observes the outcome U and observer $_D$ who observes the outcome D. Prior to the measurement those two observers have temporal parts of their bodies in common, like the two roads having a stretch of tarmac in common. Furthermore, unlike Lewis, Saunders and Wallace suggest that, 'it is at least somewhat natural to attribute two sets of thoughts to those persons' [19], p. 303.

In other words, if well informed prior to measurement, both observer U and observer D can think: 'I'm one of two types of person. I'm either a person who's going to observe U or I'm a person who's going to observe D, but I'm ignorant as to which'. This is somewhat like Deutsch's proposal [6], a difference being that Saunders and Wallace generate the idea of there being multiple observers prior to the measurement via Lewis's concept of overlap rather that Deutsch's Axiom 8 which posits non-overlapping 'parallel' universes.

I queried Saunders' and Wallace's overlap proposal, arguing that the putative pre-measurement observer U and observer D would not each be able to make indexical reference to their own bodies since before measurement their bodies have their temporal parts in common, like the overlapping roads [21]. Responding to that criticism, Saunders and Wallace emphasized that their analysis depends on an idea from linguistics known as the principle of interpretive charity, opening their reply to me with a quote from the philosopher of language Donald Davidson [22].

To see the linguistic principle of charity in action, imagine taking a bird's eye view of the idealized spin measurement given the overlap interpretation of the setup. What is seen prior to the measurement can seem to be a single observer making a single utterance of ‘I’m one of two types of person. I’m either a person who’s going to observe *U* or I’m a person who’s going to observe *D*, but I’m ignorant as to which’. If what is heard is interpreted as the single utterance of one person then it’s false, because there is one person who is going to split, not two persons one of whom is going to observe *U* and the other *D*.

However, a more ‘charitable’ interpretation of what’s heard is apparently possible; charitable because it takes what’s heard to be *true*. What’s heard can be taken to be two distinct utterances by two distinct observers even though only a single sound is heard. Rather as if the word ‘here’ written on a strip of tarmac common to those two overlapping roads were taken to refer to a position on the Chester A. Arthur Parkway and also, separately, to a position on Route 137. According to Saunders and Wallace, interpreting ‘I’m one of two types of person. I’m either a person who’s going to observe *U* or I’m a person who’s going to observe *D*, but I’m ignorant as to which’ as true is important and an apparently metaphysical concern about indexical reference can be set aside for the sake of preserving a concept of pre-measurement uncertainty in the face of branching. As Saunders and Wallace put it: “Tappenden, by contrast, does seem to be looking for deep metaphysical truths: Truths to which we have no access except via our pre-scientific intuitions, yet which we can know so surely that they bear on our choice of scientific theory. (*ibid*.: 317)”.

Saunders’ and Wallace’s ‘choice of scientific theory’ here refers to their choice of the overlap interpretation of branching, where there are two observers present prior to the idealized spin measurement, rather than the splitting interpretation where there is just one observer who splits. However, in what sense are those different interpretations ‘scientific’ rather than metaphysical? It would seem that no possible experiment could decide between them, given Everett’s hypothesis that processes which have been thought of as stochastic in fact involve branching.

5. Divergence

Following the overlap proposal, Saunders has made an alternative suggestion a bit closer to Deutsch’s original idea. He does not suggest that quantum mechanics requires a supplementary axiom, as Deutsch did, but rather that the formalism allows branching to be interpreted as the partitioning of a set ‘worlds’ which are qualitatively identical prior to branching (like Deutsch’s ‘identical universes’) but which do not overlap in the sense of having temporal parts in common [23], pp. 196–200. He refers to this view of the partitioning of a set of worlds as ‘divergence’ and writes: “Once stated in this way, the suspicion is that whether worlds in EQM (Everettian Quantum Mechanics) diverge or overlap is underdetermined by the mathematics. One can use either picture; they are better or worse adapted to different purposes [23], p. 200”.

Earlier, he writes: “The worry is not that overlapping worlds are unintelligible or inconsistent; it is that they make nonsense of ordinary beliefs [. . .] Diverging worlds, composed of objects and events that do not overlap (that are qualitatively but not numerically identical) do not suffer from this problem [23], p. 197”.

That makes Saunders’ preference clear for a divergence model of branching, rather than an overlap model. Alastair Wilson has articulated Saunders’ concept of a divergence model of branching in a different way, writing: “The diverging picture arises from a non-standard interpretation of the consistent histories formalism. The projection operators which feature in the consistent histories formalism are normally interpreted as representing token property-instantiations. This allows that objects or events in two different histories can be numerically identical, resulting in a metaphysic of overlapping Everett worlds. But if the projection operators are instead interpreted as representing types of property-instantiations, then it becomes possible for events in distinct histories to only ever be qualitatively identical to one another, generating a metaphysic of diverging Everett worlds [24], pp. 714–715”.

Wilson has developed Saunders’ divergence concept of Everettian branching into a version of what Lewis has called ‘modal realism’ which takes talk of possible worlds to refer to concretely existing worlds. As Lewis puts it: "There are so many other worlds, in fact, that absolutely *every* way that a world could possibly be is a way that some world *is* [25], p. 2, original emphases".

Wilson restricts Lewis's notion of possibility to what is physically possible according to quantum mechanics. The divergence interpretation of branching then naturally translates into a modal realism where an observer inhabits an actual world which is just one of many, concretely existing, physically possible worlds. To see how that works, consider Saunders' divergence analysis of the idealized spin measurement.

Prior to the measurement there are many observers in worlds which do not overlap. Those worlds have had qualitatively identical histories up until the measurement event, which involves corresponding measurement devices in each world. Each device, it is claimed, does not operate stochastically, rather it is determined in advance whether it will record *U* or *D* but it is in principle impossible for the observer in each world to predict what the outcome in that world will be. Each observer pre-measurement is thus subject to self-location uncertainty. Each well informed observer knows that s/he inhabits a world where the result will be exclusively either *U* or *D* but does not know which is the case.

Wilson, very plausibly, translates the statement by a pre-measurement observer of: 'I'm in a world where the measurement outcome is destined to be *U* or *D* but I don't know which' as 'Possibly I'm in a world where the outcome is destined to be *U* and possibly I'm in a world where the outcome is destined to be *D* but I don't know what is actually the case'. Thus, an observer pre-measurement, according to Wilson, should think of themself as actually inhabiting one of a set of extant, currently qualitatively identical, 'possible' worlds. Wilson's thoughts on this are fully developed in [26].

Recall that I mentioned that Deutsch has addressed the question as to why a set of qualitatively identical worlds should diverge. If those worlds do not contain stochastic processes what reason could there be for them to diverge? I also indicated possible reasons for concern about the ability of an observer to make indexical reference to objects in their environment, including their own body, both on Deutsch's conception of identical universes which are 'fungible' and in the case of overlapping worlds. There must at least be some suspicion that a similar thought applies to the Saunders-Wilson concept of divergence. I quoted Wilson above suggesting that the divergence interpretation of branching arises out of understanding quantum-mechanical representations as referring to types of property instantiations rather than token property instantiations. That would seem to make Saunders-Wilson parallel worlds fungible in the sense which Deutsch has attributed to his identical universes. Can an observer in one of a number of fungible worlds indexically refer to objects in their environment? It seems that that question needs to be addressed for any scheme which interprets branching as the partitioning of linear histories.

6. The World as Wavefunction

There is as yet no consensus amongst philosophers of physics that Everettian probability problem has been resolved, far from it. However, as we've seen, Everettian theorists have mounted some ingenious challenges to the idea that the problem is intractable. At the same time, amongst Everettian theorists there's no consensus as to how uncertainty fits into the picture. Struggling with that problem has spawned distinct and incompatible models for the metaphysics of branching and discussion is ongoing.

I now want to take a look at another problem for Everettian theory which has been waiting in the wings. The question of wavefunction monism; the idea that all of material existence just is the universal quantum wavefunction. In recent years there has been much discussion about the existential status of the wavefunction. What I want to do here is propose a metaphysics which may be appropriate for wavefunction monism in an Everettian context. We have seen how fundamental the role of metaphysics has been in the development of ideas about branching and uncertainty. Perhaps metaphysics has a fundamental role to play as well in the debate about the existential status of the wavefunction in

Everettian theory. By way of pursuing that thought, I want to discuss an idea which Wallace refers to as the Hydra View [9], p. 281, coupled with an idea which I introduced in [27].

The Hydra view is that a physicist, and the measuring device to which s/he can indexically refer, split in idealized spin measurement contexts. The pointer evolves, via decoherence, into a superposition of showing U and D. The two elements of the superposed pointer are both pointers which have the same mass and volume as the superposed pointer itself. Each element of the superposed pointer is to be considered as a novel type of part; neither a spatial part nor a temporal part but a superpositional part.

If the world is wavefunction it's the stuff of cats, dead or alive. However, how can a cat be indefinitely dead or alive? The Hydra view of what happens to Schrödinger's cat when you close its idealized, causally isolated box is that it quickly evolves into a superposition of two cats, one alive and the other dead, each of which is a superpositional part of the superposed cat. Given the setup in Schrödinger's box, the quantum amplitude of the dead cat increases with time whilst that of the live cat decreases. The masses of each of the two cats remains the same, for all practical purposes, so the superposed cat always definitely has the mass of one cat, since both its superpositional parts have the same mass. Schrödinger's cat is in an indefinite dead/alive state because the two cats which are its superpositional parts are neither both dead nor both alive.

I now propose to combine this analysis of the Schrödinger cat scenario with the concrete sets hypothesis introduced in [27], pp. 9–10. The aim there was to make intelligible the idea that branch weight can be identified with objective probability, which seems counterintuitive because, on the face of it, if quantum processes are deterministic then that must necessarily exclude the possibility that objective probability is involved. I described a thought experiment designed to show that determinism and objective probability are indeed compatible. Briefly, the idea is to imagine a large but not infinite set of isomorphic 'parallel universes' in which quantum processes are stochastic and isomorphic observers in each universe are about to undertake our model spin measurement. Each observer believes that the process about to take place is stochastic and, being well informed, s/he is able to assign what s/he believes to be objective probabilities to the possible outcomes. Given the law of large numbers, what happens when the parallel measurements take place is that the set of universes partitions into two subsets where different outcomes occur, the measures of the subsets equaling the objective probabilities attributed to the possible outcomes of the parallel stochastic measurement processes.

I then argued that an alternative interpretation of the mentality of observers is possible. Instead of it being supposed that there are individual observers in each universe it is possible to interpret the situation as involving a single observer whose mind spans all the universes. The body of the single observer is the set of isomorphic doppelgangers, one in each universe. Also, what that single observer indexically refers to as the measuring device is the *set* of isomorphic measuring devices. That single observer is in the very same mental state as the original multiple observers. The mental state is individuated by its mental content, which involves the beliefs that the measurement process about to be observed is stochastic and that objective probabilities can be assigned to what are possible outcomes. The change of interpretation does not involve a change in observers' mental content, it just involves supposing that there's a single token of the mental content rather than multiple tokens, one in each universe.

On this alternative interpretation of the setup what happens to the single observer is that s/he splits into two observers each observing a different outcome because the original set of doppelgangers partitions into two subsets, each exposed to a different result because the measuring device has partitioned into two subsets. If the proposed alternative interpretation of mentality is coherent, what the though experiment demonstrates is that it's possible that an observer who thinks that a process is stochastic is mistaken. It's intelligible that what the observer believes to be a measuring device which will show exclusively one or another of two outcomes is in fact a measuring device which will split into two devices each showing a different outcome. It's also possible that what the observer takes to be objective probabilities do not attach to possibilities but rather to the subset measures which correspond to Everettian branch weights in the imaginary setup.

The alternative interpretation of the mind-body relation in the thought experiment involves the idea that a set of isomorphic doppelgangers instances a single observer and that objects in that observers environment are sets. The interpretation requires the concrete sets hypothesis and that entails that if there exist two ordinary, everyday cats, each with a mass of 5 kg, one dead and the other alive, then the set of those two cats is also a cat. The set has a definite mass equal to the mass which the dead and live cats have in common, 5 kg. Also, the cat which is the set is neither dead nor alive because the cats which are its elements are neither both dead nor both alive.

The concrete sets hypothesis is required for the alternative interpretation of the mind-body relation and so appears to be necessary to making intelligible the idea that what has been thought to be a stochastic process having possible outcomes with objective probabilities is in fact a branching process where co-existing branches have associated objective probabilities. So, it's plausible that the concrete sets hypothesis may have a fundamental role to play in making Everettian theory intelligible. Also, the concrete sets hypothesis entails that any set of concrete objects is itself a concrete object with properties which may, or may not, be definite. Schrödinger's cat, on the Hydra view, is a superposition which has a live and a dead cat as elements (superpositional parts). What the above argument suggests is that the elements of a superposition are elements in the set-theoretic sense. In other words, superpositional parts are not a novel type of part as suggested by the Hydra view but rather set-theoretic elements.

Schrödinger's cat, on the Hydra view, is the product of decoherence. When the box is closed the radioactive sample in the poison-triggering mechanism is in a superposition which decoheres into decayed and non-decayed samples, triggering the evolution of the cat into a decohered superposition of dead and live cats. However, there's no reason to suppose that the physical evolution of a superposition should change its metaphysical constitution. In which case what physicists call the elements of any superposition are elements in the set-theoretic sense.

Let's now apply these ideas to the problem of wavefunction monism. Tim Maudlin has posed the problem very clearly: "In sum, any theory whose physical ontology is a complete wavefunction monism automatically inherits a severe interpretational problem: If all there is is the wavefunction, an extremely high-dimensional object evolving in some specified way, how does that account for the low-dimensional world of localized objects that we start off believing in, whose apparent behavior constitutes the explanandum of physics in the first place? [...] And it should be obvious that all the resources of the phrase 'configuration space' are legitimately available to a non-monist who postulates a plethora of localized particles (or strings, or whatever) in a common low-dimensional space [1], pp. 132–133, original emphasis".

Consider the bound electron in a hydrogen atom in the light of the concrete sets hypothesis and the idea that the elements of a superposition are elements in the set-theoretic sense. At any given moment the electron is a 'point particle' with indefinite position, which is to say that it has elements at different positions in the 'electron-cloud', each element being an electron. The 'electron-cloud' surrounding the nucleus is an electron which is a set of electrons.

Imagine a field full of cats, each with a mass of 5 kg. and each necessarily at a different position. The cat which is the set of those cats, according to the concrete sets hypothesis, has a definite mass of 5 kg. but indefinite position. The electron which is the set of electrons in the electron-cloud is like the set of cats in the field. A natural minimal position for a point particle would be a Planck volume so for each Planck volume in the electron-cloud there is an electron which has a share of position amplitude and phase and, again, the single bound electron in the hydrogen atom, at any given moment, is the set of all those electrons. To be sure, the picture becomes more complex if we consider the quantum wavefunction of two or more entangled point particles. Now there will be two or more elements of each particle present for each Planck volume and the relation between them will embody the entanglement of the particles at that position. For an environment such as ours, where immense numbers of particles are entangled, the picture becomes extremely complex but now we have Maudlin's 'plethora of localized particles' with which to construct a metaphysics for wavefunction monism. It may seem an extravagant speculation, but perhaps I've succeeded showing that it's not unreasonable.

7. Conclusions

Everettian theory refuses to lie down and die, despite many attempts to kill it off, yet there's no consensus amongst Everettian theorists as to how probability is to be understood in branching contexts nor how the metaphysics of branching itself is to be interpreted. There's also disagreement about what role wavefunction realism might, or might not, have to play in Everettian theory. I hope to have clarified some of the issues involved and to have made an intelligible suggestion as to how wavefunction monism may be compatible with Everettian theory.

In his Nobel address Max Born said: "How does it come about then, that great scientists such as Einstein, Schrödinger and De Broglie are nevertheless dissatisfied with the situation? [. . .] The lesson to be learned from what I have told of the origin of quantum mechanics is that probable refinements of mathematical methods will not suffice to produce a satisfactory theory, but that somewhere in our doctrine is hidden a concept, unjustified by experience, which we must eliminate to open up the road [28]".

Everett wrote: "Arguments that the world picture presented by this theory is contradicted by experience because we are unaware of any branching process are like the criticism of the Copernican theory that the mobility of the earth as a real physical fact is incompatible with the common sense interpretation of nature because we feel no such motion [2]".

That anticipates Gertrude Anscombe's recollection of an exchange with Ludwig Wittgenstein: "He once greeted me with the question: 'Why do people say that it was natural to think that the sun went round the earth rather than that the earth turned on its axis?' I replied, 'I suppose, because it looked as if the sun went round the earth'. 'Well', he asked, 'what would it have looked like if it had *looked* as if the earth turned on its axis'? [29]".

Transposed to the Everettian context the exchange might go like this. 'Why did physicists think it natural to believe that the measurement of a superposition on the pointer basis yields a single result rather than multiple results'? Reply: 'I suppose because it looked as if a single result is yielded'. Response: 'Well, what would it have looked like if it had looked as if multiple results are yielded?'

Is Born's 'hidden concept, unjustified by experience' simply the idea that physicists don't split when they observe quantum superpositions?

Funding: This research received no external funding.

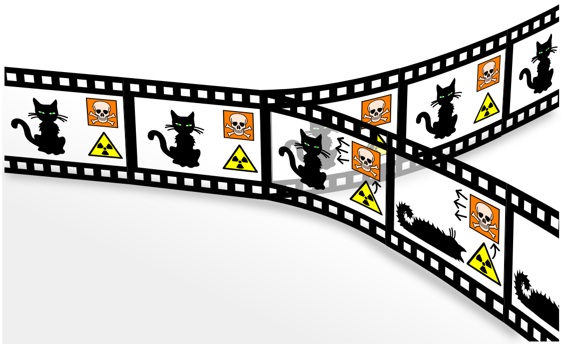
Conflicts of Interest: The authors declare no conflict of interest.

References

1. Maudlin, T. Can the world be only wavefunction? In *Many Worlds?* Saunders, S., Barrett, J., Kent, A., Wallace, D., Eds.; Oxford University Press: Oxford, UK, 2010; pp. 121–143.
2. Everett, H., III. 'Relative state' formulation of quantum mechanics. *Rev. Mod. Phys.* **1957**, *29*, 460. [CrossRef]
3. Barrett, J.A. Typical worlds. *Stud. Hist. Philos. Mod. Phys.* **2017**, *58*, 35. [CrossRef]
4. Barrett, J.A.; Byrne, P. *The Everett Interpretation of Quantum Mechanics*; Princeton University Press: Princeton, NJ, USA, 2012; p. 69.
5. DeWitt, B.S.; Graham, N. (Eds.) *The Many Worlds Interpretation of Quantum Mechanics*; Princeton University Press: Princeton, NJ, USA, 1973; p. 229.
6. Deutsch, D. Quantum theory as a universal physical theory. *Int. J. Theor. Phys.* **1985**, *24*, 20. [CrossRef]
7. Greaves, H. Probability in the Everett interpretation. *Philos. Compass* **2007**, *2*, 109–128. [CrossRef]
8. Deutsch, D. Quantum theory of probability and decisions. *Proc. R. Soc. Lond.* **1999**, *455*, 2911–2923. [CrossRef]
9. Wallace, D. *The Emergent Multiverse*; Oxford University Press: Oxford, UK, 2012.
10. Maudlin, T. Critical study of David Wallace's, the Emergent Multiverse: Quantum Theory According to the Everett Interpretation. *Noûs* **2014**, *48*, 794–808. [CrossRef]
11. Greaves, H. Understanding Deutsch's probability in a deterministic multiverse. *Stud. Hist. Philos. Mod. Phys.* **2004**, *35*, 423–456. [CrossRef]

12. Vaidman, L. On schizophrenic experiences of the neutron or why we should believe in the many-worlds interpretation of quantum theory. *Int. Stud. Philos. Sci.* **1998**, *12*, 253. [CrossRef]
13. Tappenden, P. Evidence and uncertainty in Everett's multiverse. *Br. J. Philos. Sci.* **2011**, *62*, 99–123. [CrossRef]
14. Albert, D. Chance in the Everett interpretation. In *Many Worlds?* Saunders, S., Barrett, J., Kent, A., Wallace, D., Eds.; Oxford University Press: Oxford, UK, 2010; p. 367.
15. Vaidman, L. Many-Worlds Interpretation of Quantum Mechanics. Stanford Encyclopedia of Philosophy. 2002. Available online: https://plato.stanford.edu/archives/sum2002/entries/qm-manyworlds/#6.4 (accessed on 10 September 2019).
16. Sebens, C.T.; Carroll, S.M. Self-locating uncertainty and the origin of probability in Everettian quantum mechanics. *Br. J. Philos. Sci.* **2018**, *69*, 25–74. [CrossRef]
17. McQueen, K.J.; Vaidman, L. In defence of the self-location uncertainty account of probability in the many-worlds interpretation. *Stud. Hist. Philos. Mod. Phys.* **2019**, *66*, 14–23. [CrossRef]
18. Deutsch, D. *The Beginning of Infinity*; Allen Lane: London, UK, 2011.
19. Saunders, S.; Wallace, D. Branching and uncertainty. *Br. J. Philos. Sci.* **2008**, *59*, 293–305. [CrossRef]
20. Lewis, D. Survival and identity. In *The Identity of Persons*; Rorty, A., Ed.; University of California Press: Oakland, CA, USA, 1976; pp. 17–40.
21. Tappenden, P. Saunders and Wallace on Everett and Lewis. *Br. J. Philos. Sci.* **2008**, *59*, 307–314. [CrossRef]
22. Saunders, S.; Wallace, D. Saunders and Wallace reply. *Br. J. Philos. Sci.* **2008**, *59*, 315–317. [CrossRef]
23. Saunders, S. Chance in the Everett interpretation. In *Many Worlds?* Saunders, S., Barrett, J., Kent, A., Wallace, D., Eds.; Oxford University Press: Oxford, UK, 2010; pp. 181–205.
24. Wilson, A. Objective probability in Everettian quantum mechanics. *Br. J. Philos. Sci.* **2013**, *64*, 709–737. [CrossRef]
25. Lewis, D.K. *On the Plurality of Worlds*; Blackwell: Oxford, UK, 1986.
26. Wilson, A. *The Nature of Contingency: Quantum Physics as Modal Realism*; Oxford University Press: Oxford, UK, (under pressing).
27. Tappenden, P. Objective probability and the mind-body relation. *Stud. Hist. Philos. Mod. Phys.* **2017**, *57*, 8–16. [CrossRef]
28. Born, M. Nobel lecture. 1954. Available online: https://www.nobelprize.org/uploads/2018/06/born-lecture.pdf (accessed on 11 September 2019).
29. Anscombe, G.E.M. *An Introduction to Wittgenstein's Tractatus (Revised Edition)*; Harper and Row: New York, NY, USA, 1993; p. 151.

Many-worlds interpretation



The quantum-mechanical "Schrödinger's cat" paradox according to the many-worlds interpretation. In this interpretation, every event is a branch point; the cat is both alive and dead, even before the box is opened, but the "alive" and "dead" cats are in different branches of the universe, both of which are equally real, but which do not interact with each other.[1]

The **many-worlds interpretation** is an interpretation of quantum mechanics that asserts the objective reality of the universal wavefunction and denies the actuality of wavefunction collapse. Many-worlds implies that all possible alternate histories and futures are real, each representing an actual "world" (or "universe"). In lay terms, the hypothesis states there is a very large—perhaps infinite[2]—number of universes, and everything that could possibly have happened in our past, but did not, has occurred in the past of some other universe or universes. The theory is also referred to as **MWI**, the **relative state formulation**, the **Everett interpretation**, the **theory of the universal wavefunction**, **many-universes interpretation**, or just **many-worlds**.

The original relative state formulation is due to Hugh Everett in 1957.[3][4] Later, this formulation was popularized and renamed *many-worlds* by Bryce Seligman DeWitt in the 1960s and 1970s.[1][5][6][7] The decoherence approaches to interpreting quantum theory have been further explored and developed,[8][9][10] becoming quite popular. MWI is one of many multiverse hypotheses in physics and philosophy. It is currently considered a mainstream interpretation along with the other decoherence interpretations, collapse theories (including the historical Copenhagen interpretation),[11] and hidden variable theories such as the Bohmian mechanics.

Before many-worlds, reality had always been viewed as a single unfolding history. Many-worlds, however, views reality as a many-branched tree, wherein every possible quantum outcome is realised.[12] Many-worlds reconciles the observation of non-deterministic events, such as random radioactive decay, with the fully deterministic equations of quantum physics.

In many-worlds, the subjective appearance of wavefunction collapse is explained by the mechanism of quantum decoherence, and this is supposed to resolve all of the correlation paradoxes of quantum theory, such as the EPR paradox[13][14] and Schrödinger's cat,[1] since every possible outcome of every event defines or exists in its own "history" or "world".

1 Outline

Hugh Everett III (1930–1982) was the first physicist who proposed the many-worlds interpretation (MWI) of quantum physics, which he termed his "relative state" formulation.

Although several versions of many-worlds have been proposed since Hugh Everett's original work,[4] they all contain one key idea: the equations of physics that model the time evolution of systems *without* embedded observers are sufficient for modelling systems which *do* contain observers; in particular there is no observation-triggered wave function collapse which the Copenhagen interpretation proposes. Provided the theory is linear with respect to the wavefunction, the exact form of the quantum dynamics modelled, be it the non-relativistic Schrödinger equation, relativistic quantum field theory or some form of quantum gravity or string theory, does not alter the validity of MWI since MWI is a metatheory applicable to all linear quantum theories, and there is no experimental evidence for any non-linearity of the wavefunction in physics.[15][16] MWI's main conclusion is that the universe (or multiverse in this context) is composed of a quantum superposition of very many, possibly even non-denumerably infinitely[2] many, increasingly divergent, non-communicating parallel universes or quantum worlds.[7]

The idea of MWI originated in Everett's Princeton Ph.D. thesis "The Theory of the Universal Wavefunction",[7] developed under his thesis advisor John Archibald Wheeler, a shorter summary of which was published in 1957 entitled "Relative State Formulation of Quantum Mechanics" (Wheeler contributed the title "relative state";[17] Everett originally called his approach the "Correlation Interpretation", where "correlation" refers to quantum entanglement). The phrase "many-worlds" is due to Bryce DeWitt,[7] who was responsible for the wider popularisation of Everett's theory, which had been largely ignored for the first decade after publication. DeWitt's phrase "many-worlds" has become so much more popular than Everett's "Universal Wavefunction" or Everett–Wheeler's "Relative State Formulation" that many forget that this is only a difference of terminology; the content of both of Everett's papers and DeWitt's popular article is the same.

The many-worlds interpretation shares many similarities with later, other "post-Everett" interpretations of quantum mechanics which also use decoherence to explain the process of measurement or wavefunction collapse. MWI treats the other histories or worlds as real since it regards the universal wavefunction as the "basic physical entity"[18] or "the fundamental entity, obeying at all times a deterministic wave equation".[19] The other decoherent interpretations, such as consistent histories, the Existential Interpretation etc., either regard the extra quantum worlds as metaphorical in some sense, or are agnostic about their reality; it is sometimes hard to distinguish between the different varieties. MWI is distinguished by two qualities: it assumes realism,[18][19] which it assigns to the wavefunction, and it has the minimal formal structure possible, rejecting any hidden variables, quantum potential, any form of a collapse postulate (i.e., Copenhagenism) or mental postulates (such as the many-minds interpretation makes).

Decoherent interpretations of many-worlds using einselection to explain how a small number of classical pointer states can emerge from the enormous Hilbert space of superpositions have been proposed by Wojciech H. Zurek. "Under scrutiny of the environment, only pointer states remain unchanged. Other states decohere into mixtures of stable pointer states that can persist, and, in this sense, exist: They are einselected."[20] These ideas complement MWI and bring the interpretation in line with our perception of reality.

Many-worlds is often referred to as a theory, rather than just an interpretation, by those who propose that many-worlds can make testable predictions (such as David Deutsch) or is falsifiable (such as Everett) or by those who propose that all the other, non-MW interpretations, are inconsistent, illogical or unscientific in their handling of measurements; Hugh Everett argued that his formulation was a metatheory, since it made statements about other interpretations of quantum theory; that it was the "only completely coherent approach to explaining both the contents of quantum mechanics and the appearance of the world."[21] Deutsch is dismissive that many-worlds is an "interpretation", saying that calling it an interpretation "is like talking about dinosaurs as an 'interpretation' of fossil records."[22]

2 Interpreting wavefunction collapse

As with the other interpretations of quantum mechanics, the many-worlds interpretation is motivated by behavior that can be illustrated by the double-slit experiment. When particles of light (or anything else) are passed through the double slit, a calculation assuming wave-like behavior of light can be used to identify where the particles are likely to be observed. Yet when the particles are observed in this experiment, they appear as particles (i.e., at definite places) and not as non-localized waves.

Some versions of the Copenhagen interpretation of quantum mechanics proposed a process of "collapse" in which an indeterminate quantum system would probabilistically collapse down onto, or select, just one determinate outcome to "explain" this phenomenon of observation. Wavefunction collapse was widely regarded as artificial and *ad hoc*, so an alternative interpretation in which the behavior of measurement could be understood from more fundamental physical principles was considered desirable.

Everett's Ph.D. work provided such an alternative interpretation. Everett stated that for a composite system – for example a subject (the "observer" or measuring apparatus) observing an object (the "observed" system, such as a particle) – the statement that either the observer or the observed has a well-defined state is meaningless; in modern parlance, the observer and the observed have become entangled; we can only specify the state of one *relative* to the other, i.e., the state of the observer and the observed are correlated *after* the observation is made. This led Everett to derive from the unitary, deterministic dynamics alone (i.e., without assuming wavefunction collapse) the notion of a *relativity of states*.

Everett noticed that the unitary, deterministic dynamics alone decreed that after an observation is made each element of the quantum superposition of the combined subject–object wavefunction contains two “relative states": a “collapsed” object state and an associated observer who has observed the same collapsed outcome; what the observer sees and the state of the object have become correlated by the act of measurement or observation. The subsequent evolution of each pair of relative subject–object states proceeds with complete indifference as to the presence or absence of the other elements, *as if* wavefunction collapse has occurred, which has the consequence that later observations are always consistent with the earlier observations. Thus the *appearance* of the object's wavefunction's collapse has emerged from the unitary, deterministic theory itself. (This answered Einstein's early criticism of quantum theory, that the theory should define what is observed, not for the observables to define the theory).[23] Since the wavefunction merely appears to have collapsed then, Everett reasoned, there was no need to actually assume that it had collapsed. And so, invoking Occam's razor, he removed the postulate of wavefunction collapse from the theory.

3 Probability

A consequence of removing wavefunction collapse from the quantum formalism is that the Born rule requires derivation, since many-worlds derives its interpretation from the formalism. Attempts have been made, by many-world advocates and others, over the years to *derive* the Born rule, rather than just conventionally *assume* it, so as to reproduce all the required statistical behaviour associated with quantum mechanics. There is no consensus on whether this has been successful.[24][25][26]

3.1 Frequency-Based Approaches

Everett (1957) briefly derived the Born rule by showing that the Born rule was the only possible rule, and that its derivation was as justified as the procedure for defining probability in classical mechanics. Everett stopped doing research in theoretical physics shortly after obtaining his Ph.D., but his work on probability has been extended by a number of people. Andrew Gleason (1957) and James Hartle (1965) independently reproduced Everett's work[27] which was later extended.[28][29] These results are closely related to Gleason's theorem, a mathematical result according to which the Born probability measure is the only one on Hilbert space that can be constructed purely from the quantum state vector.[30]

Bryce DeWitt and his doctoral student R. Neill Graham later provided alternative (and longer) derivations to Everett's derivation of the Born rule.[7] They demonstrated that the norm of the worlds where the usual statistical rules of quantum theory broke down vanished, in the limit where the number of measurements went to infinity.

3.2 Decision Theory

A decision-theoretic derivation of the Born rule from Everettarian assumptions, was produced by David Deutsch (1999)[31] and refined by Wallace (2002–2009)[32][33][34][35] and Saunders (2004).[36][37] Deutsch's derivation is a two-stage proof: first he shows that the number of orthonormal Everett-worlds after a branching is proportional to the conventional probability density. Then he uses game theory to show that these are all equally likely to be observed. The last step in particular has been criticised for circularity.[38][39] Some other reviews have been positive, although the status of these arguments remains highly controversial; some theoretical physicists have taken them as supporting the case for parallel universes.[40][41] In the *New Scientist* article, reviewing their presentation at a September 2007 conference,[42][43] Andy Albrecht, a physicist at the University of California at Davis, is quoted as saying “This work will go down as one of the most important developments in the history of science.”[40]

The Born rule and the collapse of the wave function have been obtained in the framework of the relative-state formulation of quantum mechanics by Armando V.D.B. Assis. He has proved that the Born rule and the collapse of the wave function follow from a game-theoretical strategy, namely the Nash equilibrium within a von Neumann zero-sum game between nature and observer.[44]

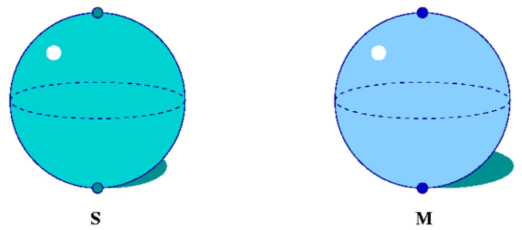
3.3 Symmetries and Envariance

Wojciech H. Zurek (2005)[45] has produced a derivation of the Born rule, where decoherence has replaced Deutsch's informatic assumptions.[46] Lutz Polley (2000) has produced Born rule derivations where the informatic assumptions are replaced by symmetry arguments.[47][48]

Charles Sebens and Sean M. Carroll, building on work by Lev Vaidman,[49] proposed a similar approach based on self-locating uncertainty.[50] In this approach, decoherence creates multiple identical copies of observers, who can assign credences to being on different branches using the Born rule.

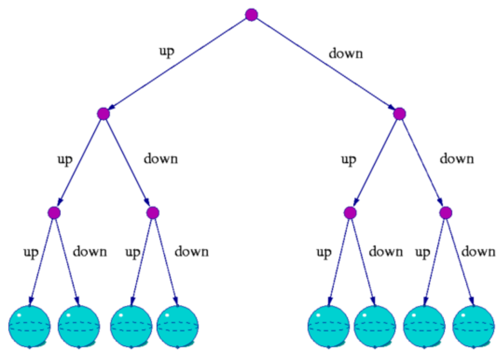
4 Brief overview

In Everett's formulation, a measuring apparatus **M** and an object system **S** form a composite system, each of which prior to measurement exists in well-defined (but time-dependent) states. Measurement is regarded as causing **M** and **S** to interact. After **S** interacts with **M**, it is no longer possible to describe either system by an indepen-



*Schematic representation of pair of "smallest possible" quantum mechanical systems prior to interaction: Measured system **S** and measurement apparatus **M**. Systems such as **S** are referred to as 1-qubit systems.*

dent state. According to Everett, the only meaningful descriptions of each system are relative states: for example the relative state of **S** given the state of **M** or the relative state of **M** given the state of **S**. In DeWitt's formulation, the state of **S** after a sequence of measurements is given by a quantum superposition of states, each one corresponding to an alternative measurement history of **S**.



Schematic illustration of splitting as a result of a repeated measurement.

For example, consider the smallest possible truly quantum system **S**, as shown in the illustration. This describes for instance, the spin-state of an electron. Considering a specific axis (say the z-axis) the north pole represents spin "up" and the south pole, spin "down". The superposition states of the system are described by (the surface of) a sphere called the Bloch sphere. To perform a measurement on **S**, it is made to interact with another similar system **M**. After the interaction, the combined system is described by a state that ranges over a six-dimensional space (the reason for the number six is explained in the article on the Bloch sphere). This six-dimensional object can also be regarded as a quantum superposition of two "alternative histories" of the original system **S**, one in which "up" was observed and the other in which "down" was observed. Each subsequent binary measurement (that is interaction with a system **M**) causes a similar split in the history tree. Thus after three measurements, the system can be regarded as a quantum superposition of 8 = 2 × 2 × 2 copies of the original system **S**.

The accepted terminology is somewhat misleading because it is incorrect to regard the universe as splitting at certain times; at any given instant there is one state in one universe.

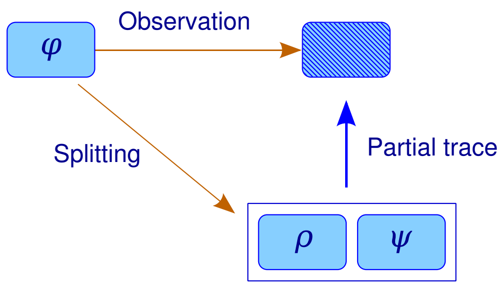
5 Relative state

In his 1957 doctoral dissertation, Everett proposed that rather than modeling an isolated quantum system subject to external observation, one could mathematically model an object as well as its observers as purely physical systems within the mathematical framework developed by Paul Dirac, von Neumann and others, discarding altogether the *ad hoc* mechanism of wave function collapse. Since Everett's original work, there have appeared a number of similar formalisms in the literature. One such idea is discussed in the next section.

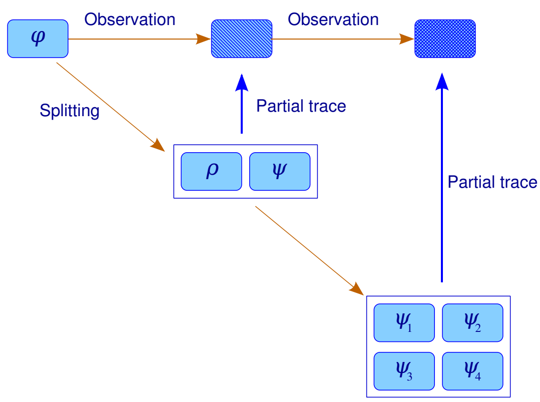
The relative state formulation makes two assumptions. The first is that the wavefunction is not simply a description of the object's state, but that it actually is entirely equivalent to the object, a claim it has in common with some other interpretations. The second is that observation or measurement has no special laws or mechanics, unlike in the Copenhagen interpretation which considers the wavefunction collapse as a special kind of event which occurs as a result of observation. Instead, measurement in the relative state formulation is the consequence of a configuration change in the memory of an observer described by the same basic wave physics as the object being modeled.

The many-worlds interpretation is DeWitt's popularisation of Everett's work, who had referred to the combined observer–object system as being split by an observation, each split corresponding to the different or multiple possible outcomes of an observation. These splits generate a possible tree as shown in the graphic below. Subsequently DeWitt introduced the term "world" to describe a complete measurement history of an observer, which corresponds roughly to a single branch of that tree. Note that "splitting" in this sense, is hardly new or even quantum mechanical. The idea of a space of complete alternative histories had already been used in the theory of probability since the mid-1930s for instance to model Brownian motion.

Under the many-worlds interpretation, the Schrödinger equation, or relativistic analog, holds all the time everywhere. An observation or measurement of an object by an observer is modeled by applying the wave equation to the entire system comprising the observer *and* the object. One consequence is that every observation can be thought of as causing the combined observer–object's wavefunction to change into a quantum superposition of two or more non-interacting branches, or split



Partial trace as relative state. Light blue rectangle on upper left denotes system in pure state. Trellis shaded rectangle in upper right denotes a (possibly) mixed state. Mixed state from observation is partial trace of a linear superposition of states as shown in lower right-hand corner.



Successive measurements with successive splittings

into many “worlds”. Since many observation-like events have happened, and are constantly happening, there are an enormous and growing number of simultaneously existing states.

If a system is composed of two or more subsystems, the system’s state will be a superposition of products of the subsystems’ states. Once the subsystems interact, their states are no longer independent. Each product of subsystem states in the overall superposition evolves over time independently of other products. The subsystems states have become correlated or entangled and it is no longer possible to consider them independent of one another. In Everett’s terminology each subsystem state was now *correlated* with its *relative state*, since each subsystem must now be considered relative to the other subsystems with which it has interacted.

6 Properties of the theory

- MWI removes the observer-dependent role in the quantum measurement process by replacing wavefunction collapse with quantum decoherence. Since the role of the observer lies at the heart of most if not all “quantum paradoxes,” this automatically resolves a number of problems; see for example Schrödinger’s cat thought experiment, the EPR paradox, von Neumann's “boundary problem” and even wave-particle duality. Quantum cosmology also becomes intelligible, since there is no need anymore for an observer outside of the universe.

- MWI is a realist, deterministic, local theory, akin to classical physics (including the theory of relativity), at the expense of losing counterfactual definiteness. MWI achieves this by removing wavefunction collapse, which is indeterministic and non-local, from the deterministic and local equations of quantum theory.[51]

- MWI (or other, broader multiverse considerations) provides a context for the anthropic principle which may provide an explanation for the fine-tuned universe.[52][53]

- MWI, being a decoherent formulation, is axiomatically more streamlined than the Copenhagen and other collapse interpretations; and thus favoured under certain interpretations of Occam’s razor.[54] Of course there are other decoherent interpretations that also possess this advantage with respect to the collapse interpretations.

7 Comparative properties and possible experimental tests

One of the salient properties of the many-worlds interpretation is that it does not require an exceptional method of wave function collapse to explain it. “It seems that there is no experiment distinguishing the MWI from other no-collapse theories such as Bohmian mechanics or other variants of MWI... In most no-collapse interpretations, the evolution of the quantum state of the Universe is the same. Still, one might imagine that there is an experiment distinguishing the MWI from another no-collapse interpretation based on the difference in the correspondence between the formalism and the experience (the results of experiments).”[55]

However, in 1985, David Deutsch published three related thought experiments which could test the theory vs the Copenhagen interpretation.[56] The experiments require macroscopic quantum state preparation and quantum erasure by a hypothetical quantum computer which is currently outside experimental possibility. Since then Lockwood (1989), Vaidman and others have made similar proposals.[55] These proposals also require an advanced technology which is able to place a macroscopic object in a coherent superposition, another task for which it is uncertain whether it will ever be possible. Many other controversial ideas have been put forward though, such as a recent claim that cosmological observations could test the theory,[57] and another claim by Rainer Plaga (1997), published in *Foundations of Physics*, that communication might be possible between worlds.[58]

7.1 Copenhagen interpretation

In the Copenhagen interpretation, the mathematics of quantum mechanics allows one to predict probabilities for the occurrence of various events. When an event occurs, it becomes part of the definite reality, and alternative possibilities do not. There is no necessity to say anything definite about what is not observed.

7.2 The universe decaying to a new vacuum state

Any event that changes the number of observers in the universe may have experimental consequences.[59] Quantum tunnelling to a new vacuum state would reduce the number of observers to zero (i.e., kill all life). Some cosmologists argue that the universe is in a false vacuum state and that consequently the universe should have already experienced quantum tunnelling to a true vacuum state. This has not happened and is cited as evidence in favor of many-worlds. In some worlds, quantum tunnelling to a true vacuum state has happened but most other worlds escape this tunneling and remain viable. This can be thought of as a variation on quantum suicide.

7.3 Many-minds

Main article: Many-minds interpretation

The *many-minds* interpretation is a multi-world interpretation that defines the splitting of reality on the level of the observers' minds. In this, it differs from Everett's many-worlds interpretation, in which there is no special role for the observer's mind.[58]

8 Common objections

- The many-worlds interpretation is very vague about the ways to determine when splitting happens, and nowadays usually the criterion is that the two branches have decohered. However, present day understanding of decoherence does not allow a completely precise, self-contained way to say when the two branches have decohered/"do not interact", and hence many-worlds interpretation remains arbitrary. This objection is saying that it is not clear what is precisely meant by branching, and point to the lack of self-contained criteria specifying branching.

  MWI response: the decoherence or "splitting" or "branching" is complete when the measurement is complete. In Dirac notation a measurement is complete when:

  $$\langle O_i | O_j \rangle = \delta_{ij}$$ [60]

  where O_i represents the observer having detected the object system in the ith state. Before the measurement has started the observer states are identical; after the measurement is complete the observer states are orthonormal.[4][7] Thus a measurement defines the branching process: the branching is as well- or ill-defined as the measurement is; the branching is as complete as the measurement is complete – which is to say that the delta function above represents an idealised measurement. Although true "for all practical purposes" in reality the measurement, and hence the branching, is never fully complete, since delta functions are unphysical,[61]

  Since the role of the observer and measurement per se plays no special role in MWI (measurements are handled as all other interactions are) there is no need for a precise definition of what an observer or a measurement is — just as in Newtonian physics no precise definition of either an observer or a measurement was required or expected. In all circumstances the universal wavefunction is still available to give a complete description of reality.

  Also, it is a common misconception to think that branches are completely separate. In Everett's formulation, they may in principle quantum interfere (i.e., "merge" instead of "splitting") with each other in the future,[62] although this requires all "memory" of the earlier branching event to be lost, so no observer ever sees two branches of reality.[63][64]

- MWI states that there is no special role, or need for precise definition of measurement in MWI, yet

Everett uses the word "measurement" repeatedly throughout its exposition.

> MWI response: "measurements" are treated as a subclass of interactions, which induce subject–object correlations in the combined wavefunction. There is nothing special about measurements (such as the ability to trigger a wave function collapse), that cannot be dealt with by the usual unitary time development process.[3] This is why there is no precise definition of measurement in Everett's formulation, although some other formulations emphasize that measurements must be effectively irreversible or create classical information.

- The splitting of worlds forward in time, but not backwards in time (i.e., merging worlds), is time asymmetric and incompatible with the time symmetric nature of Schrödinger's equation, or CPT invariance in general.[65]

> MWI response: The splitting is time asymmetric; this observed temporal asymmetry is due to the boundary conditions imposed by the Big Bang[66]

- There is circularity in Everett's measurement theory. Under the assumptions made by Everett, there are no 'good observations' as defined by him, and since his analysis of the observational process depends on the latter, it is void of any meaning. The concept of a 'good observation' is the projection postulate in disguise and Everett's analysis simply derives this postulate by having assumed it, without any discussion.[67]

> MWI response: Everett's treatment of observations / measurements covers *both* idealised good measurements and the more general bad or approximate cases.[68] Thus it is legitimate to analyse probability in terms of measurement; no circularity is present.

- Talk of probability in Everett presumes the existence of a preferred basis to identify measurement outcomes for the probabilities to range over. But the existence of a preferred basis can only be established by the process of decoherence, which is itself probabilistic[38] or arbitrary.[69]

> MWI response: Everett analysed branching using what we now call the "measurement basis". It is fundamental theorem of quantum theory that nothing measurable or empirical is changed by adopting a different basis. Everett was therefore free to choose whatever basis he liked. The measurement basis was simply the simplest basis in which to analyse the measurement process.[70][71]

- We cannot be sure that the universe is a quantum multiverse until we have a theory of everything and, in particular, a successful theory of quantum gravity.[72] If the final theory of everything is non-linear with respect to wavefunctions then many-worlds would be invalid.[1][4][5][6][7]

> MWI response: All accepted quantum theories of fundamental physics are linear with respect to the wavefunction. While quantum gravity or string theory may be non-linear in this respect there is no evidence to indicate this at the moment.[15][16]

- Conservation of energy is grossly violated if at every instant near-infinite amounts of new matter are generated to create the new universes.

> MWI response: There are two responses to this objection. First, the law of conservation of energy says that energy is conserved *within each universe*. Hence, even if "new matter" were being generated to create new universes, this would not violate conservation of energy. Second, conservation of energy is not violated since the energy of each branch has to be weighted by its probability, according to the standard formula for the conservation of energy in quantum theory. This results in the total energy of the multiverse being conserved.[73]

- Occam's Razor rules against a plethora of unobservable universes – Occam would prefer just one universe; i.e., any non-MWI.

> MWI response: Occam's razor actually is a constraint on the complexity of physical theory, not on

the number of universes. MWI is a simpler theory since it has fewer postulates.[54] Occams's razor is often cited by MWI adherents as an advantage of MWI.

- Unphysical universes: If a state is a superposition of two states Ψ_A and Ψ_B , i.e., $\Psi = (a\Psi_A + b\Psi_B)$, i.e., weighted by coefficients a and b, then if $b \ll a$, what principle allows a universe with vanishingly small probability b to be instantiated on an equal footing with the much more probable one with probability a? This seems to throw away the information in the probability amplitudes.

  MWI response: The magnitude of the coefficients provides the weighting that makes the branches or universes "unequal", as Everett and others have shown, leading the emergence of the conventional probabilistic rules.[1][4][5][6][7][74]

- Violation of the principle of locality, which contradicts special relativity: MWI splitting is instant and total: this may conflict with relativity, since an alien in the Andromeda galaxy can't know I collapse an electron over here before she collapses hers there: the relativity of simultaneity says we can't say which electron collapsed first – so which one splits off another universe first? This leads to a hopeless muddle with everyone splitting differently. Note: EPR is not a get-out here, as the alien's and my electrons need never have been part of the same quantum, i.e., entangled.

  MWI response: the splitting can be regarded as causal, local and relativistic, spreading at, or below, the speed of light (e.g., we are not split by Schrödinger's cat until we look in the box).[75] For spacelike separated splitting you can't say which occurred first — but this is true of all spacelike separated events, simultaneity is not defined for them. Splitting is no exception; many-worlds is a local theory.[51]

9 Reception

There is a wide range of claims that are considered "many-worlds" interpretations. It was often claimed by those who do not believe in MWI[76] that Everett himself was not entirely clear[77] as to what he believed; however, MWI adherents (such as DeWitt, Tegmark, Deutsch and others) believe they fully understand Everett's meaning as implying the literal existence of the other worlds. Additionally, recent biographical sources make it clear that Everett believed in the literal reality of the other quantum worlds.[22] Everett's son reported that Hugh Everett "never wavered in his belief over his many-worlds theory".[78] Also Everett was reported to believe "his many-worlds theory guaranteed him immortality".[79]

One of MWI's strongest advocates is David Deutsch.[80] According to Deutsch, the single photon interference pattern observed in the double slit experiment can be explained by interference of photons in multiple universes. Viewed in this way, the single photon interference experiment is indistinguishable from the multiple photon interference experiment. In a more practical vein, in one of the earliest papers on quantum computing,[81] he suggested that parallelism that results from the validity of MWI could lead to "*a method by which certain probabilistic tasks can be performed faster by a universal quantum computer than by any classical restriction of it*". Deutsch has also proposed that when reversible computers become conscious that MWI will be testable (at least against "naive" Copenhagenism) via the reversible observation of spin.[63]

Asher Peres was an outspoken critic of MWI. For example, a section in his 1993 textbook had the title *Everett's interpretation and other bizarre theories*. Peres not only questioned whether MWI is really an "interpretation", but rather, if *any* interpretations of quantum mechanics are needed at all. An interpretation can be regarded as a purely formal transformation, which adds nothing to the rules of the quantum mechanics. Peres seems to suggest that positing the existence of an infinite number of non-communicating parallel universes is highly suspect per those who interpret it as a violation of Occam's razor, i.e., that it does not minimize the number of hypothesized entities. However, it is understood that the number of elementary particles are not a gross violation of Occam's Razor, one counts the types, not the tokens. Max Tegmark remarks that the alternative to many-worlds is "many words", an allusion to the complexity of von Neumann's collapse postulate. On the other hand, the same derogatory qualification "many words" is often applied to MWI by its critics who see it as a word game which obfuscates rather than clarifies by confounding the von Neumann branching of possible worlds with the Schrödinger parallelism of many worlds in superposition.

MWI is considered by some to be unfalsifiable and hence unscientific because the multiple parallel universes are non-communicating, in the sense that no information can be passed between them. Others[63] claim MWI is directly testable. Everett regarded MWI as falsifiable since any test that falsifies conventional quantum theory would also falsify MWI.[21]

According to Martin Gardner, the "other" worlds of MWI have two different interpretations: real or unreal; he claims that Stephen Hawking and Steve Weinberg both favour the unreal interpretation.[82] Gardner also claims that the nonreal interpretation is favoured by the majority of physicists, whereas the "realist" view is only supported by MWI experts such as Deutsch and Bryce DeWitt. Hawking has said that "according to Feynman's idea", all the other histories are as "equally real" as our own,[83] and Martin Gardner reports Hawking saying that MWI is "trivially true".[84] In a 1983 interview, Hawking also said he regarded the MWI as "self-evidently correct" but was dismissive towards questions about the interpretation of quantum mechanics, saying, "When I hear of Schrödinger's cat, I reach for my gun." In the same interview, he also said, "But, look: All that one does, really, is to calculate conditional probabilities—in other words, the probability of A happening, given B. I think that that's all the many worlds interpretation is. Some people overlay it with a lot of mysticism about the wave function splitting into different parts. But all that you're calculating is conditional probabilities."[85] Elsewhere Hawking contrasted his attitude towards the "reality" of physical theories with that of his colleague Roger Penrose, saying, "He's a Platonist and I'm a positivist. He's worried that Schrödinger's cat is in a quantum state, where it is half alive and half dead. He feels that can't correspond to reality. But that doesn't bother me. I don't demand that a theory correspond to reality because I don't know what it is. Reality is not a quality you can test with litmus paper. All I'm concerned with is that the theory should predict the results of measurements. Quantum theory does this very successfully."[86] For his own part, Penrose agrees with Hawking that QM applied to the universe implies MW, although he considers the current lack of a successful theory of quantum gravity negates the claimed universality of conventional QM.[72]

9.1 Polls

Advocates of MWI often cite a poll of 72 "leading cosmologists and other quantum field theorists"[87] conducted by the American political scientist David Raub in 1995 showing 58% agreement with "Yes, I think MWI is true".[88]

The poll is controversial: for example, Victor J. Stenger remarks that Murray Gell-Mann's published work explicitly rejects the existence of simultaneous parallel universes. Collaborating with James Hartle, Gell-Mann is working toward the development a more "palatable" *post-Everett quantum mechanics*. Stenger thinks it's fair to say that most physicists dismiss the many-world interpretation as too extreme, while noting it "has merit in finding a place for the observer inside the system being analyzed and doing away with the troublesome notion of wave function collapse".[89]

Max Tegmark also reports the result of a "highly unscientific" poll taken at a 1997 quantum mechanics workshop.[90] According to Tegmark, "The many worlds interpretation (MWI) scored second, comfortably ahead of the consistent histories and Bohm interpretations." Such polls have been taken at other conferences, for example, in response to Sean Carroll's observation, "As crazy as it sounds, most working physicists buy into the many-worlds theory"[91] Michael Nielsen counters: "at a quantum computing conference at Cambridge in 1998, a many-worlder surveyed the audience of approximately 200 people... Many-worlds did just fine, garnering support on a level comparable to, but somewhat below, Copenhagen and decoherence." However, Nielsen notes that it seemed most attendees found it to be a waste of time: Asher Peres "got a huge and sustained round of applause… when he got up at the end of the polling and asked 'And who here believes the laws of physics are decided by a democratic vote?'"[92]

A 2005 poll of fewer than 40 students and researchers taken after a course on the Interpretation of Quantum Mechanics at the Institute for Quantum Computing University of Waterloo found "Many Worlds (and decoherence)" to be the least favored.[93]

A 2011 poll of 33 participants at an Austrian conference found 6 endorsed MWI, 8 "Information-based/information-theoretical", and 14 Copenhagen;[94] the authors remark that the results are similar to Tegmark's 1998 poll.

10 Speculative implications

Speculative physics deals with questions which are also discussed in science fiction.

10.1 Quantum suicide thought experiment

Main article: Quantum suicide and immortality

Quantum suicide, as a thought experiment, was published independently by Hans Moravec in 1987[95][96] and Bruno Marchal in 1988[97][98] and was independently developed further by Max Tegmark in 1998.[99] It attempts to distinguish between the Copenhagen interpretation of quantum mechanics and the Everett many-worlds interpretation by means of a variation of the Schrödinger's cat thought experiment, from the cat's point of view. **Quantum immortality** refers to the subjective experience of surviving quantum suicide regardless of the odds.[100]

10.2 Weak coupling

Another speculation is that the separate worlds remain weakly coupled (e.g., by gravity) permitting "communication between parallel universes". A possible test of this using quantum-optical equipment is described in a 1997

Foundations of Physics article by Rainer Plaga.[58] It involves an isolated ion in an ion trap, a quantum measurement that would yield two parallel worlds (their difference just being in the detection of a single photon), and the excitation of the ion from only one of these worlds. If the excited ion can be detected from the other parallel universe, then this would constitute direct evidence in support of the many-worlds interpretation and would automatically exclude the orthodox, "logical", and "many-histories" interpretations. The reason the ion is isolated is to make it not participate immediately in the decoherence which insulates the parallel world branches, therefore allowing it to act as a gateway between the two worlds, and if the measure apparatus could perform the measurements quickly enough before the gateway ion is decoupled then the test would succeed (with electronic computers the necessary time window between the two worlds would be in a time scale of milliseconds or nanoseconds, and if the measurements are taken by humans then a few seconds would still be enough). R. Plaga shows that macroscopic decoherence timescales are a possibility. The proposed test is based on technical equipment described in a 1993 *Physical Review* article by Itano et al.[101] and R. Plaga says that this level of technology is enough to realize the proposed inter-world communication experiment. The necessary technology for precision measurements of single ions already exists since the 1970s, and the ion recommended for excitation is $^{199}Hg^{+}$. The excitation methodology is described by Itano et al. and the time needed for it is given by the Rabi flopping formula[102]

Such a test as described by R. Plaga would mean that energy transfer is possible between parallel worlds. This does not violate the fundamental principles of physics because these require energy conservation only for the whole universe and not for the single parallel branches.[58] Neither the excitation of the single ion (which is a degree of freedom of the proposed system) leads to decoherence, something which is proven by Welcher Weg detectors which can excite atoms without momentum transfer (which causes the loss of coherence).[103]

The proposed test would allow for low-bandwidth inter-world communication, the limiting factors of bandwidth and time being dependent on the technology of the equipment. Because of the time needed to determine the state of the partially decohered isolated excited ion based on Itano et al.'s methodology, the ion would decohere by the time its state is determined during the experiment, so Plaga's proposal would pass just enough information between the two worlds to confirm their parallel existence and nothing more. The author contemplates that with increased bandwidth, one could even transfer television imagery across the parallel worlds.[58] For example, Itano et al.'s methodology could be improved (by lowering the time needed for state determination of the excited ion) if a more efficient process were found for the detection of fluorescence radiation using 194 nm photons.[58]

A 1991 article by J.Polchinski also supports the view that inter-world communication is a theoretical possibility.[104] Other authors in a 1994 preprint article also contemplated similar ideas.[105]

The reason inter-world communication seems like a possibility is because decoherence which separates the parallel worlds is never fully complete,[106][107] therefore weak influences from one parallel world to another can still pass between them,[106][108] and these should be measurable with advanced technology. Deutsch proposed such an experiment in a 1985 *International Journal of Theoretical Physics* article,[109] but the technology it requires involves human-level artificial intelligence.[58]

10.3 Similarity to modal realism

The many-worlds interpretation has some similarity to modal realism in philosophy, which is the view that the possible worlds used to interpret modal claims exist and are of a kind with the actual world. Unlike the possible worlds of philosophy, however, in quantum mechanics counterfactual alternatives can influence the results of experiments, as in the Elitzur–Vaidman bomb-testing problem or the Quantum Zeno effect. Also, while the worlds of the many-worlds interpretation all share the same physical laws, modal realism postulates a world for every way things could conceivably have been.

10.4 Time travel

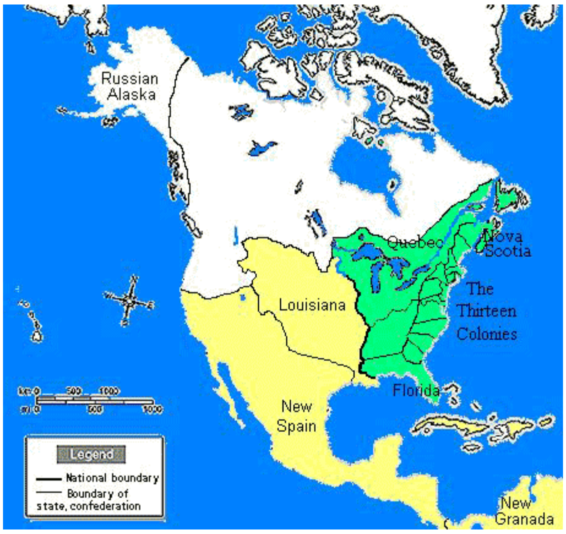
The many-worlds interpretation could be one possible way to resolve the paradoxes[80] that one would expect to arise *if* time travel turns out to be permitted by physics (permitting closed timelike curves and thus violating causality). Entering the past would itself be a quantum event causing branching, and therefore the timeline accessed by the time traveller simply would be another timeline of many. In that sense, it would make the Novikov self-consistency principle unnecessary.

11 Many-worlds in literature and science fiction

Main article: Parallel universe (fiction)
See also: Alternate History

The many-worlds interpretation (and the somewhat related concept of possible worlds) has been associated to numerous themes in literature, art and science fiction.

Some of these stories or films violate fundamental principles of causality and relativity, and are extremely misleading since the information-theoretic structure of the path space of multiple universes (that is information flow between different paths) is very likely extraordinarily com-



A map from Robert Sobel's *novel* For Want of a Nail*, an artistic illustration of how small events – in this example the branching or point of divergence from our timeline's history is in October 1777 – can profoundly alter the course of history. According to the many-worlds interpretation every event, even microscopic, is a branch point; all possible alternative histories actually exist.*[1]

plex. Also see Michael Clive Price's FAQ referenced in the external links section below where these issues (and other similar ones) are dealt with more decisively.

Another kind of popular illustration of many-worlds splittings, which does not involve information flow between paths, or information flow backwards in time considers alternate outcomes of historical events. According to the many-worlds interpretation, all of the historical speculations entertained within the alternate history genre are realized in parallel universes.[1]

The many-worlds interpretation of reality was anticipated with remarkable fidelity in Olaf Stapledon's 1937 science fiction novel Star Maker, in a paragraph describing one of the many universes created by the Star Maker god of the title. "In one inconceivably complex cosmos, whenever a creature was faced with several possible courses of action, it took them all, thereby creating many distinct temporal dimensions and distinct histories of the cosmos. Since in every evolutionary sequence of the cosmos there were very many creatures, and each was constantly faced with many possible courses, and the combinations of all their courses were innumerable, an infinity of distinct universes exfoliated from every moment of every temporal sequence in this cosmos."

12 See also

- Consistent histories
- EPR paradox
- *Fabric of Reality*
- Garden of Forking Paths
- Interpretations of quantum mechanics
- Many-minds interpretation
- Multiverse
- Multiple histories
- *The Beginning of Infinity*
- Quantum immortality – a thought experiment.
- Wave function collapse

13 Notes

[1] Bryce Seligman DeWitt, Quantum Mechanics and Reality: Could the solution to the dilemma of indeterminism be a universe in which all possible outcomes of an experiment actually occur?, *Physics Today*, 23(9) pp 30–40 (September 1970) "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." See also *Physics Today*, letters followup, 24(4), (April 1971), pp 38–44

[2] Osnaghi, Stefano; Freitas, Fabio; Olival Freire, Jr (2009). "The Origin of the Everettian Heresy" (PDF). *Studies in History and Philosophy of Modern Physics* **40**: 97–123. doi:10.1016/j.shpsb.2008.10.002.

[3] Hugh Everett Theory of the Universal Wavefunction, Thesis, Princeton University, (1956, 1973), pp 1–140

[4] Everett, Hugh (1957). "Relative State Formulation of Quantum Mechanics". *Reviews of Modern Physics* **29**: 454–462. Bibcode:1957RvMP...29..454E. doi:10.1103/RevModPhys.29.454.

[5] Cecile M. DeWitt, John A. Wheeler eds, The Everett–Wheeler Interpretation of Quantum Mechanics, *Battelle Rencontres: 1967 Lectures in Mathematics and Physics* (1968)

[6] Bryce Seligman DeWitt, The Many-Universes Interpretation of Quantum Mechanics, *Proceedings of the International School of Physics "Enrico Fermi" Course IL: Foundations of Quantum Mechanics*, Academic Press (1972)

[7] Bryce Seligman DeWitt, R. Neill Graham, eds, *The Many-Worlds Interpretation of Quantum Mechanics*, Princeton Series in Physics, Princeton University Press (1973), ISBN 0-691-08131-X Contains Everett's thesis: The Theory of the Universal Wavefunction, pp 3–140.

[8] H. Dieter Zeh, On the Interpretation of Measurement in Quantum Theory, *Foundation of Physics*, vol. 1, pp. 69–76, (1970).

[9] Wojciech Hubert Zurek, Decoherence and the transition from quantum to classical, *Physics Today*, vol. 44, issue 10, pp. 36–44, (1991).

[10] Wojciech Hubert Zurek, Decoherence, einselection, and the quantum origins of the classical, *Reviews of Modern Physics*, 75, pp 715–775, (2003)

[11] The Many Worlds Interpretation of Quantum Mechanics

[12] David Deutsch argues that a great deal of fiction is close to a fact somewhere in the so called multiverse, *Beginning of Infinity*, p. 294

[13] Bryce Seligman DeWitt, R. Neill Graham, eds, *The Many-Worlds Interpretation of Quantum Mechanics*, Princeton Series in Physics, Princeton University Press (1973), ISBN 0-691-08131-X Contains Everett's thesis: The Theory of the Universal Wavefunction, where the claim to resolves all paradoxes is made on pg 118, 149.

[14] Hugh Everett, Relative State Formulation of Quantum Mechanics, *Reviews of Modern Physics* vol 29, (July 1957) pp 454–462. The claim to resolve EPR is made on page 462

[15] Steven Weinberg, *Dreams of a Final Theory: The Search for the Fundamental Laws of Nature* (1993), ISBN 0-09-922391-0, pg 68–69

[16] Steven Weinberg *Testing Quantum Mechanics*, Annals of Physics Vol 194 #2 (1989), pg 336–386

[17] John Archibald Wheeler, *Geons, Black Holes & Quantum Foam*, ISBN 0-393-31991-1. pp 268–270

[18] Everett 1957, section 3, 2nd paragraph, 1st sentence

[19] Everett [1956]1973, "Theory of the Universal Wavefunction", chapter 6 (e)

[20] Zurek, Wojciech (March 2009). "Quantum Darwinism". *Nature Physics* **5** (3): 181–188. arXiv:0903.5082. Bibcode:2009NatPh...5..181Z. doi:10.1038/nphys1202.

[21] Everett

[22] Peter Byrne, The Many Worlds of Hugh Everett III: Multiple Universes, Mutual Assured Destruction, and the Meltdown of a Nuclear Family, ISBN 978-0-19-955227-6

[23] "Whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed." Albert Einstein to Werner Heisenberg, objecting to placing observables at the heart of the new quantum mechanics, during Heisenberg's 1926 lecture at Berlin; related by Heisenberg in 1968, quoted by Abdus Salam, *Unification of Fundamental Forces*, Cambridge University Press (1990) ISBN 0-521-37140-6, pp 98–101

[24] N.P. Landsman, "The conclusion seems to be that no generally accepted derivation of the Born rule has been given to date, but this does not imply that such a derivation is impossible in principle.", in *Compendium of Quantum Physics* (eds.) F.Weinert, K. Hentschel, D.Greenberger and B. Falkenburg (Springer, 2008), ISBN 3-540-70622-4

[25] Adrian Kent (May 5, 2009), *One world versus many: the inadequacy of Everettian accounts of evolution, probability, and scientific confirmation*

[26] Kent, Adrian (1990). "Against Many-Worlds Interpretations". *Int.J.Mod.Phys* **A5**: 1745–1762. arXiv:gr-qc/9703089. Bibcode:1990IJMPA...5.1745K. doi:10.1142/S0217751X90000805.

[27] James Hartle, Quantum Mechanics of Individual Systems, *American Journal of Physics*, 1968, vol 36 (#8), pp. 704–712

[28] E. Farhi, J. Goldstone & S. Gutmann. *How probability arises in quantum mechanics.*, Ann. Phys. (N.Y.) 192, 368–382 (1989).

[29] Pitowsky, I. (2005). "Quantum mechanics as a theory of probability". *Eprint arXiv: quant-ph/0510095*: 10095. arXiv:quant-ph/0510095. Bibcode:2005quant.ph.10095P.

[30] Gleason, A. M. (1957). "Measures on the closed subspaces of a Hilbert space". *Journal of Mathematics and Mechanics* **6**: 885–893. doi:10.1512/iumj.1957.6.56050. MR 0096113.

[31] Deutsch, D. (1999). Quantum Theory of Probability and Decisions. *Proceedings of the Royal Society of London* A455, 3129–3137. .

[32] David Wallace: Quantum Probability and Decision Theory, Revisited

[33] David Wallace. Everettian Rationality: defending Deutsch's approach to probability in the Everett interpretation. Stud. Hist. Phil. Mod. Phys. 34 (2003), 415–438.

[34] David Wallace (2003), Quantum Probability from Subjective Likelihood: improving on Deutsch's proof of the probability rule

[35] David Wallace, 2009,A formal proof of the Born rule from decision-theoretic assumptions

[36] Simon Saunders: Derivation of the Born rule from operational assumptions. Proc. Roy. Soc. Lond. A460, 1771–1788 (2004).

[37] Simon Saunders, 2004: What is Probability?

[38] David J Baker, Measurement Outcomes and Probability in Everettian Quantum Mechanics, *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics*, Volume 38, Issue 1, March 2007, Pages 153–169

[39] H. Barnum, C. M. Caves, J. Finkelstein, C. A. Fuchs, R. Schack: Quantum Probability from Decision Theory? *Proc. Roy. Soc. Lond.* A456, 1175–1182 (2000).

[40] Merali, Zeeya (2007-09-21). "Parallel universes make quantum sense". *New Scientist* (2622). Retrieved 2013-11-22. (Summary only).

[41] Breitbart.com, Parallel universes exist – study, Sept 23 2007

[42] Perimeter Institute, Seminar overview, Probability in the Everett interpretation: state of play, David Wallace – Oxford University, 21 Sept 2007

[43] Perimeter Institute, Many worlds at 50 conference, September 21–24, 2007

[44] Armando V.D.B. Assis (2011). "Assis, Armando V.D.B. On the nature of $a_k^* a_k$ and the emergence of the Born rule. Annalen der Physik, 2011.". *Annalen der Physik (Berlin)* **523**: 883–897. arXiv:1009.1532. Bibcode:2011AnP...523..883A. doi:10.1002/andp.201100062. delete character in |title= at position 40 (help)

[45] Wojciech H. Zurek: Probabilities from entanglement, Born's rule from envariance, *Phys. Rev.* A71, 052105 (2005).

[46] Schlosshauer, M.; Fine, A. (2005). "On Zurek's derivation of the Born rule". *Found. Phys.* **35**: 197–213. arXiv:quant-ph/0312058. Bibcode:2005FoPh...35..197S. doi:10.1007/s10701-004-1941-6.

[47] Lutz Polley, Position eigenstates and the statistical axiom of quantum mechanics, contribution to conference *Foundations of Probability and Physics*, Vaxjo, Nov 27 – Dec 1, 2000

[48] Lutz Polley, Quantum-mechanical probability from the symmetries of two-state systems

[49] Vaidman, L. "Probability in the Many-Worlds Interpretation of Quantum Mechanics." In: Ben-Menahem, Y., & Hemmo, M. (eds), The Probable and the Improbable: Understanding Probability in Physics, Essays in Memory of Itamar Pitowsky. Springer.

[50] Sebens, C.T. and Carroll, S.M., Self-Locating Uncertainty and the Origin of Probability in Everettian Quantum Mechanics.

[51] Mark A. Rubin, Locality in the Everett Interpretation of Heisenberg-Picture Quantum Mechanics, *Foundations of Physics Letters*, 14, (2001) , pp. 301–322, arXiv:quant-ph/0103079

[52] Paul C.W. Davies, *Other Worlds*, chapters 8 & 9 *The Anthropic Principle & Is the Universe an accident?*, (1980) ISBN 0-460-04400-1

[53] Paul C.W. Davies, *The Accidental Universe*, (1982) ISBN 0-521-28692-1

[54] Everett FAQ "Does many-worlds violate Ockham's Razor?"

[55] Vaidman, Lev. "Many-Worlds Interpretation of Quantum Mechanics". The Stanford Encyclopedia of Philosophy.

[56] Deutsch, D., (1986) 'Three experimental implications of the Everett interpretation', in R. Penrose and C.J. Isham (eds.), Quantum Concepts of Space and Time, Oxford: The Clarendon Press, pp. 204–214.

[57] Page, D., (2000) 'Can Quantum Cosmology Give Observational Consequences of Many-Worlds Quantum Theory?'

[58] Plaga, R. (1997). "On a possibility to find experimental evidence for the many-worlds interpretation of quantum mechanics". *Foundations of Physics* **27**: 559–577. arXiv:quant-ph/9510007. Bibcode:1997FoPh...27..559P. doi:10.1007/BF02550677.

[59] Page, Don N. (2000). "Can Quantum Cosmology Give Observational Consequences of Many-Worlds Quantum Theory?". arXiv:gr-qc/0001001. doi:10.1063/1.1301589.

[60] Bryce Seligman DeWitt, Quantum Mechanics and Reality: Could the solution to the dilemma of indeterminism be a universe in which all possible outcomes of an experiment actually occur?, *Physics Today*, 23(9) pp 30–40 (September 1970); see equation 10

[61] Penrose, R. *The Road to Reality*, §21.11

[62] Tegmark, Max The Interpretation of Quantum Mechanics: Many Worlds or Many Words?, 1998. To quote: "What Everett does NOT postulate: *"At certain magic instances, the world undergoes some sort of metaphysical 'split' into two branches that subsequently never interact."* This is not only a misrepresentation of the MWI, but also inconsistent with the Everett postulate, since the subsequent time evolution could in principle make the two terms...interfere. According to the MWI, there is, was and always will be only one wavefunction, and only decoherence calculations, not postulates, can tell us when it is a good approximation to treat two terms as non-interacting."

[63] Paul C.W. Davies, J.R. Brown, *The Ghost in the Atom* (1986) ISBN 0-521-31316-3, pp. 34–38: "The Many-Universes Interpretation", pp 83–105 for David Deutsch's test of MWI and reversible quantum memories

[64] Christoph Simon, 2009, *Conscious observers clarify many worlds*

[65] Joseph Gerver, The past as backward movies of the future, *Physics Today*, letters followup, 24(4), (April 1971), pp 46–7

[66] Bryce Seligman DeWitt, *Physics Today*,letters followup, 24(4), (April 1971), pp 43

[67] Arnold Neumaier's comments on the Everett FAQ, 1999 & 2003

[68] Everett [1956] 1973, "*Theory of the Universal Wavefunction*", chapter V, section 4 "Approximate Measurements", pp. 100–103 (e)

[69] Stapp, Henry (2002). "The basis problem in many-world theories" (PDF). *Canadian Journal of Physics* **80**: 1043–1052. arXiv:quant-ph/0110148. Bibcode:2002CaJPh..80.1043S. doi:10.1139/p02-068.

[70] Brown, Harvey R; Wallace, David (2005). "Solving the measurement problem: de Broglie–Bohm loses out to Everett" (PDF). *Foundations of Physics* **35**: 517–540. arXiv:quant-ph/0403094. Bibcode:2005FoPh...35..517B. doi:10.1007/s10701-004-2009-3.

[71] Mark A Rubin (2005), There Is No Basis Ambiguity in Everett Quantum Mechanics, *Foundations of Physics Letters*, Volume 17, Number 4 / August, 2004, pp 323–341

[72] Penrose, Roger (August 1991). "Roger Penrose Looks Beyond the Classic-Quantum Dichotomy". Sciencewatch. Retrieved 2007-10-21.

[73] Everett FAQ "Does many-worlds violate conservation of energy?"

[74] Everett FAQ "How do probabilities emerge within many-worlds?"

[75] Everett FAQ "When does Schrodinger's cat split?"

[76] Jeffrey A. Barrett, *The Quantum Mechanics of Minds and Worlds*, Oxford University Press, 1999. According to Barrett (loc. cit. Chapter 6) "There are many many-worlds interpretations."

[77] Barrett, Jeffrey A. (2010). Zalta, Edward N., ed. "Everett's Relative-State Formulation of Quantum Mechanics" (Fall 2010 ed.). The Stanford Encyclopedia of Philosophy. Again, according to Barrett "It is... unclear precisely how this was supposed to work."

[78] Aldhous, Peter (2007-11-24). "Parallel lives can never touch". *New Scientist* (2631). Retrieved 2007-11-21.

[79] Eugene Shikhovtsev's Biography of Everett, in particular see "*Keith Lynch remembers 1979–1980*"

[80] David Deutsch, *The Fabric of Reality: The Science of Parallel Universes And Its Implications*, Penguin Books (1998), ISBN 0-14-027541-X

[81] Deutsch, David (1985). "Quantum theory, the Church–Turing principle and the universal quantum computer". *Proceedings of the Royal Society of London A* **400**: 97–117. Bibcode:1985RSPSA.400...97D. doi:10.1098/rspa.1985.0070.

[82] A response to Bryce DeWitt, Martin Gardner, May 2002

[83] Award winning 1995 Channel 4 documentary "Reality on the rocks: Beyond our Ken" where, in response to Ken Campbell's question "all these trillions of Universes of the Multiverse, are they as real as this one seems to be to me?" Hawking states, "Yes.... According to Feynman's idea, every possible history (of Ken) is equally real."

[84] Gardner, Martin (2003). *Are universes thicker than blackberries?*. W.W. Norton. p. 10. ISBN 978-0-393-05742-3.

[85] Ferris, Timothy (1997). *The Whole Shebang*. Simon & Schuster. pp. 345. ISBN 978-0-684-81020-1.

[86] Hawking, Stephen; Roger Penrose (1996). *The Nature of Space and Time*. Princeton University Press. pp. 121. ISBN 978-0-691-03791-2.

[87] Elvridge., Jim (2008-01-02). *The Universe – Solved!*. pp. 35–36. ISBN 978-1-4243-3626-5. OCLC 247614399. 58% believed that the Many Worlds Interpretation (MWI) was true, including Stephen Hawking and Nobel Laureates Murray Gell-Mann and Richard Feynman

[88] Bruce., Alexandra. "How does reality work?". *Beyond the bleep : the definitive unauthorized guide to What the bleep do we know!?*. p. 33. ISBN 978-1-932857-22-1. [the poll was] published in the French periodical *Sciences et Avenir* in January 1998

[89] Stenger, V.J. (1995). *The Unconscious Quantum: Metaphysics in Modern Physics and Cosmology*. Prometheus Books. p. 176. ISBN 978-1-57392-022-3. LCCN lc95032599. Gell-Mann and collaborator James Hartle, along with a score of others, have been working to develop a more palatable interpretation of quantum mechanics that is free of the problems that plague all the interpretations we have considered so far. This new interpretation is called, in its various incarnations, **post-Everett quantum mechanics**, alternate histories, consistent histories, or decoherent histories. I will not be overly concerned with the detailed differences between these characterizations and will use the terms more or less interchangeably.

[90] Max Tegmark on many-worlds (contains MWI poll)

[91] Caroll, Sean (1 April 2004). "Preposterous Universe". Archived from the original on 8 September 2004.

[92] Nielsen, Michael (3 April 2004). "Michael Nielsen: The Interpretation of Quantum Mechanics". Archived from the original on 20 May 2004.

[93] Interpretation of Quantum Mechanics class survey

[94] "A Snapshot of Foundational Attitudes Toward Quantum Mechanics", Schlosshauer et al 2013

[95] "The Many Minds Approach". 25 October 2010. Retrieved 7 December 2010. This idea was first proposed by Austrian mathematician Hans Moravec in 1987...

[96] Moravec, Hans (1988). "The Doomsday Device". *Mind Children: The Future of Robot and Human Intelligence*. Harvard: Harvard University Press. p. 188. ISBN 978-0-674-57618-6. (If MWI is true, apocalyptic particle accelerators won't function as advertised).

[97] Marchal, Bruno (1988). "Informatique théorique et philosophie de l'esprit" [Theoretical Computer Science and Philosophy of Mind]. *Acte du 3ème colloque international Cognition et Connaissance [Proceedings of the 3rd International Conference Cognition and Knowledge]* (Toulouse): 193–227.

[98] Marchal, Bruno (1991). De Glas, M.; Gabbay, D., eds. "Mechanism and personal identity" (PDF). *Proceedings of WOCFAI 91* (Paris. Angkor.): 335–345.

[99] Tegmark, Max The Interpretation of Quantum Mechanics: Many Worlds or Many Words?, 1998

[100] Tegmark, Max (November 1998). "Quantum immortality". Retrieved 25 October 2010.

[101] W.M.Itano et al., Phys.Rev. A47,3354 (1993).

[102] M.SargentIII,M.O.Scully and W.E.Lamb, Laser physics (Addison-Wesley, Reading, 1974), p.27.

[103] M.O.Scully and H.Walther, Phys.Rev. A39,5229 (1989).

[104] J.Polchinski, Phys.Rev.Lett. 66,397 (1991).

[105] M.Gell-Mann and J.B.Hartle, Equivalent Sets of Histories and Multiple Quasiclassical Domains, preprint University of California at Santa Barbara UCSBTH-94-09 (1994).

[106] H.D.Zeh, Found.Phys. 3,109 (1973).

[107] H.D.Zeh, Phys.Lett.A 172,189 (1993).

[108] A.Albrecht, Phys.Rev. D48,3768 (1993).

[109] D.Deutsch, Int.J.theor.Phys. 24,1 (1985).

14 Further reading

- Jeffrey A. Barrett, *The Quantum Mechanics of Minds and Worlds*, Oxford University Press, Oxford, 1999.
- Peter Byrne, *The Many Worlds of Hugh Everett III: Multiple Universes, Mutual Assured Destruction, and the Meltdown of a Nuclear Family*, Oxford University Press, 2010.
- Jeffrey A. Barrett and Peter Byrne, eds., "The Everett Interpretation of Quantum Mechanics: Collected Works 1955–1980 with Commentary", Princeton University Press, 2012.
- Julian Brown, *Minds, Machines, and the Multiverse*, Simon & Schuster, 2000, ISBN 0-684-81481-1
- Paul C.W. Davies, *Other Worlds*, (1980) ISBN 0-460-04400-1
- James P. Hogan, *The Proteus Operation* (science fiction involving the many-worlds interpretation, time travel and World War 2 history), Baen, Reissue edition (August 1, 1996) ISBN 0-671-87757-7
- Adrian Kent, One world versus many: the inadequacy of Everettian accounts of evolution, probability, and scientific confirmation
- Andrei Linde and Vitaly Vanchurin, How Many Universes are in the Multiverse?
- Osnaghi, Stefano; Freitas, Fabio; Olival Freire, Jr (2009). "The Origin of the Everettian Heresy" (PDF). *Studies in History and Philosophy of Modern Physics* **40**: 97–123. doi:10.1016/j.shpsb.2008.10.002. A study of the painful three-way relationship between Hugh Everett, John A Wheeler and Niels Bohr and how this affected the early development of the many-worlds theory.
- Asher Peres, *Quantum Theory: Concepts and Methods*, Kluwer, Dordrecht, 1993.
- Mark A. Rubin, Locality in the Everett Interpretation of Heisenberg-Picture Quantum Mechanics, *Foundations of Physics Letters*, 14, (2001), pp. 301–322, arXiv:quant-ph/0103079
- David Wallace, Harvey R. Brown, Solving the measurement problem: de Broglie–Bohm loses out to Everett, *Foundations of Physics*, arXiv:quant-ph/0403094
- David Wallace, Worlds in the Everett Interpretation, *Studies in the History and Philosophy of Modern Physics*, 33, (2002), pp. 637–661, arXiv:quant-ph/0103092
- John A. Wheeler and Wojciech Hubert Zurek (eds), *Quantum Theory and Measurement*, Princeton University Press, (1983), ISBN 0-691-08316-9
- Sean M. Carroll, Charles T. Sebens, *Many Worlds, the Born Rule, and Self-Locating Uncertainty*, arXiv:1405.7907

15 External links

- Everett's Relative-State Formulation of Quantum Mechanics – Jeffrey A. Barrett's article on Everett's formulation of quantum mechanics in the Stanford Encyclopedia of Philosophy.
- Many-Worlds Interpretation of Quantum Mechanics – Lev Vaidman's article on the many-worlds interpretation of quantum mechanics in the Stanford Encyclopedia of Philosophy.
- Hugh Everett III Manuscript Archive (UC Irvine) – Jeffrey A. Barrett, Peter Byrne, and James O. Weatherall (eds.).
- Michael C Price's Everett FAQ – a clear FAQ-style presentation of the theory.
- The Many-Worlds Interpretation of Quantum Mechanics – a description for the lay reader with links.
- Against Many-Worlds Interpretations by Adrian Kent
- Many-Worlds is a "lost cause" according to R. F. Streater
- The many worlds of quantum mechanics John Sankey
- Max Tegmark's web page
- Henry Stapp's critique of MWI, focusing on the basis problem Canadian J. Phys. 80,1043–1052 (2002).
- Everett hit count on arxiv.org

- Many Worlds 50th anniversary conference at Oxford
- “Many Worlds at 50” conference at Perimeter Institute
- Scientific American report on the Many Worlds 50th anniversary conference at Oxford
- Highfield, Roger (September 21, 2007). “Parallel universe proof boosts time travel hopes”. The Daily Telegraph. Archived from the original on 2007-10-20. Retrieved 2007-10-26..
- HowStuffWorks article
- Physicists Calculate Number of Parallel Universes Physorg.com October 16, 2009.
- TED-Education video – How many universes are there?.

16 Text and image sources, contributors, and licenses

16.1 Text

- **Many-worlds interpretation** *Source:* https://en.wikipedia.org/wiki/Many-worlds_interpretation?oldid=712895104 *Contributors:* AxelBoldt, Derek Ross, LC~enwiki, CYD, Zundark, Timo Honkasalo, The Anome, WillWare, Eclecticology, Josh Grosse, Darius Bacon, Nate Silva, Roadrunner, Maury Markowitz, FvdP, Stevertigo, Michael Hardy, JakeVortex, Oliver Pereira, Gabbe, Ixfd64, Alfio, William M. Connolley, Aarchiba, Evercat, HPA, Richj, Charles Matthews, Timwi, Terse, Grendelkhan, Phys, Fairandbalanced, Bevo, Andy Fugard, Nnh, BenRG, Fredrik, Vespristiano, Altenmann, Arkuat, Rholton, Bkell, ElBenevolente, Carnildo, Pablo-flores, Giftlite, Gtrmp, Barbara Shack, Wolfkeeper, Lethe, Bfinn, Wwoods, Ebonmuse, Ryanaxp, Wmahan, Mmm~enwiki, ChicXulub, Quadell, Piotrus, MadIce, Khaosworks, CSTAR, Togo~enwiki, Latitude0116, Sam Hocevar, Lumidek, Jcorgan, Eyv, Robin klein, Acsenray, Chris Howard, D6, Freakofnurture, Rich Farmbrough, Guanabot, Leibniz, Florian Blaschke, Dbachmann, Pavel Vozenilek, Nchaimov, Ben Standeven, El C, Haxwell, Kotuku33, SamRushing, Ehaque, Danski14, Plumbago, SlimVirgin, Batmanand, Hdeasy, Schaefer, Fourthords, Count Iblis, Pauli133, DV8 2XL, Kromozone, Dan100, Falcorian, Firsfron, Woohookitty, Linas, Dandv, JonBirge, Thruston, SDC, Joke137, Pfalstad, Marudubshinki, Mandarax, QuaestorXVII, Graham87, Grammarbot, Rjwilmsi, Ckoenigsberg, Eyu100, Aero66, HappyCamper, Theodork, Wragge, Arnero, ZoneSeek, Diza, Saswann, Chobot, DVdm, Korg, McGinnis, YurikBot, NTBot~enwiki, RussBot, Fabartus, Bhny, Gaius Cornelius, Vincej, Bboyneko, Thane, Draeco, David R. Ingham, Joncolvin, Nti2005, Schlafly, Brian Olsen, Kxjan, Inhighspeed, Pnrj, Emersoni, Zwobot, Kkmurray, Light current, Geoffrey.landis, Radioflux, Nixer, Ilmari Karonen, NeilN, Teo64x, SmackBot, Rex the first, JohnSankey, C.Fred, Jrockley, Dave Kielpinski, MalafayaBot, Silly rabbit, Imaginaryoctopus, Salmar, Shantrika, Calbaer, Denis-Diderot, Savidan, DavidBoden, Ryan Roos, Hunter2005, DJIndica, Lambiam, Ser Amantio di Nicolao, Dr. Sunglasses, Mgiganteus1, Ckatz, Santa Sangre, Dicklyon, Hypnosifl, Eridani, Stephen B Streater, HisSpaceResearch, Dreftymac, Joseph Solis in Australia, Brian Wowk, Courcelles, Laplace's Demon, Bstepp99, Mustbe, 8754865, JForget, Will314159, CmdrObot, Vyznev Xnebara, AshLin, Denis MacEoin, Rgonsalv, Myasuda, Gregbard, Dragon's Blood, Cydebot, Peterbyrne, Peterdjones, Michael C Price, Alexnye, Geewee, Michael D. Wolok, Mbell, Headbomb, Parsiferon, Cj67, Stannered, Cyclonenim, AntiVandalBot, Mukake, Czj, MER-C, CosineKitty, Txomin, Magioladitis, SHCarter, Skew-t, Brusegadi, Torchiest, Duendeverde, Plexos, Sm8900, R'n'B, J.delanoy, Maurice Carbonaro, Kevin aylward, 5Q5, Coastal593, Mathglot, Shawn in Montreal, Gill110951, Tarotcards, Eli the Barrow-boy~enwiki, Sarge009, Phatius McBluff, Ajfweb, Inwind, Sheliak, Neuromath, VolkovBot, Jdcaust, Eve Hall, Xnquist, Aymatth2, Don4of4, TBond, Wiae, Ar-wiki, Sapphic, Spinningspark, Hrimpurstala, AlleborgoBot, Quantum Person, Yintan, Wing gundam, Likebox, Flyer22 Reborn, JohnSawyer, JohnnyMrNinja, Longi 93, AussieScribe, Randy Kryn, VanishedUser sdu9aya9fs787sads, Martarius, ClueBot, EoGuy, General Epitaph, EMC125, Djr32, Tianasez, Estirabot, Vanhoabui, Sun Creator, Resuna, SchreiberBike, Carriearchdale, Thingg, Ctkohl, DumZiBoT, BarretB, XLinkBot, Sanchoquixote, Kbdankbot, Addbot, Miskaton, Gregz08, Zahd, Tanhabot, Thirteenangrymen, Mac Dreamstate, Proxima Centauri, Ld100, Lightbot, Taketa, زرشک, Zorrobot, Whitneyz32, Legobot, MichelCPrice, Yobot, Pink!Teen, AnomieBOT, Unara, Citation bot, DirlBot, LilHelpa, Gap9551, Measles, Omnipaedista, Targeran, WaysToEscape, FrescoBot, ایلیا2010, Machine Elf 1735, MorphismOfDoom, Citation bot 1, I dream of horses, Jonesey95, Chatfecter, Grok42, Jusses2, Fredkinfollower, SkyMachine, Dc987, Duke159, Lhollo, Greg-Wooledge, Jamesabloom, George Richard Leeming, Rekcana, Feelingsman22, Slightsmile, Italia2006, ZéroBot, Cogiati, Gahr gardner, Quantumavik, RUBEN TESOLIN, H3llBot, Quondum, Quantholic, L Kensington, Senjuto, Surajt88, Ihardlythinkso, Kartasto, Teapeat, Rememberway, ClueBot NG, Nobody60, Incompetence, Kazzie1995, Kasirbot, Helpful Pixie Bot, Bibcode Bot, BG19bot, Boriaj, Stelpa, FiveColourMap, AIMW32, Huntingg, Eqb1987, Willempramschot, Brendan.Oz, Harizotoh9, Dule1101, Modalizer, Khazar2, JYBot, Mogism, Corn cheese, Reatlas, Epicgenius, Jamesmcmahon0, A Certain Lack of Grandeur, Thevideodrome, Arfæst Ealdwrítere, Bardoligneo, Stamptrader, Fixuture, Ismael755, Melcous, 2PeterElls, Monkbot, Kalipsos, MazeHatter, Jonkirstenhof, CV9933, Azealia911, Fixing.your.problems., Karhu360, Allwyncjose and Anonymous: 273

16.2 Images

- **File:Commons-logo.svg** *Source:* https://upload.wikimedia.org/wikipedia/en/4/4a/Commons-logo.svg *License:* CC-BY-SA-3.0 *Contributors:* ? *Original artist:* ?
- **File:Edit-clear.svg** *Source:* https://upload.wikimedia.org/wikipedia/en/f/f2/Edit-clear.svg *License:* Public domain *Contributors:* The *Tango! Desktop Project*. *Original artist:*

  The people from the Tango! project. And according to the meta-data in the file, specifically: "Andreas Nilsson, and Jakub Steiner (although minimally)."
- **File:Hugh-Everett.jpg** *Source:* https://upload.wikimedia.org/wikipedia/en/c/cf/Hugh-Everett.jpg *License:* Fair use *Contributors:*

  http://ucispace.lib.uci.edu/handle/10575/1060
  http://sites.uci.edu/ucisca/2011/09/15/hugh-everett-iii-and-quantum-physics/ *Original artist:* ?
- **File:Many-worlds-bloch.png** *Source:* https://upload.wikimedia.org/wikipedia/en/d/d6/Many-worlds-bloch.png *License:* Cc-by-sa-3.0 *Contributors:* ? *Original artist:* ?
- **File:Many-worlds.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/8/82/Many-worlds.svg *License:* CC-BY-SA-3.0 *Contributors:* en:Image:Many-worlds.png *Original artist:* Traced by User:Stannered
- **File:Paths-many-worlds.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/3/3b/Paths-many-worlds.svg *License:* CC-BY-SA-3.0 *Contributors:* en:Image:Paths-many-worlds.png *Original artist:* Traced by User:Stannered
- **File:Qm_template_pic_4.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/f/fe/Qm_template_pic_4.svg *License:* CC0 *Contributors:* Own work *Original artist:* Maschen
- **File:Question_book-new.svg** *Source:* https://upload.wikimedia.org/wikipedia/en/9/99/Question_book-new.svg *License:* Cc-by-sa-3.0 *Contributors:*

  Created from scratch in Adobe Illustrator. Based on Image:Question book.png created by User:Equazcion *Original artist:*

  Tkgd2007
- **File:Schroedingers_cat_film.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/c/c8/Schroedingers_cat_film.svg *License:* CC0 *Contributors:* Own work *Original artist:* Christian Schirm

- **File:Sobel_North_America.gif** *Source:* https://upload.wikimedia.org/wikipedia/commons/f/f4/Sobel_North_America.gif *License:* CC-BY-SA-3.0 *Contributors:* No machine-readable source provided. Own work assumed (based on copyright claims). *Original artist:* No machine-readable author provided. Roke~commonswiki assumed (based on copyright claims).
- **File:Splittings-1.png** *Source:* https://upload.wikimedia.org/wikipedia/commons/2/2b/Splittings-1.png *License:* CC-BY-SA-3.0 *Contributors:* enwiki *Original artist:* User:Jecowa
- **File:Wikibooks-logo.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/f/fa/Wikibooks-logo.svg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* User:Bastique, User:Ramac et al.
- **File:Wikinews-logo.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/2/24/Wikinews-logo.svg *License:* CC BY-SA 3.0 *Contributors:* This is a cropped version of Image:Wikinews-logo-en.png. *Original artist:* Vectorized by Simon 01:05, 2 August 2006 (UTC) Updated by Time3000 17 April 2007 to use official Wikinews colours and appear correctly on dark backgrounds. Originally uploaded by Simon.
- **File:Wikiquote-logo.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/f/fa/Wikiquote-logo.svg *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:Wikisource-logo.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/4/4c/Wikisource-logo.svg *License:* CC BY-SA 3.0 *Contributors:* Rei-artur *Original artist:* Nicholas Moreau
- **File:Wikiversity-logo-Snorky.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/1/1b/Wikiversity-logo-en.svg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* Snorky
- **File:Wiktionary-logo-en.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/f/f8/Wiktionary-logo-en.svg *License:* Public domain *Contributors:* Vector version of Image:Wiktionary-logo-en.png. *Original artist:* Vectorized by Fvasconcellos (talk · contribs), based on original logo tossed together by Brion Vibber

16.3 Content license

-

WIKIPEDIA

Many-worlds interpretation

The **many-worlds interpretation** is an interpretation of quantum mechanics that asserts the objective reality of the universal wavefunction and denies the actuality of wavefunction collapse. The existence of the other worlds makes it possible to remove randomness and action at a distance from quantum theory and thus from all physics. Many-worlds implies that all possible alternate histories and futures are real, each representing an actual "world" (or "universe"). In layman's terms, the hypothesis states there is a very large—perhaps infinite[2]—number of universes, and everything that could possibly have happened in our past, but did not, has occurred in the past of some other universe or universes. The theory is also referred to as **MWI**, the **relative state formulation**, the **Everett interpretation**, the **theory of the universal wavefunction**, **many-universes interpretation**, **multiverse theory** or just **many-worlds**.

The quantum-mechanical "Schrödinger's cat" theorem according to the many-worlds interpretation. In this interpretation, every event is a branch point; the cat is both alive and dead, even before the box is opened, but the "alive" and "dead" cats are in different branches of the universe, both of which are equally real, but which do not interact with each other.[1]

The original relative state formulation is due to Hugh Everett in 1957.[3][4] Later, this formulation was popularized and renamed *many-worlds* by Bryce Seligman DeWitt in the 1960s and 1970s.[1][5][6][7] The decoherence approaches to interpreting quantum theory have been further explored and developed,[8][9][10] becoming quite popular. MWI is one of many multiverse hypotheses in physics and philosophy. It is currently considered a mainstream interpretation along with the other decoherence interpretations, collapse theories (including the historical Copenhagen interpretation),[11] and hidden variable theories such as the Bohmian mechanics.

Before many-worlds, reality had always been viewed as a single unfolding history. Many-worlds, however, views historical reality as a many-branched tree, wherein every possible quantum outcome is realised.[12] Many-worlds reconciles the observation of non-deterministic events, such as random radioactive decay, with the fully deterministic equations of quantum physics.

In many-worlds, the subjective appearance of wavefunction collapse is explained by the mechanism of quantum decoherence, and this is supposed to resolve all of the correlation paradoxes of quantum theory, such as the EPR paradox[13][14] and Schrödinger's cat,[1] since every possible outcome of every event defines or exists in its own "history" or "world".

Contents

Origin

In Dublin in 1952 Erwin Schrödinger gave a lecture in which at one point he jocularly warned his audience that what he was about to say might "seem lunatic". He went on to assert that what the equation that won him a Nobel prize seems to be describing is several different histories, they are "not alternatives but all really happen simultaneously". This is the earliest known reference to the many-worlds.[15][16]

Outline

Although several versions of many-worlds have been proposed since Hugh Everett's original work,[4] they all contain one key idea: the equations of physics that model the time evolution of systems *without* embedded observers are sufficient for modelling systems which *do* contain observers; in particular there is no observation-triggered wave function collapse which the Copenhagen interpretation proposes. Provided the theory is linear with respect to the wavefunction, the exact form of the quantum dynamics modelled, be it the non-relativistic Schrödinger equation, relativistic quantum field theory or some form of quantum gravity or string theory, does not alter the validity of MWI since MWI is a metatheory applicable to all linear quantum theories, and there is no experimental evidence for any non-linearity of the wavefunction in physics.[17][18] MWI's main conclusion is that the universe (or multiverse in this context) is composed of a quantum superposition of very many, possibly even non-denumerably infinitely[2] many, increasingly divergent, non-communicating parallel universes or quantum worlds.[7]

The idea of MWI originated in Everett's Princeton Ph.D. thesis "The Theory of the Universal Wavefunction",[7] developed under his thesis advisor John Archibald Wheeler, a shorter summary of which was published in 1957 entitled "Relative State Formulation of Quantum Mechanics" (Wheeler contributed the title "relative state";[19] Everett originally called his approach the "Correlation Interpretation", where "correlation" refers to quantum entanglement). The phrase "many-worlds" is due to Bryce DeWitt,[7] who was responsible for the wider popularisation of Everett's theory, which had been largely ignored for the first decade after publication. DeWitt's phrase "many-worlds" has become so much more popular than Everett's "Universal Wavefunction" or Everett–Wheeler's "Relative State Formulation" that many forget that this is only a difference of terminology; the content of both of Everett's papers and DeWitt's popular article is the same.

The many-worlds interpretation shares many similarities with later, other "post-Everett" interpretations of quantum mechanics which also use decoherence to explain the process of measurement or wavefunction collapse. MWI treats the other histories or worlds as real since it regards the universal wavefunction as the "basic physical entity"[20] or "the fundamental entity, obeying at all times a deterministic wave equation".[21] The other decoherent interpretations, such as consistent histories, the Existential Interpretation etc., either regard the extra quantum worlds as metaphorical in some sense, or are agnostic about their reality; it is sometimes hard to distinguish between the different varieties. MWI is distinguished by two qualities: it assumes realism,[20][21] which it assigns to the wavefunction, and it has the minimal formal structure possible, rejecting any hidden variables, quantum potential, any form of a collapse postulate (i.e., Copenhagenism) or mental postulates (such as the many-minds interpretation makes).

Decoherent interpretations of many-worlds using einselection to explain how a small number of classical pointer states can emerge from the enormous Hilbert space of superpositions have been proposed by Wojciech H. Zurek. "Under scrutiny of the environment, only pointer states remain unchanged. Other states decohere into mixtures of stable pointer states that can persist, and, in this sense, exist: They are einselected."[22] These ideas complement MWI and bring the interpretation in line with our perception of reality

Many-worlds is often referred to as a theory, rather than just an interpretation, by those who propose that many-worlds can make testable predictions (such as David Deutsch) or is falsifiable (such as Everett) or by those who propose that all the other, non-MW interpretations, are inconsistent, illogical or unscientific in their handling of measurements; Hugh Everett argued that his formulation was a metatheory, since it made statements about other interpretations of quantum theory; that it was the "only completely coherent approach to explaining both the contents of quantum mechanics and the appearance of the world."[23] Deutsch is dismissive that many-worlds is an "interpretation", saying that calling it an interpretation "is like talking about dinosaurs as an 'interpretation' of fossil records."[24]

Interpreting wavefunction collapse

As with the other interpretations of quantum mechanics, the many-worlds interpretation is motivated by behavior that can be illustrated by the double-slit experiment. When particles of light (or anything else) are passed through the double slit, a calculation assuming wave-like behavior of light can be used to identify where the particles are likely to be observed. Yet when the particles are observed in this experiment, they appear as particles (i.e., at definite places) and not as non-localized waves.

Some versions of the Copenhagen interpretation of quantum mechanics proposed a process of "collapse" in which an indeterminate quantum system would probabilistically collapse down onto, or select, just one determinate outcome to "explain" this phenomenon of observation. Wavefunction collapse was widely regarded as artificial and *ad hoc*, so an alternative interpretation in which the behavior of measurement could be understood from more fundamental physical principles was considered desirable.

Everett's Ph.D. work provided such an alternative interpretation. Everett stated that for a composite system – for example a subject (the "observer" or measuring apparatus) observing an object (the "observed" system, such as a particle) – the statement that either the observer or the observed has a well-defined state is meaningless; in modern parlance, the observer and the observed have become entangled; we can only specify the state of one *relative* to the other, i.e., the state of the observer and the observed are correlated *after* the observation is made. This led Everett to derive from the unitary, deterministic dynamics alone (i.e., without assuming wavefunction collapse) the notion of a *relativity of states*.

Everett noticed that the unitary, deterministic dynamics alone decreed that after an observation is made each element of the quantum superposition of the combined subject–object wavefunction contains two "relative states": a "collapsed" object state and an associated observer who has observed the same collapsed outcome; what the observer sees and the state of the object have become correlated by the act of measurement or observation. The subsequent evolution of each pair of relative subject–object states proceeds with complete indifference as to the presence or absence of the other elements, *as if* wavefunction collapse has occurred, which has the consequence that later observations are always consistent with the earlier observations. Thus the *appearance* of the object's wavefunction's collapse has emerged from the unitary, deterministic theory itself. (This answered Einstein's early criticism of quantum theory, that the theory should define what is observed, not for the observables to define the theory).[25] Since the wavefunction merely appears to have collapsed then, Everett reasoned, there was no need to actually assume that it had collapsed. And so, invoking Occam's razor, he removed the postulate of wavefunction collapse from the theory

The unreal/real interpretation

According to Martin Gardner, the "other" worlds of MWI have two different interpretations: real or unreal; he claims that Stephen Hawking and Steven Weinberg both favour the unreal interpretation.[26] Gardner also claims that the nonreal interpretation is favoured by the majority of physicists, whereas the "realist" view is only supported by MWI experts such as Deutsch and Bryce DeWitt. Hawking has said that "according to Feynman's idea", all the other histories are as "equally real" as our own,[27] and Martin Gardner reports Hawking saying that MWI is "trivially true".[28] In a 1983 interview, Hawking also said he regarded the MWI as "self-evidently correct" but was dismissive towards questions about the interpretation of quantum mechanics, saying, "When I hear of Schrödinger's cat, I reach for my gun." In the same interview, he also said, "But, look: All that one does, really, is to calculate conditional probabilities—in other words, the probability of A happening, given B. I think that that's all the many worlds interpretation is. Some people overlay it with a lot of mysticism about the wave function splitting into different parts. But all that you're calculating is conditional probabilities."[29] Elsewhere Hawking contrasted his attitude towards the "reality" of physical theories with that of his colleague Roger Penrose, saying, "He's a Platonist and I'm a positivist. He's worried that Schrödinger's cat is in a quantum state, where it is half alive and half dead. He feels that can't correspond to reality. But that doesn't bother me. I don't demand that a theory correspond to reality because I don't know what it is. Reality is not a quality you can test with litmus paper. All I'm concerned with is that the theory should predict the results of measurements. Quantum theory does this very successfully."[30] For his own part, Penrose agrees with Hawking that QM applied to the universe implies MW, although he considers the current lack of a successful theory of quantum gravity negates the claimed universality of conventional QM.[31]

Similarities with the de Broglie–Bohm interpretation

Kim Joris Boström has proposed a non-relativistic quantum mechanical theory that combines elements of the de Broglie–Bohm mechanics and that of Everett's many-'worlds'. In particular, the unreal MW interpretation of Hawking and Weinberg is similar to the Bohmian concept of unreal empty branch 'worlds':

> The second issue with Bohmian mechanics may at first sight appear rather harmless, but which on a closer look develops considerable destructive power: the issue of empty branches. These are the components of the post-measurement state that do not guide any particles because they do not have the actual configuration q in their support. At first sight, the empty branches do not appear problematic but on the contrary very helpful as they enable the theory to explain unique outcomes of measurements. Also, they seem to explain why there is an effective "collapse of the wavefunction", as in ordinary quantum mechanics. On a closer view, though, one must admit that these empty branches do not actually disappear. As the wavefunction is taken to describe a really existing field, all their branches really exist and will evolve forever by the Schrödinger dynamics, no matter how many of them will become empty in the course of the evolution. Every branch of the global wavefunction potentially describes a complete world which is, according to Bohm's ontology, only a possible world that would be the actual world if only it were filled with particles, and which is in every respect identical to a corresponding world in Everett's theory. Only one branch at a time is occupied by particles, thereby representing the actual world, while all other branches, though really existing as part of a really existing wavefunction, are empty and thus contain some sort of "zombie worlds" with planets, oceans, trees, cities, cars and people who talk like us and behave like us, but who do not actually exist. Now, if the Everettian theory may be accused of ontological extravagance, then Bohmian mechanics could be accused of ontological wastefulness. On top of the ontology of empty branches comes the additional ontology of particle positions that are, on account of the quantum equilibrium hypothesis, forever unknown to the observer. Yet, the actual configuration is never needed for the calculation of the statistical predictions in experimental reality, for these can be obtained by mere wavefunction algebra. From this perspective, Bohmian mechanics may appear as a wasteful and redundant theory. I think it is considerations like these that are the biggest obstacle in the way of a general acceptance of Bohmian mechanics.[32]

Probability

Attempts have been made, by many-world advocates and others, over the years to *derive* the Born rule, rather than just conventionally *assume* it, so as to reproduce all the required statistical behaviour associated with quantum mechanics. There is no consensus on whether this has been successful.[33][34][35]

Frequency-based approaches

Everett (1957) briefly derived the Born rule by showing that the Born rule was the only possible rule, and that its derivation was as justified as the procedure for defining probability in classical mechanics. Everett stopped doing research in theoretical physics shortly after obtaining his Ph.D., but his work on probability has been extended by a number of people. Andrew Gleason (1957) and James Hartle (1965) independently reproduced Everett's work[36] which was later extended.[37][38] These results are closely related to Gleason's theorem, a mathematical result according to which the Born probability measure is the only one on Hilbert space that can be constructed purely from the quantum state vector.[39]

Bryce DeWitt and his doctoral student R. Neill Graham later provided alternative (and longer) derivations to Everett's derivation of the Born rule.[7] They demonstrated that the norm of the worlds where the usual statistical rules of quantum theory broke down vanished, in the limit where the number of measurements went to infinity

Decision theory

A decision-theoretic derivation of the Born rule from Everettarian assumptions, was produced by David Deutsch (1999)[40] and refined by Wallace (2002–2009)[41][42][43][44] and Saunders (2004).[45][46] Some reviews have been positive, although the status of these arguments remains highly controversial; some theoretical physicists have taken them as supporting the case for parallel universes.[47] In the *New Scientist* article, reviewing their presentation at a September 2007 conference,[48][49] Andy Albrecht, a physicist at the University of California at Davis, is quoted as saying "This work will go down as one of the most important developments in the history of science."[47]

The Born rule and the collapse of the wave function have been obtained in the framework of the relative-state formulation of quantum mechanics by Armando V. D. B. Assis. He has proved that the Born rule and the collapse of the wave function follow from a game-theoretical strategy, namely the Nash equilibrium within a von Neumann zero-sum game between nature and observer.[50]

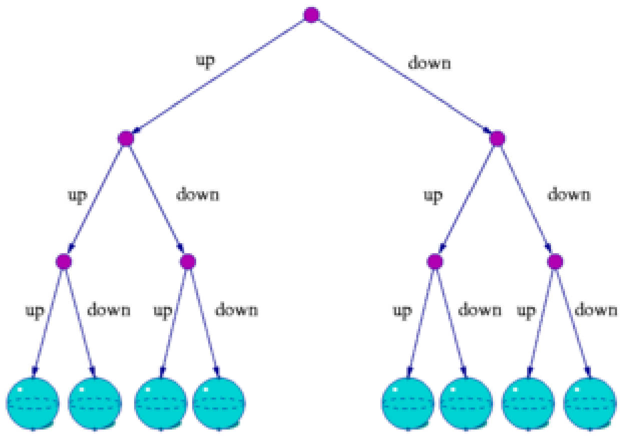
Symmetries and invariance

Wojciech H. Zurek (2005)[51] has produced a derivation of the Born rule, where decoherence has replaced Deutsch's informatic assumptions.[52] Lutz Polley (2000) has produced Born rule derivations where the informatic assumptions are replaced by symmetry arguments.[53][54]

Charles Sebens and Sean M. Carroll, building on work by Lev Vaidman,[55] proposed a similar approach based on self-locating uncertainty.[56] In this approach, decoherence creates multiple identical copies of observers, who can assign credences to being on different branches using the Born rule.

MWI overview

In Everett's formulation, a measuring apparatus **M** and an object system **S** form a composite system, each of which prior to measurement exists in well-defined (but time-dependent) states. Measurement is regarded as causing **M** and **S** to interact. After **S** interacts with **M**, it is no longer possible to describe either system by an independent state. According to Everett, the only meaningful descriptions of each system are relative states: for example the relative state of **S** given the state of **M** or the relative state of **M** given the state of **S**. In DeWitt's formulation, the state of **S** after a sequence of measurements is given by a quantum superposition of states, each one corresponding to an alternative measurement history of **S**.



Schematic illustration of splitting as a result of a repeated measurement.

For example, consider the smallest possible truly quantum system **S**, as shown in the illustration. This describes for instance, the spin-state of an electron. Considering a specific axis (say the *z*-axis) the north pole represents spin "up" and the south pole, spin "down". The superposition states of the system are described by (the surface of) a sphere called the Bloch sphere. To perform a measurement on **S**, it is made to interact with another similar system **M**. After the interaction, the combined system is described by a state that ranges over a six-dimensional space (the reason for the number six is explained in the article on the Bloch sphere). This six-dimensional object can also be regarded as a quantum superposition of two "alternative histories" of the original system **S**, one in which "up" was observed and the other in which "down" was observed. Each subsequent binary measurement (that is interaction with a system **M**) causes a similar split in the history tree. Thus after three measurements, the system can be regarded as a quantum superposition of 8 = 2 × 2 × 2 copies of the original system **S**.

The accepted terminology is somewhat misleading because it is incorrect to regard the universe as splitting at certain times; at any given instant there is one state in one universe.

Relative state

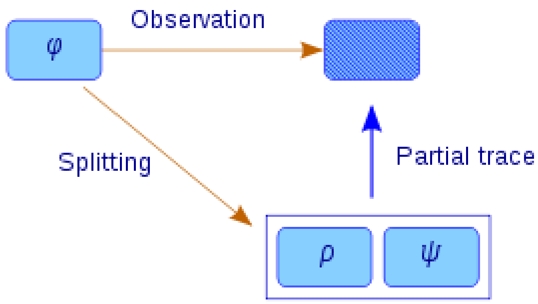
In his 1957 doctoral dissertation, Everett proposed that rather than modeling an isolated quantum system subject to external observation, one could mathematically model an object as well as its observers as purely physical systems within the mathematical framework developed by Paul Dirac, von Neumann and others, discarding altogether the *ad hoc* mechanism of wave function collapse.

Since Everett's original work, there have appeared a number of similar formalisms in the literature. One such is the relative state formulation. It makes two assumptions: first, the wavefunction is not simply a description of the object's state, but that it actually is entirely equivalent to the object, a claim it has in common with some other interpretations. Secondly, observation or measurement has no special laws or mechanics, unlike in the Copenhagen interpretation which considers the wavefunction collapse as a special kind of event which occurs as a result of observation. Instead, measurement in the relative state formulation is the consequence of a configuration change in the memory of an observer described by the same basic wave physics as the object being modeled.

The many-worlds interpretation is DeWitt's popularisation of Everett's work, who had referred to the combined observer–object system as being split by an observation, each split corresponding to the different or multiple possible outcomes of an observation. These splits generate a possible tree as shown in the graphic below. Subsequently, DeWitt introduced the term "world" to describe a complete measurement history of an observer, which corresponds roughly to a single branch of that tree. Note that "splitting" in this sense is hardly new or even quantum mechanical. The idea of a space of complete alternative histories had already been used in the theory of probability since the mid-1930s for instance to model Brownian motion.

Under the many-worlds interpretation, the Schrödinger equation, or relativistic analog, holds all the time everywhere. An observation or measurement is modeled by applying the wave equation to the entire system comprising the observer *and* the object. One consequence is that every observation can be thought of as causing the combined observer–object's wavefunction to change into a quantum superposition of two or more non-interacting branches, or split into many "worlds". Since many observation-like events have happened and are constantly happening, there are an enormous and growing number of simultaneously existing states.

If a system is composed of two or more subsystems, the system's state will be a superposition of products of the subsystems' states. Each product of subsystem states in the overall superposition evolves over time independently of other products. Once the subsystems interact, their states have become correlated or entangled and it is no longer possible to consider them independent of one another. In Everett's terminology each subsystem state was now *correlated* with its *relative state*, since each subsystem must now be considered relative to the other subsystems with which it has interacted.



Partial trace as relative state. Light blue rectangle on upper left denotes system in pure state. Trellis shaded rectangle in upper right denotes a (possibly) mixed state. Mixed state from observation is partial trace of a linear superposition of states as shown in lower right-hand corner

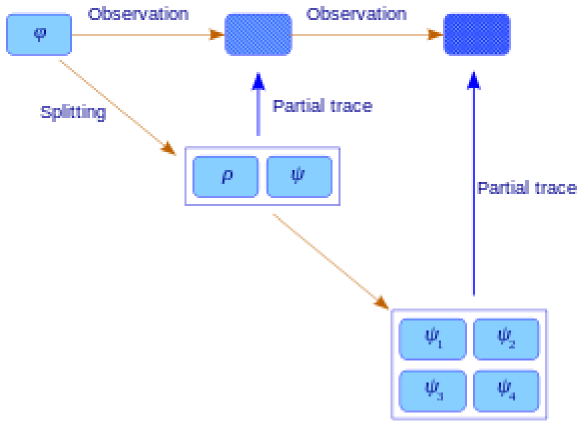
Properties of the theory

MWI removes the observer-dependent role in the quantum measurement process by replacing wavefunction collapse with quantum decoherence Since the role of the observer lies at the heart of most if not all "quantum paradoxes," this automatically resolves a number of problems; see for example Schrödinger's cat thought experiment, the EPR paradox, von Neumann's "boundary problem" and even wave-particle duality. Quantum cosmology also becomes intelligible, since there is no need anymore for an observer outside of the universe.

MWI is a realist, deterministic, arguably local theory, akin to classical physics (including the theory of relativity), at the expense of losing counterfactual definiteness. MWI achieves this by removing wavefunction collapse, which is indeterministic and non-local, from the deterministic and local equations of quantum theory.[57]

MWI (or other, broader multiverse considerations) provides a context for the anthropic principle which may provide an explanation for the fine-tuned universe.[58][59]

MWI, being a decoherent formulation, is axiomatically more streamlined than the Copenhagen and other collapse interpretations; and thus favoured under certain interpretations of Occam's razor.[60] Of course there are other decoherent interpretations that also possess this advantage with respect to the collapse interpretations.



Successive measurements with successive splittings

Comparative properties and possible experimental tests

One of the salient properties of the many-worlds interpretation is that it does not require an exceptional method of wave function collapse to explain it. "It seems that there is no experiment distinguishing the MWI from other no-collapse theories such as Bohmian mechanics or other variants of MWI... In most no-collapse interpretations, the evolution of the quantum state of the Universe is the same. Still, one might imagine that there is an experiment distinguishing the MWI from another no-collapse interpretation based on the difference in the correspondence between the formalism and the experience (the results of experiments)."[61]

However, in 1985, David Deutsch published three related thought experiments which could test the theory vs the Copenhagen interpretation.[62] The experiments require macroscopic quantum state preparation and quantum erasure by a hypothetical quantum computer which is currently outside experimental possibility. Since then Lockwood (1989), Vaidman and others have made similar proposals.[61] These proposals also require an advanced technology which is able to place a macroscopic object in a coherent superposition, another task which it is uncertain will ever be possible to perform. Many other controversial ideas have been put forward though, such as a recent claim that cosmological observations could test the theory,[63] and another claim by Rainer Plaga (1997), published in *Foundations of Physics*, that communication might be possible between worlds.[64]

Copenhagen interpretation

In the Copenhagen interpretation, the mathematics of quantum mechanics allows one to predict probabilities for the occurrence of various events. When an event occurs, it becomes part of the definite reality, and alternative possibilities do not. There is no necessity to say anything definite about what is not observed.

The universe decaying to a new vacuum state

Any event that changes the number of observers in the universe may have experimental consequences.[65] Quantum tunnelling to a new vacuum state would reduce the number of observers to zero (i.e., kill all life). Some cosmologists argue that the universe is in a false vacuum state and that consequently the universe should have already experienced quantum tunnelling to a true vacuum state. This has not happened and is cited as evidence in favor of many-worlds. In some worlds, quantum tunnelling to a true vacuum state has happened but most other worlds escape this tunneling and remain viable. This can be thought of as a variation on quantum suicide.

Many-minds

The *many-minds* interpretation is a multi-world interpretation that defines the splitting of reality on the level of the observers' minds. In this, it differs from Everett's many-worlds interpretation, in which there is no special role for the observer's mind.[64]

Common objections

The many-worlds interpretation is very vague about the ways to determine when splitting happens, and nowadays usually the criterion is that the two branches have decohered. However, present day understanding of decoherence does not allow a completely precise, self-contained way to say when the two branches have decohered/"do not interact", and hence many-worlds interpretation remains arbitrary. This objection is saying that it is not clear what is precisely meant by branching, and point to the lack of self-contained criteria specifying branching.

> MWI response: the decoherence or "splitting" or "branching" is complete when the measurement is complete. In Dirac notation a measurement is complete when:
>
> $$\langle O_i|O_j\rangle = \delta_{ij}$$ [66]
>
> where O_i represents the observer having detected the object system in the *i*th state. Before the measurement has started the observer states are identical; after the measurement is complete the observer states are orthonormal.[4][7] Thus a measurement defines the branching process: the branching is as well- or ill-defined as the measurement is; the branching is as complete as the measurement is complete – which is to say that the delta function above represents an idealised measurement. Although true "for all practical purposes" in reality the measurement, and hence the branching, is never fully complete, since delta functions are unphysical,[67]
> Since the role of the observer and measurement per se plays no special role in MWI (measurements are handled as all other interactions are) there is no need for a precise definition of what an observer or a measurement is — just as in Newtonian physics no precise definition of either an observer or a measurement was required or expected. In all circumstances the universal wavefunction is still available to give a complete description of reality.
> Also, it is a common misconception to think that branches are completely separate. In Everett's formulation, they may in principle quantum interfere (i.e., "merge" instead of "splitting") with each other in the future,[68] although this requires all "memory" of the earlier branching event to be lost, so no observer ever sees two branches of reality.[69][70]

MWI states that there is no special role, or need for precise definition of measurement in MWI, yet Everett uses the word "measurement" repeatedly throughout its exposition.

> MWI response: "measurements" are treated as a subclass of interactions, which induce subject–object correlations in the combined wavefunction. There is nothing special about measurements (such as the ability to trigger a wave function collapse), that cannot be dealt with by the usual unitary time development process.[3] This is why there is no precise definition of measurement in Everett's formulation, although some other formulations emphasize that measurements must be effectively irreversible or create classical information.

The splitting of worlds forward in time, but not backwards in time (i.e., merging worlds), is time asymmetric and incompatible with the time symmetric nature of Schrödinger's equation, or CPT invariance in general.[71]

> MWI response: The splitting is time asymmetric; this observed temporal asymmetry is due to the boundary conditions imposed by the Big Bang[72]

There is circularity in Everett's measurement theory. Under the assumptions made by Everett, there are no 'good observations' as defined by him, and since his analysis of the observational process depends on the latter, it is void of any meaning. The concept of a 'good observation' is the projection postulate in disguise and Everett's analysis simply derives this postulate by having assumed it, without any discussion.[73]

> MWI response: Everett's treatment of observations / measurements covers *both* idealised good measurements and the more general bad or approximate cases.[74] Thus it is legitimate to analyse probability in terms of measurement; no circularity is present.

Talk of probability in Everett presumes the existence of a preferred basis to identify measurement outcomes for the probabilities to range over. But the existence of a preferred basis can only be established by the process of decoherence, which is itself probabilistic[75] or arbitrary.[76]

> MWI response: Everett analysed branching using what we now call the "measurement basis". It is fundamental theorem of quantum theory that nothing measurable or empirical is changed by adopting a different basis. Everett was therefore free to choose whatever basis he liked. The measurement basis was simply the simplest basis in which to analyse the measurement process.[77][78]

We cannot be sure that the universe is a quantum multiverse until we have a theory of everything and, in particular, a successful theory of quantum gravity.[31] If the final theory of everything is non-linear with respect to wavefunctions then many-worlds would be invalid.[1][4][5][6][7]

> MWI response: All accepted quantum theories of fundamental physics are linear with respect to the wavefunction. While quantum gravity or string theory may be non-linear in this respect there is no evidence to indicate this at the moment.[17][18]

Conservation of energy is grossly violated if at every instant near-infinite amounts of new matter are generated to create the new universes.

> MWI response: There are two responses to this objection. First, the law of conservation of energy says that energy is conserved *within each universe*. Hence, even if "new matter" were being generated to create new universes, this would not violate conservation of energy. Second, conservation of energy is not violated since the energy of each branch has to be weighted by its probability, according to the standard formula for the conservation of energy in quantum theory. This results in the total energy of the multiverse being conserved.[79]

Occam's razor rules against a plethora of unobservable universes – Occam would prefer just one universe; i.e., any non-MWI.

MWI response: Occam's razor actually is a constraint on the complexity of physical theory, not on the number of universes. MWI is a simpler theory since it has fewer postulates.[60] Occams's razor is often cited by MWI adherents as an advantage of MWI.

Unphysical universes: If a state is a superposition of two states Ψ_A and Ψ_B, i.e., $\Psi = (a\Psi_A + b\Psi_B)$, i.e., weighted by coefficients a and b, then if $b \ll a$, what principle allows a universe with vanishingly small probability b to be instantiated on an equal footing with the much more probable one with probability a? This seems to throw away the information in the probability amplitudes.

MWI response: The magnitude of the coefficients provides the weighting that makes the branches or universes "unequal", as Everett and others have shown, leading the emergence of the conventional probabilistic rules.[1][4][5][6][7][80]

Violation of the principle of locality, which contradicts special relativity: MWI splitting is instant and total: this may conflict with relativity, since an alien in the Andromeda galaxy can't know I collapse an electron over here before she collapses hers there: the relativity of simultaneity says we can't say which electron collapsed first – so which one splits off another universe first? This leads to a hopeless muddle with everyone splitting differently. Note: EPR is not a get-out here, as the alien's and my electrons need never have been part of the same quantum, i.e., entangled.

MWI response: the splitting can be regarded as causal, local and relativistic, spreading at, or below, the speed of light (e.g., we are not split by Schrödinger's cat until we look in the box).[81] For spacelike separated splitting you can't say which occurred first — but this is true of all spacelike separated events, simultaneity is not defined for them. Splitting is no exception; many-worlds is a local theory.[57]

Reception

There is a wide range of claims that are considered "many-worlds" interpretations. It was often claimed by those who do not believe in MWI[82] that Everett himself was not entirely clear[83] as to what he believed; however, MWI adherents (such as DeWitt, Tegmark, Deutsch and others) believe they fully understand Everett's meaning as implying the literal existence of the other worlds. Additionally, recent biographical sources make it clear that Everett believed in the literal reality of the other quantum worlds.[24] Everett's son reported that Hugh Everett "never wavered in his belief over his many-worlds theory".[84] Also Everett was reported to believe "his many-worlds theory guaranteed him immortality".[85]

One of MWI's strongest advocates is David Deutsch.[86] According to Deutsch, the single photon interference pattern observed in the double slit experiment can be explained by interference of photons in multiple universes. Viewed in this way, the single photon interference experiment is indistinguishable from the multiple photon interference experiment. In a more practical vein, in one of the earliest papers on quantum computing,[87] he suggested that parallelism that results from the validity of MWI could lead to "*a method by which certain probabilistic tasks can be performed faster by a universal quantum computer than by any classical restriction of it*". Deutsch has also proposed that when reversible computers become conscious then MWI will be testable (at least against "naive" Copenhagenism) via the reversible observation of spin.[69]

Asher Peres was an outspoken critic of MWI. For example, a section in his 1993 textbook had the title *Everett's interpretation and other bizarre theories*. Peres not only questioned whether MWI is really an "interpretation", but rather, if *any* interpretations of quantum mechanics are needed at all. An interpretation can be regarded as a purely formal transformation, which adds nothing to the rules of the quantum mechanics. Peres seems to suggest that positing the existence of an infinite number of non-communicating parallel universes is highly suspect per those who interpret it as a violation of Occam's razor, i.e., that it does not minimize the number of hypothesized entities. However, it is understood that the number of elementary particles are not a gross violation of Occam's razor, one counts the types, not the tokens. Max Tegmark remarks that the alternative to many-worlds is "many words", an allusion to the complexity of von Neumann's collapse postulate. On the other hand, the same derogatory qualification "many words" is often applied to MWI by its critics who see it as a word game which obfuscates rather than clarifies by confounding the von Neumann branching of possible worlds with the Schrödinger parallelism of many worlds in superposition.

MWI is considered by some to be unfalsifiable and hence unscientific because the multiple parallel universes are non-communicating, in the sense that no information can be passed between them. Others[69] claim MWI is directly testable. Everett regarded MWI as falsifiable since any test that falsifies conventional quantum theory would also falsify MWI.[23]

Polls

Advocates of MWI often cite a poll of 72 "leading cosmologists and other quantum field theorists" [88] conducted by the American political scientist David Raub in 1995 showing 58% agreement with "Yes, I think MWI is true".[89]

However, the poll is controversial. For example, Victor J. Stenger remarks that Murray Gell-Mann's published work explicitly rejects the existence of simultaneous parallel universes. Collaborating with James Hartle, Gell-Mann is working toward the development a more "palatable" *post-Everett quantum mechanics*. Stenger thinks it's fair to say that most physicists dismiss the many-world interpretation as too extreme, while noting it "has merit in finding a place for the observer inside the system being analyzed and doin away with the troublesome notion of wave function collapse".[90]

Max Tegmark also reports the result of a "highly unscientific" poll taken at a 1997 quantum mechanics workshop.[91] According to Tegmark, "The many worlds interpretation (MWI) scored second, comfortably ahead of the consistent histories and Bohm interpretations." Such polls have been taken at other conferences, for example, in response to Sean Carroll's observation, "As crazy as it sounds, most working physicists buy into the many-worlds theory" [92] Michael Nielsen counters: "at a quantum computing conference at Cambridge in 1998, a many-worlder surveyed the audience of approximately 200 people... Many-worlds did just fine, garnering support on a level comparable to, but somewhat below, Copenhagen and decoherence." However, Nielsen notes that it seemed most attendees found it to be a waste of time: Asher Peres "got a huge and sustained round of applause… when he got up at the end of the polling and asked 'And who here believes the laws of physics are decided by a democratic vote?'"[93]

A 2005 poll of fewer than 40 students and researchers taken after a course on the Interpretation of Quantum Mechanics at the Institute for Quantum Computing University of Waterloo found "Many Worlds (and decoherence)" to be the least favored.[94]

A 2011 poll of 33 participants at an Austrian conference found 6 endorsed MWI, 8 "Information-based/information-theoretical", and 14 Copenhagen;[95] the authors remark that the results are similar to the previous Tegmark's 1998 poll.

Speculative implications

Speculative physics deals with questions which are also discussed in science fiction.

Quantum suicide thought experiment

Quantum suicide, as a thought experiment, was published independently by Hans Moravec in 1987[96][97] and Bruno Marchal in 1988[98][99] and was independently developed further by Max Tegmark in 1998.[100] It attempts to distinguish between the Copenhagen interpretation of quantum mechanics and the Everett many-worlds interpretation by means of a variation of the Schrödinger's cat thought experiment, from the cat's point of view. **Quantum immortality** refers to the subjective experience of surviving quantum suicide regardless of the odds.[101]

Weak coupling

Another speculation is that the separate worlds remain weakly coupled (e.g., by gravity) permitting "communication between parallel universes". A possible test of this using quantum-optical equipment is described in a 1997 *Foundations of Physics* article by Rainer Plaga.[64] It involves an isolated ion in an ion trap, a quantum measurement that would yield two parallel worlds (their difference just being in the detection of a single photon), and the excitation of the ion from only one of these worlds. If the excited ion can be detected from the other parallel universe, then this would constitute direct evidence in support of the many-worlds interpretation and would automatically exclude the orthodox, "logical", and "many-histories" interpretations. The reason the ion is isolated is to make it not participate immediately in the decoherence which insulates the parallel world branches, therefore allowing it to act as a gateway between the two worlds, and if the measure apparatus could perform the measurements quickly enough before the gateway ion is decoupled then the test would succeed (with electronic computers the necessary time window between the two worlds would be in a time scale of milliseconds or nanoseconds, and if the measurements are taken by humans then a few seconds would still be enough). R. Plaga shows that macroscopic decoherence timescales are a possibility. The proposed test is based on technical equipment described in a 1993 *Physical Review* article by Itano et al.[102] and R. Plaga says that this level of technology is enough to realize the proposed inter-world communication experiment. The necessary technology for precision measurements of single ions already exists since the 1970s, and the ion recommended for excitation is $^{199}Hg^{+}$. The excitation methodology is described by Itano et al. and the time needed for it is given by the Rabi flopping formula.[103]

Such a test as described by R. Plaga would mean that energy transfer is possible between parallel worlds. This does not violate the fundamental principles of physics because these require energy conservation only for the whole universe and not for the single parallel branches.[64] Neither the excitation of the single ion (which is a degree of freedom of the proposed system) leads to decoherence, something which is proven by Welcher Weg detectors which can excite atoms without momentum transfer (which causes the loss of coherence).[104]

The proposed test would allow for low-bandwidth inter-world communication, the limiting factors of bandwidth and time being dependent on the technology of the equipment. Because of the time needed to determine the state of the partially decohered isolated excited ion based on Itano et al.'s methodology, the ion would decohere by the time its state is determined during the experiment, so Plaga's proposal would pass just enough information between the two worlds to confirm their parallel existence and nothing more. The author contemplates that with increased bandwidth, one could even transfer television imagery across the parallel worlds.[64] For example, Itano et al.'s methodology could be improved (by lowering the time needed for state determination of the excited ion) if a more efficient process were found for the detection of fluorescence radiation using 194 nm photons.[64]

A 1991 article by J. Polchinski also supports the view that inter-world communication is a theoretical possibility.[105] Other authors in a 1994 preprint article also contemplated similar ideas.[106]

The reason inter-world communication seems like a possibility is because decoherence which separates the parallel worlds is never fully complete,[107][108] therefore weak influences from one parallel world to another can still pass between them,[107][109] and these should be measurable with advanced technology. Deutsch proposed such an experiment in a 1985 *International Journal of Theoretical Physics* article,[110] but the technology it requires involves human-level artificial intelligence.[64]

Absurd or highly improbable timelines

Many MWI proponents assert that every physically possible event has to be represented in the multiversal stack, and by definition this would include highly unlikely scenarios and timelines. Bryce Seligman DeWitt has stated that "[Everett, Wheeler and Graham] do not in the end exclude any element of the superposition. All the worlds are there, even those in which everything goes wrong and all the statistical laws break down." [111] Borrowing a phase from T.H. White's The Once and Future King, Murray Gell-Mann describes the implications of his Totalitarian principle, as "Everything not forbidden is compulsory."[112] Max Tegmark has affirmed in numerous statements that absurd or highly unlikely events are inevitable under the MWI interpretation. To quote Tegmark, "Things inconsistent with the laws of physics will never happen - everything else will... it's important to keep track of the statistics, since even if everything conceivable happens somewhere, really freak events happen only exponentially rarely".[113] Frank J. Tipler, although a strong advocate for the many-worlds interpretation, has expressed some skepticism regarding this aspect of the theory. In a 2015 interview he stated "We simply don't know...it might be that the modulus over the wavefunction of that possibility [i.e. an extremely absurd yet physically possible event] is zero in which case there is no such world...There are universes out there, which you could imagine which...would not be actualized."[114]

Similarity to modal realism

The many-worlds interpretation has some similarity to modal realism in philosophy, which is the view that the possible worlds used to interpret modal claims exist and are of a kind with the actual world. Unlike the possible worlds of philosophy, however, in quantum mechanics counterfactual alternatives can influence the results of experiments, as in the Elitzur–Vaidman bomb-testing problem or the Quantum Zeno effect. Also, while the worlds of the many-worlds interpretation all share the same physical laws, modal realism postulates a world for every way things could conceivably have been.

Time travel

The many-worlds interpretation could be one possible way to resolve the paradoxes[86] that one would expect to arise *if* time travel turns out to be permitted by physics (permitting closed timelike curves and thus violating causality). Entering the past would itself be a quantum event causing branching, and therefore the timeline accessed by the time traveller simply would be another timeline of many. In that sense, it would make the Novikov self-consistency principle unnecessary.

See also

- Alternate history
- Consistent histories
- EPR paradox
- *Fabric of Reality*
- Garden of Forking Paths
- Interpretations of quantum mechanics
- Many-minds interpretation
- Multiple histories
- Parallel universes in fiction
- *The Beginning of Infinity*
- Quantum immortality – a thought experiment.
- Wave function collapse

Notes

1. Bryce Seligman DeWitt, Quantum Mechanics and Reality: Could the solution to the dilemma of indeterminism be a universe in which all possible outcomes of an experiment actually occur?, *Physics Today*, 23(9) pp 30–40 (September 1970) "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." See also *Physics Today*, letters followup, 24(4), (April 1971), pp 38–44
2. Osnaghi, Stefano; Freitas, Fabio; Olival Freire, Jr (2009). "The Origin of the Everettian Heresy" (http://stefano.osnaghi.free.fr/Everett.pdf) (PDF). *Studies in History and Philosophy of Modern Physics* **40** (2): 97–123. Bibcode: 2009SHPMP..40...97O (http://adsabs.harvard.edu/abs/2009SHPMP..40...97O). CiteSeerX 10.1.1.397.3933 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.397.3933). doi: 10.1016/j.shpsb.2008.10.002 (https://doi.org/10.1016%2Fj.shpsb.2008.10.002)
3. Hugh Everett Theory of the Universal Wavefunction (https://www.pbs.org/wgbh/nova/manyworlds/pdf/dissertation.pdf), Thesis, Princeton University, (1956, 1973), pp 1–140
4. Everett, Hugh (1957). "Relative State Formulation of Quantum Mechanics" (https://web.archive.org/web/20111027191052/http://www.univer.omsk.su/omsk/Sci/Everett/paper1957.html). *Reviews of Modern Physics* **29** (3): 454–462. Bibcode: 1957RvMP...29..454E (http://adsabs.harvard.edu/abs/1957RvMP...29..454E). doi: 10.1103/RevModPhys.29.454 (https://doi.org/10.1103%2FRevModPhys.29.454). Archived from the original (http://www.univer.omsk.su/omsk/Sci/Everett/paper1957.html) on 2011-10-27. Retrieved 2011-10-24.
5. Cecile M. DeWitt, John A. Wheeler eds, The Everett–Wheeler Interpretation of Quantum Mechanics, *Battelle Rencontres: 1967 Lectures in Mathematics and Physics* (1968)
6. Bryce Seligman DeWitt, The Many-Universes Interpretation of Quantum Mechanics, *Proceedings of the International School of Physics "Enrico Fermi" Course IL: Foundations of Quantum Mechanics*, Academic Press (1972)
7. Bryce Seligman DeWitt, R. Neill Graham, eds, *The Many-Worlds Interpretation of Quantum Mechanics*, Princeton Series in Physics, Princeton University Press (1973), ISBN 0-691-08131-X Contains Everett's thesis: The Theory of the Universal Wavefunction, pp 3–140.
8. H. Dieter Zeh, On the Interpretation of Measurement in Quantum Theory, *Foundations of Physics*, vol. 1, pp. 69–76, (1970).

9. Wojciech Hubert Zurek, Decoherence and the transition from quantum to classical, *Physics Today*, vol. 44, issue 10, pp. 36–44, (1991).
10. Wojciech Hubert Zurek, Decoherence, einselection, and the quantum origins of the classical, *Reviews of Modern Physics*, 75, pp 715–775, (2003)
11. The Many Worlds Interpretation of Quantum Mechanics (http://www.hep.upenn.edu/~max/everett.ps)
12. David Deutsch argues that a great deal of fiction is close to a fact somewhere in the so called multiverse, *Beginning of Infinity*, p. 294
13. Bryce Seligman DeWitt, R. Neill Graham, eds, *The Many-Worlds Interpretation of Quantum Mechanics*, Princeton Series in Physics, Princeton University Press (1973), ISBN 0-691-08131-X Contains Everett's thesis: The Theory of the Universal Wavefunction, where the claim to resolves all paradoxes is made on pg 118, 149.
14. Hugh Everett, Relative State Formulation of Quantum Mechanics (http://www.univer.omsk.su/omsk/Sci/Everett/paper1957.html) Archived (https://web.archive.org/web/20111027191052/http://www.univer.omsk.su/omsk/Sci/Everett/paper1957.html) 2011-10-27 at the Wayback Machine, *Reviews of Modern Physics* vol 29, (July 1957) pp 454–462. The claim to resolve EPR is made on page 462
15. David Deutsch. The Beginning of infinity. Page 310.
16. Blincoe, Nicholas (2012-04-05). "Erwin Schrödinger and the Quantum Revolution by John Gribbin: review" (https://www.telegraph.co.uk/culture/books/bookreviews/9188438/Erwin-Schrodinger-and-the-Quantum-Revolution-by-John-Gribbin-review.html). *The Telegraph*. ISSN 0307-1235 (https://www.worldcat.org/issn/0307-1235). Retrieved 2019-02-10.
17. Steven Weinberg, *Dreams of a Final Theory: The Search for the Fundamental Laws of Nature* (1993), ISBN 0-09-922391-0, pg 68–69
18. Steven Weinberg *Testing Quantum Mechanics*, Annals of Physics Vol 194 #2 (1989), pg 336–386
19. John Archibald Wheeler, *Geons, Black Holes & Quantum Foam*, ISBN 0-393-31991-1. pp 268–270
20. Everett 1957, section 3, 2nd paragraph, 1st sentence
21. Everett [1956]1973, "Theory of the Universal Wavefunction", chapter 6 (e)
22. Zurek, Wojciech (March 2009). "Quantum Darwinism". *Nature Physics*. **5** (3): 181–188. arXiv:0903.5082 (https://arxiv.org/abs/0903.5082). Bibcode:2009NatPh...5..181Z (http://adsabs.harvard.edu/abs/2009NatPh...5..181Z). doi:10.1038/nphys1202 (https://doi.org/10.1038%2Fnphys1202).
23. Everett (http://space.mit.edu/home/tegmark/everett/)
24. Peter Byrne, The Many Worlds of Hugh Everett III: Multiple Universes, Mutual Assured Destruction, and the Meltdown of a Nuclear Family (https://www.amazon.co.uk/dp/0199552274), ISBN 978-0-19-955227-6
25. "Whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed." Albert Einstein to Werner Heisenberg, objecting to placing observables at the heart of the new quantum mechanics, during Heisenberg's 1926 lecture at Berlin; related by Heisenberg in 1968, quoted by Abdus Salam, *Unification of Fundamental Forces*, Cambridge University Press (1990) ISBN 0-521-37140-6, pp 98–101
26. A response to Bryce DeWitt (https://web.archive.org/web/20071021033103/http://findarticles.com/p/articles/mi_m2843/is_3_26/ai_85932634), Martin Gardner, May 2002
27. Award winning 1995 Channel 4 documentary "Reality on the rocks: Beyond our Ken" "Archived copy" (https://web.archive.org/web/20071022030220/http://www.windfallfilms.com/html/awards.htm). Archived from the original (http://www.windfallfilms.com/html/awards.htm) on 2007-10-22. Retrieved 2007-10-20. where, in response to Ken Campbell's question "all these trillions of Universes of the Multiverse, are they as real as this one seems to be to me?" Hawking states, "Yes.... According to Feynman's idea, every possible history (of Ken) is equally real."
28. Gardner, Martin (2003). *Are universes thicker than blackberries?* (https://books.google.com/books?id=z9jH9mYO5IC&pg=PA10&lpg=PA10). W.W. Norton. p. 10. ISBN 978-0-393-05742-3.
29. Ferris, Timothy (1997). *The Whole Shebang*. Simon & Schuster. pp. 345 (https://books.google.com/books?id=qjYbQ7EBAKwC&lpg=PP1&pg=PA345#v=onepage&q&f=false). ISBN 978-0-684-81020-1.
30. Hawking, Stephen; Roger Penrose (1996). *The Nature of Space and Time*. Princeton University Press. pp. 121 (https://books.google.com/books?id=LstaQTXP65cC&lpg=PP1&pg=PA121#v=onepage&q&f=false). ISBN 978-0-691-03791-2.
31. Penrose, Roger (August 1991). "Roger Penrose Looks Beyond the Classic-Quantum Dichotomy" (https://web.archive.org/web/20071023063403/http://www.sciencewatch.com/interviews/roger_penrose2.htm). Sciencewatch. Archived from the original (http://www.sciencewatch.com/interviews/roger_penrose2.htm) on 2007-10-23. Retrieved 2007-10-21.

32. Kim Joris Boström (2012). "Combining Bohm and Everett: Axiomatics for a Standalone Quantum Mechanics". arXiv:1208.5632 (https://arxiv.org/abs/1208.5632) [quant-ph (https://arxiv.org/archive/quant-ph)].
33. N.P. Landsman, "The conclusion seems to be that no generally accepted derivation of the Born rule has been given to date, but this does not imply that such a derivation is impossible in principle." (http://www.math.ru.nl/~landsman/Born.pdf), in *Compendium of Quantum Physics* (eds.) F.Weinert, K. Hentschel, D.Greenberger and B. Falkenburg (Springer, 2008), ISBN 3-540-70622-4
34. Kent, Adrian (2010). "One world versus many: The inadequacy of Everettian accounts of evolution, probability, and scientific confirmation". In S. Saunders; J. Barrett; A. Kent; D. Wallace (eds.). *Many Worlds? Everett, Quantum Theory and Reality*. Oxford University Press. arXiv:0905.0624 (https://arxiv.org/abs/0905.0624). Bibcode:2009arXiv0905.0624K (http://adsabs.harvard.edu/abs/2009arXiv0905.0624K).
35. Kent, Adrian (1990). "Against Many-Worlds Interpretations". *Int. J. Mod. Phys. A* **5** (9): 1745–1762. arXiv:gr-qc/9703089 (https://arxiv.org/abs/gr-qc/9703089). Bibcode:1990IJMPA...5.1745K (http://adsabs.harvard.edu/abs/1990IJMPA...5.1745K). doi:10.1142/S0217751X90000805 (https://doi.org/10.1142%2FS0217751X90000805).
36. James Hartle, Quantum Mechanics of Individual Systems, *American Journal of Physics*, 1968, vol 36 (#8), pp. 704–712
37. E. Farhi, J. Goldstone & S. Gutmann. *How probability arises in quantum mechanics.*, Ann. Phys. (N.Y.) 192, 368–382 (1989).
38. Pitowsky, I. (2005). "Quantum mechanics as a theory of probability". arXiv:quant-ph/0510095 (https://arxiv.org/abs/quant-ph/0510095).
39. Gleason, A. M. (1957). "Measures on the closed subspaces of a Hilbert space". *Journal of Mathematics and Mechanics*. **6** (4): 885–893. doi:10.1512/iumj.1957.6.56050 (https://doi.org/10.1512%2Fiumj.1957.6.56050). MR 0096113 (https://www.ams.org/mathscinet-getitem?mr=0096113).
40. Deutsch, David (1999). "Quantum Theory of Probability and Decisions". *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*. **455** (1988): 3129–3137. arXiv:quant-ph/9906015 (https://arxiv.org/abs/quant-ph/9906015). Bibcode:1999RSPSA.455.3129D (http://adsabs.harvard.edu/abs/1999RSPSA.455.3129D). doi:10.1098/rspa.1999.0443 (https://doi.org/10.1098%2Frspa.1999.0443).
41. Wallace, David (2002). "Quantum Probability and Decision Theory, Revisited". arXiv:quant-ph/0211104 (https://arxiv.org/abs/quant-ph/0211104).
42. Wallace, David (2003). "Everettian Rationality: defending Deutsch's approach to probability in the Everett interpretation". *Stud. Hist. Phil. Mod. Phys*. **34** (3): 415–438. arXiv:quant-ph/0303050 (https://arxiv.org/abs/quant-ph/0303050). Bibcode:2003SHPMP..34..415W (http://adsabs.harvard.edu/abs/2003SHPMP..34..415W). doi:10.1016/S1355-2198(03)00036-4 (https://doi.org/10.1016%2FS1355-2198%2803%2900036-4).
43. Wallace, David (2003). "Quantum Probability from Subjective Likelihood: Improving on Deutsch's proof of the probability rule". arXiv:quant-ph/0312157 (https://arxiv.org/abs/quant-ph/0312157).
44. Wallace, David (2009). "A formal proof of the Born rule from decision-theoretic assumptions". arXiv:0906.2718 (https://arxiv.org/abs/0906.2718) [quant-ph (https://arxiv.org/archive/quant-ph)].
45. Saunders, Simon (2004). "Derivation of the Born rule from operational assumptions". *Proc. Roy. Soc. Lond. A*. **460** (2046): 1771–1788. arXiv:quant-ph/0211138 (https://arxiv.org/abs/quant-ph/0211138). Bibcode:2004RSPSA.460.1771S (http://adsabs.harvard.edu/abs/2004RSPSA.460.1771S). doi:10.1098/rspa.2003.1230 (https://doi.org/10.1098%2Frspa.2003.1230).
46. Saunders, Simon (2004). "What is Probability?". *Quo Vadis Quantum Mechanics?*. The Frontiers Collection. pp. 209–238. arXiv:quant-ph/0412194 (https://arxiv.org/abs/quant-ph/0412194). doi:10.1007/3-540-26669-0_12 (https://doi.org/10.1007%2F3-540-26669-0_12). ISBN 978-3-540-22188-3.
47. Merali, Zeeya (2007-09-21). "Parallel universes make quantum sense" (https://www.newscientist.com/article/mg19526223.700-parallel-universes-make-quantum-sense.html). *New Scientist* (2622). Retrieved 2013-11-22. (Summary only).
48. Perimeter Institute, Seminar overview, Probability in the Everett interpretation: state of play, David Wallace – Oxford University, 21 Sept 2007 (http://www.perimeterinstitute.ca/index.php?option=com_content&task=view&id=50&Itemid=83&lecture_id=6167)
49. Perimeter Institute, Many worlds at 50 conference, September 21–24, 2007 (http://www.perimeterinstitute.ca/manyworlds/) Archived (https://web.archive.org/web/20071020145922/http://perimeterinstitute.ca/manyworlds/) 2007-10-20 at the Wayback Machine

50. Armando V. D. B. Assis (2011). "Assis, Armando V. D. B. On the nature of $a_k^* a_k$ and the emergence of the Born rule". *Annalen der Physik*. **523** (11): 883–897. arXiv:1009.1532 (https://arxiv.org/abs/1009.1532). Bibcode:2011AnP...523..883A (http://adsabs.harvard.edu/abs/2011AnP...523..883A). doi:10.1002/andp.201100062 (https://doi.org/10.1002%2Fandp.201100062).
51. Zurek, Wojciech H. (2005). "Probabilities from entanglement, Born's rule from envariance". *Phys. Rev. A*. **71** (5): 052105. arXiv:quant-ph/0405161 (https://arxiv.org/abs/quant-ph/0405161). Bibcode:2005PhRvA..71e2105Z (http://adsabs.harvard.edu/abs/2005PhRvA..71e2105Z). doi:10.1103/physreva.71.052105 (https://doi.org/10.1103%2Fphysreva.71.052105).
52. Schlosshauer, M.; Fine, A. (2005). "On Zurek's derivation of the Born rule". *Found. Phys*. **35** (2): 197–213. arXiv:quant-ph/0312058 (https://arxiv.org/abs/quant-ph/0312058). Bibcode:2005FoPh...35..197S (http://adsabs.harvard.edu/abs/2005FoPh...35..197S). doi:10.1007/s10701-004-1941-6 (https://doi.org/10.1007%2Fs10701-004-1941-6).
53. Polley, L (2001). "Position eigenstates and the Statistical Axiom of Quantum Mechanics". *Foundations of Probability and Physics*. pp. 314–320. arXiv:quant-ph/0102113 (https://arxiv.org/abs/quant-ph/0102113). doi:10.1142/9789812810809_0022 (https://doi.org/10.1142%2F9789812810809_0022). ISBN 978-981-02-4846-8.
54. Polley, L (1999). "Quantum-mechanical probability from the symmetries of two-state systems". arXiv:quant-ph/9906124 (https://arxiv.org/abs/quant-ph/9906124).
55. Vaidman, L. "Probability in the Many-Worlds Interpretation of Quantum Mechanics." In: Ben-Menahem, Y., & Hemmo, M. (eds), The Probable and the Improbable: Understanding Probability in Physics, Essays in Memory of Itamar Pitowsky. Springer.
56. Sebens, Charles T; Carroll, Sean M (2014). "Self-Locating Uncertainty and the Origin of Probability in Everettian Quantum Mechanics". arXiv:1405.7577 (https://arxiv.org/abs/1405.7577) [quant-ph (https://arxiv.org/archive/quant-ph)].
57. Mark A. Rubin, Locality in the Everett Interpretation of Heisenberg-Picture Quantum Mechanics, *Foundations of Physics Letters*, 14, (2001) , pp. 301–322, arXiv:quant-ph/0103079
58. Paul C.W. Davies, *Other Worlds*, chapters 8 & 9 *The Anthropic Principle* & *Is the Universe an accident?*, (1980) ISBN 0-460-04400-1
59. Paul C.W. Davies, *The Accidental Universe*, (1982) ISBN 0-521-28692-1
60. Everett FAQ "Does many-worlds violate Ockham's Razor?" (http://www.hedweb.com/manworld.htm#ockham's)
61. Vaidman, Lev (2018). *Many-Worlds Interpretation of Quantum Mechanics* (http://plato.stanford.edu/entries/qm-manyworlds/). The Stanford Encyclopedia of Philosophy.
62. Deutsch, D., (1986) 'Three experimental implications of the Everett interpretation', in R. Penrose and C.J. Isham (eds.), Quantum Concepts of Space and Time, Oxford: The Clarendon Press, pp. 204–214.
63. Page, D., (2000) Can Quantum Cosmology Give Observational Consequences of Many-Worlds Quantum Theory? (http://xxx.lanl.gov/abs/gr-qc/0001001)
64. Plaga, R. (1997). "On a possibility to find experimental evidence for the many-worlds interpretation of quantum mechanics". *Foundations of Physics*. **27** (4): 559–577. arXiv:quant-ph/9510007 (https://arxiv.org/abs/quant-ph/9510007). Bibcode:1997FoPh...27..559P (http://adsabs.harvard.edu/abs/1997FoPh...27..559P). doi:10.1007/BF02550677 (https://doi.org/10.1007%2FBF02550677).
65. Page, Don N. (2000). *Can Quantum Cosmology Give Observational Consequences of Many-Worlds Quantum Theory?*. *Eighth Canadian Conference on General Relativity and Relativistic Astrophysics*. **493**. pp. 225–232. arXiv:gr-qc/0001001 (https://arxiv.org/abs/gr-qc/0001001). Bibcode:1999AIPC..493..225P (http://adsabs.harvard.edu/abs/1999AIPC..493..225P). doi:10.1063/1.1301589 (https://doi.org/10.1063%2F1.1301589). ISBN 978-1563969058.
66. Bryce Seligman DeWitt, Quantum Mechanics and Reality: Could the solution to the dilemma of indeterminism be a universe in which all possible outcomes of an experiment actually occur?, *Physics Today*, 23(9) pp 30–40 (September 1970); see equation 10
67. Penrose, R. *The Road to Reality*, §21.11

68. Tegmark, Max (1997). "The Interpretation of Quantum Mechanics: Many Worlds or Many Words?". *Fortschritte der Physik*. **46** (6–8): 855–862. arXiv:quant-ph/9709032 (https://arxiv.org/abs/quant-ph/9709032). doi:10.1002/(SICI)1521-3978(199811)46:6/8<855::AID-PROP855>3.0.CO;2-Q (https://doi.org/10.1002%2F%28SICI%291521-3978%28199811%2946%3A6%2F8%3C855%3A%3AAID-PROP855%3E3.0.CO%3B2-Q). To quote: "What Everett does NOT postulate: *"At certain magic instances, the world undergoes some sort of metaphysical 'split' into two branches that subsequently never interact."* This is not only a misrepresentation of the MWI, but also inconsistent with the Everett postulate, since the subsequent time evolution could in principle make the two terms...interfere. According to the MWI, there is, was and always will be only one wavefunction, and only decoherence calculations, not postulates, can tell us when it is a good approximation to treat two terms as non-interacting."
69. Paul C.W. Davies, J.R. Brown, *The Ghost in the Atom* (1986) ISBN 0-521-31316-3, pp. 34–38: "The Many-Universes Interpretation", pp 83–105 for David Deutsch's test of MWI and reversible quantum memories
70. Simon, Christoph (2009). "Conscious observers clarify many worlds". arXiv:0908.0322 (https://arxiv.org/abs/0908.0322) [quant-ph (https://arxiv.org/archive/quant-ph)].
71. Joseph Gerver, The past as backward movies of the future, *Physics Today*, letters followup, 24(4), (April 1971), pp 46–7
72. Bryce Seligman DeWitt, *Physics Today*, letters followup, 24(4), (April 1971), pp 43
73. Arnold Neumaier's comments on the Everett FAQ, 1999 & 2003 (http://www.mat.univie.ac.at/~neum/manyworlds.txt)
74. Everett [1956] 1973, "*Theory of the Universal Wavefunction*", chapter V, section 4 "Approximate Measurements", pp. 100–103 (e)
75. David J Baker, Measurement Outcomes and Probability in Everettian Quantum Mechanics (http://philsci-archive.pitt.edu/archive/00002717/01/OutcomeProbEverett.pdf), *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics*, Volume 38, Issue 1, March 2007, Pages 153–169
76. Stapp, Henry (2002). "The basis problem in many-world theories" (http://www-physics.lbl.gov/~stapp/bp.PDF) (PDF). *Canadian Journal of Physics* **80** (9): 1043–1052. arXiv:quant-ph/0110148 (https://arxiv.org/abs/quant-ph/0110148). Bibcode:2002CaJPh..80.1043S (http://adsabs.harvard.edu/abs/2002CaJPh..80.1043S). doi:10.1139/p02-068 (https://doi.org/10.1139%2Fp02-068).
77. Brown, Harvey R; Wallace, David (2005). "Solving the measurement problem: de Broglie–Bohm loses out to Everett" (http://philsci-archive.pitt.edu/archive/00001659/01/Cushing.pdf) (PDF). *Foundations of Physics* **35** (4): 517–540. arXiv:quant-ph/0403094 (https://arxiv.org/abs/quant-ph/0403094). Bibcode:2005FoPh...35..517B (http://adsabs.harvard.edu/abs/2005FoPh...35..517B). doi:10.1007/s10701-004-2009-3 (https://doi.org/10.1007%2Fs10701-004-2009-3).
78. Rubin, Mark A (2003). "There is No Basis Ambiguity in Everett Quantum Mechanics". *Foundations of Physics Letters*. **17** (4): 323–341. arXiv:quant-ph/0310186 (https://arxiv.org/abs/quant-ph/0310186). Bibcode:2004FoPhL..17..323R (http://adsabs.harvard.edu/abs/2004FoPhL..17..323R). doi:10.1023/B:FOPL.0000035668.37005.e0 (https://doi.org/10.1023%2FB%3AFOPL.0000035668.37005.e0).
79. Everett FAQ "Does many-worlds violate conservation of energy?" (http://www.hedweb.com/manworld.htm#conservation)
80. Everett FAQ "How do probabilities emerge within many-worlds?" (http://www.hedweb.com/manworld.htm#probabilities)
81. Everett FAQ "When does Schrodinger's cat split?" (http://www.hedweb.com/manworld.htm#splitish)
82. Jeffrey A. Barrett, *The Quantum Mechanics of Minds and Worlds*, Oxford University Press, 1999. According to Barrett (loc. cit. Chapter 6) "There are many many-worlds interpretations."
83. Barrett, Jeffrey A. (2010). Zalta, Edward N. (ed.). "Everett's Relative-State Formulation of Quantum Mechanics" (http://plato.stanford.edu/archives/fall2010/entries/qm-everett/) (Fall 2010 ed.). The Stanford Encyclopedia of Philosophy. Again, according to Barrett "It is... unclear precisely how this was supposed to work."
84. Aldhous, Peter (2007-11-24). "Parallel lives can never touch" (https://www.newscientist.com/article/mg19626311.800-interview-parallel-lives-can-never-touch.html). *New Scientist* (2631). Retrieved 2007-11-21.
85. Eugene Shikhovtsev's Biography of Everett, in particular see "*Keith Lynch remembers 1979–1980*" (http://space.mit.edu/home/tegmark/everett/everett.html#e23)
86. David Deutsch, *The Fabric of Reality: The Science of Parallel Universes And Its Implications*, Penguin Books (1998), ISBN 0-14-027541-X

87. Deutsch, David (1985). "Quantum theory, the Church–Turing principle and the universal quantum computer". *Proceedings of the Royal Society of London A*. **400** (1818): 97–117. Bibcode:1985RSPSA.400...97D (http://adsabs.harvard.edu/abs/1985RSPSA.400...97D). CiteSeerX 10.1.1.144.7936 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.144.7936). doi:10.1098/rspa.1985.0070 (https://doi.org/10.1098%2Frspa.1985.0070).
88. Elvridge., Jim (2008-01-02). *The Universe – Solved!*. pp. 35–36. ISBN 978-1-4243-3626-5. OCLC 247614399 (https://www.worldcat.org/oclc/247614399). "58% believed that the Many Worlds Interpretation (MWI) was true, including Stephen Hawking and Nobel Laureates Murray Gell-Mann and Richard Feynman"
89. Bruce., Alexandra (2005). "How does reality work?". *Beyond the bleep : the definitive unauthorized guide to What the bleep do we know!?*. p. 33. ISBN 978-1-932857-22-1. "[the poll was] published in the French periodical *Sciences et Avenir* in January 1998"
90. Stenger, V.J. (1995). *The Unconscious Quantum: Metaphysics in Modern Physics and Cosmology* (https://books.google.com/books?id=1ZbvAAAAMAAJ). Prometheus Books. p. 176. ISBN 978-1-57392-022-3. LCCN lc95032599 (https://lccn.loc.gov/lc95032599). "Gell-Mann and collaborator James Hartle, along with a score of others, have been working to develop a more palatable interpretation of quantum mechanics that is free of the problems that plague all the interpretations we have considered so far. This new interpretation is called, in its various incarnations, **post-Everett quantum mechanics**, alternate histories, consistent histories, or decoherent histories. I will not be overly concerned with the detailed differences between these characterizations and will use the terms more or less interchangeably."
91. Max Tegmark on many-worlds (contains MWI poll) (http://space.mit.edu/home/tegmark/quantum.html)
92. Caroll, Sean (1 April 2004). "Preposterous Universe" (https://web.archive.org/web/20040908014703/http://preposterousuniverse.blogspot.com/2004_04_01_preposterousuniverse_archive.html#108087902367974365). Archived from the original (http://preposterousuniverse.blogspot.com/2004_04_01_preposterousuniverse_archive.html#108087902367974365) on 8 September 2004.
93. Nielsen, Michael (3 April 2004). "Michael Nielsen: The Interpretation of Quantum Mechanics" (https://web.archive.org/web/20040520222807/http://www.qinfo.org/people/nielsen/blog/archive/000060.html). Archived from the original (http://www.qinfo.org/people/nielsen/blog/archive/000060.html) on 20 May 2004.
94. Survey Results (http://www.iqc.ca/~qipcourse/interpret/survey.html) Archived (https://web.archive.org/web/20101104152717/http://www.iqc.ca/~qipcourse/interpret/survey.html) 2010-11-04 at the Wayback Machine
95. Schlosshauer, Maximilian; Kofler, Johannes; Zeilinger, Anton (2013). "A Snapshot of Foundational Attitudes Toward Quantum Mechanics". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*. **44** (3): 222–230. arXiv:1301.1069 (https://arxiv.org/abs/1301.1069). Bibcode:2013SHPMP..44..222S (http://adsabs.harvard.edu/abs/2013SHPMP..44..222S). doi:10.1016/j.shpsb.2013.04.004 (https://doi.org/10.1016%2Fj.shpsb.2013.04.004).
96. "The Many Minds Approach" (http://www.thestargarden.co.uk/ManyMinds.html). 25 October 2010. Retrieved 7 December 2010. "This idea was first proposed by Austrian mathematician Hans Moravec in 1987..."
97. Moravec, Hans (1988). "The Doomsday Device" (https://books.google.com/books?id=56mb7XuSx3QC&lpg=PP188&pg=PA188). *Mind Children: The Future of Robot and Human Intelligence*. Harvard: Harvard University Press. p. 188. ISBN 978-0-674-57618-6. (If MWI is true, apocalyptic particle accelerators won't function as advertised).
98. Marchal, Bruno (1988). "Informatique théorique et philosophie de l'esprit" [Theoretical Computer Science and Philosophy of Mind]. *Acte du 3ème colloque international Cognition et Connaissance [Proceedings of the 3rd International Conference Cognition and Knowledge]*: 193–227.
99. Marchal, Bruno (1991). De Glas, M.; Gabbay, D. (eds.). "Mechanism and personal identity" (http://iridia.ulb.ac.be/~marchal/publications/M&PI_15-MAI-91.pdf) (PDF). *Proceedings of WOCFAI 91*: 335–345.
100. Tegmark, Max (1997). "The Interpretation of Quantum Mechanics: Many Worlds or Many Words?". *Fortschritte der Physik*. **46** (6–8): 855–862. arXiv:quant-ph/9709032 (https://arxiv.org/abs/quant-ph/9709032). doi:10.1002/(SICI)1521-3978(199811)46:6/8<855::AID-PROP855>3.0.CO;2-Q (https://doi.org/10.1002%2F%28SICI%291521-3978%28199811%2946%3A6%2F8%3C855%3A%3AAID-PROP855%3E3.0.CO%3B2-Q).
101. Tegmark, Max (November 1998). "Quantum immortality" (http://space.mit.edu/home/tegmark/quantum.html#immortality). Retrieved 25 October 2010.
102. W.M.Itano et al., Phys. Rev A47,3354 (1993).
103. M. SargentIII, M. O. Scully and W.E. Lamb, Laser physics (Addison-Wesley, Reading, 1974), p. 27.
104. M.O. Scully and H. Walther, Phys. Rev. A 39,5229 (1989).
105. J. Polchinski, Phys. Rev Lett. 66,397 (1991).

106. M. Gell-Mann and J. B. Hartle, Equivalent Sets of Histories and Multiple Quasiclassical Domains, preprint University of California at Santa Barbara UCSBTH-94-09 (1994).
107. H. D. Zeh, Found.Phys. 3,109 (1973).
108. H. D. Zeh, Phys. Lett. A 172,189 (1993).
109. A. Albrecht, Phys. Rev D 48, 3768 (1993).
110. Deutsch, David (1985). "Quantum theory as a universal physical theory". *International Journal of Theoretical Physics*. **24** (1): 1–41. CiteSeerX 10.1.1.205.5427 (https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.205.5427). doi:10.1007/bf00670071 (https://doi.org/10.1007%2Fbf00670071). ISSN 0020-7748 (https://www.worldcat.org/issn/0020-7748). "The actual performance of this experiment, involving as it does fairly detailed adjustments inside an observer's brain and sense organs, is far beyond present-day technology, but perhaps not quite as far as it might seem at first sight."
111. DeWitt, Bryce S. (1970). "Quantum mechanics and reality". *Physics Today*. **23** (9): 30–35. Bibcode:1970PhT....23i..30D (http://adsabs.harvard.edu/abs/1970PhT....23i..30D). doi:10.1063/1.3022331 (https://doi.org/10.1063%2F1.3022331)
112. Johnson, G. (1999). Strange Beauty: Murray Gell-Mann and the Revolution in Twentieth-Century Physics. Knopf. p. 224. ISBN 978-0-679-43764-2
113. Max Tegmark: Q and A (Multiverse Philosophy) http://space.mit.edu/home/tegmark/crazy.html
114. Audio interview with Frank Tipler - White Gardenia interview with Frank Tipler, December 2015 https://www.youtube.com/watch?v=kMkp1kZN5n4&t=26s

Further reading

- Jeffrey A. Barrett, *The Quantum Mechanics of Minds and Worlds*, Oxford University Press, Oxford, 1999.
- Peter Byrne, *The Many Worlds of Hugh Everett III: Multiple Universes, Mutual Assured Destruction, and the Meltdown of a Nuclear Family*, Oxford University Press, 2010.
- Jeffrey A. Barrett and Peter Byrne, eds., "The Everett Interpretation of Quantum Mechanics: Collected Works 1955–1980 with Commentary", Princeton University Press, 2012.
- Julian Brown, *Minds, Machines, and the Multiverse*, Simon & Schuster, 2000, ISBN 0-684-81481-1
- Paul C.W. Davies, *Other Worlds*, (1980) ISBN 0-460-04400-1
- James P. Hogan, *The Proteus Operation* (science fiction involving the many-worlds interpretation, time travel and World War 2 history), Baen, Reissue edition (August 1, 1996) ISBN 0-671-87757-7
- Andrei Linde; Vitaly Vanchurin (2009). "How many universes are in the multiverse?". *Physical Review D*. **81** (8): 083525. arXiv:0910.1589. Bibcode:2010PhRvD..81h3525L. doi:10.1103/PhysRevD.81.083525
- Osnaghi, Stefano; Freitas, Fabio; Olival Freire, Jr (2009). "The Origin of the Everettian Heresy" (PDF). *Studies in History and Philosophy of Modern Physics*. **40** (2): 97–123. Bibcode:2009SHPMP..40...97O. CiteSeerX 10.1.1.397.3933. doi:10.1016/j.shpsb.2008.10.002. A study of the painful three-way relationship between Hugh Everett, John A Wheeler and Niels Bohr and how this affected the early development of the many-worlds theory.
- Asher Peres, *Quantum Theory: Concepts and Methods*, Kluwer, Dordrecht, 1993.
- Mark A. Rubin, Locality in the Everett Interpretation of Heisenberg-Picture Quantum Mechanics, *Foundations of Physics Letters*, 14, (2001), pp. 301–322, arXiv:quant-ph/0103079
- David Wallace, Harvey R. Brown, Solving the measurement problem: de Broglie–Bohm loses out to Everett, *Foundations of Physics*, arXiv:quant-ph/0403094
- David Wallace, Worlds in the Everett Interpretation, *Studies in History and Philosophy of Modern Physics*, 33, (2002), pp. 637–661, arXiv:quant-ph/0103092
- John A. Wheeler and Wojciech Hubert Zurek (eds), *Quantum Theory and Measurement*, Princeton University Press, (1983), ISBN 0-691-08316-9
- Sean M. Carroll, Charles T. Sebens, *Many Worlds, the Born Rule, and Self-Locating Uncertainty*, arXiv:1405.7907

External links

- "Everettian Interpretations of Quantum Mechanics". *Internet Encyclopedia of Philosophy*.
- Everett's Relative-State Formulation of Quantum Mechanics – Jeffrey A. Barrett's article on Everett's formulation of quantum mechanics in the Stanford Encyclopedia of Philosophy.
- Many-Worlds Interpretation of Quantum Mechanics – Lev Vaidman's article on the many-worlds interpretation of quantum mechanics in the Stanford Encyclopedia of Philosophy.

- Hugh Everett III Manuscript Archive (UC Irvine) – Jeffrey A. Barrett, Peter Byrne, and James O. Weatherall (eds.).
- Michael C Price's Everett FAQ – a clear FAQ-style presentation of the theory.
- The Many-Worlds Interpretation of Quantum Mechanics – a description for the lay reader with links.
- Many-Worlds is a "lost cause" according to R. F. Streater
- The many worlds of quantum mechanics John Sankey
- Max Tegmark's web page
- Henry Stapp's critique of MWI, focusing on the basis problem Canadian J. Phys. 80,1043–1052 (2002).
- Everett hit count on arxiv.org
- Many Worlds 50th anniversary conference at Oxford
- "Many Worlds at 50" conference at Perimeter Institute
- Scientific American report on the Many Worlds 50th anniversary conference at Oxford
- Highfield, Roger (September 21, 2007). "Parallel universe proof boosts time travel hopes". The Daily Telegraph. Archived from the original on October 20, 2007. Retrieved 2007-10-26..
- HowStuffWorks article
- Physicists Calculate Number of Parallel Universes Physorg.com October 16, 2009.
- TED-Education video – How many universes are there?
