Many-Worlds Interpretation

The relative state formulation was put forward by Hugh Everett, III in 1957 [139] and popularized by DeWitt as a many-worlds interpretation (MWI) [140]. The formulation is based on applying the Schrödinger equation to all systems. Everett [139, p. 457] considers a machine with a sensor that contains a memory as a sufficient condition for an observer:

> *As models for observers we can, if we wish, consider automatically functioning machines, possessing sensory apparatus and coupled to recording devices capable of registering past sensory data and machine configurations.*

Everett agrees that a superposition of system plus apparatus will generally occur in a manner that is similar to that shown in external orthogonalization resulting in Equation (4.2) reproduced below:

$$\sum_r c_r e^{i\theta_r} \ |\phi_r\rangle \otimes |\Psi_r\rangle.$$

Consider an observer to be a system with memory $|\Psi_r\rangle$ and the phenomenon being observed $|\phi_r\rangle$. Equation (4.2) is interpreted by Everett to be a superposition whereby the individual terms have a characteristic such that each term is an observer with a memory that is correlated to a particular phenomenon of a corresponding relative state $|\phi_r\rangle$. Everett proposes that there are many branches that simultaneously exist, whereby in each branch there exists an observer memory that is correlated to the corresponding relative state [139]:

> *Nevertheless, there is a representation in terms of a superposition, each element of which contains a definite observer state and a corresponding system state. Thus with each succeeding observation (or interaction), the observer state "branches" into a number of different states. Each branch represents a different outcome of the measurement and the corresponding eigenstate for the object-system state. All branches exist simultaneously in the superposition after any given sequence of observations.*

Everett in his original paper expected that such branching processes for the typical observer are equivalent to the Born statistical rule (this issue will be revisited shortly in the subsection *MWI and Born's Rule*) [139]:

> *In conclusion, the continuous evolution of the state function of a composite system with time gives a complete mathematical model for*

processes that involve an idealized observer. When interaction occurs, the result of the evolution in time is a superposition of states, each element of which assigns a different state to the memory of the observer. Judged by the state of the memory in almost all of the observer states, the probabilistic conclusion of the usual "external observation" formulation of quantum theory are valid. In other words, pure Process 2 wave mechanics, without any initial probability assertions, leads to all the probability concepts of the familiar formalism.

Moreover, Everett does not see a need to destroy the superposition terms:

From the viewpoint of the theory, all elements of a superposition (all "branches") are "actual", none any more "real" than the rest. It is unnecessary to suppose that all but one are somehow destroyed, since all separate elements of a superposition individually obey the wave function equation with complete indifference to the presence or absence ("actuality" or not) of any other elements.

Everett in [139] considers an observer that will make a number of sequential measurements which generate a particular outcome sequence in the memory of the observer. To illustrate in detail Everett's procedure, we consider the sequential measurement of two spin ½ particles in Figure 4.1. The *i* th, *i*=1,2 spin ½ particle is initially in the state given by:

$$\sqrt{a}|\uparrow\rangle_i + \sqrt{1-a}|\downarrow\rangle_i.$$

Before the *j* th branching process occurs, the state of the *k* th distinct reality or universe will be denoted $|\psi_{\mathcal{U}_{j,k}}\rangle$. The initial state of the two particles in the first universe is denoted by

$$|\psi_{\mathcal{U}_{1,1}}\rangle = \left(\sqrt{a}|\uparrow\rangle_1 + \sqrt{1-a}|\downarrow\rangle_1\right)\left(\sqrt{a}|\uparrow\rangle_2 + \sqrt{1-a}|\downarrow\rangle_2\right)$$

where it assumed that the multiplication between the two particles is shorthand for the tensor product. An observation or measurement on the first spin particle will be made by using device M_1 and on the second spin particle by using a second device M_2. The observation can be taken to be complete in MWI when it is registered in the memory of the device. Unitarily, the observer-particle is in a superposition of Equation (4.2) for which there are two terms. One term is for which M_1 is in the state having registered spin up, represented as $|\uparrow\rangle_{M_1}$ and for which the spin ½ particle is also found in the state $|\uparrow\rangle_1$. The second term is for which M_1 is in the state having registered spin down, represented as $|\downarrow\rangle_{M_1}$ and for which the spin ½ particle is found in the state $|\downarrow\rangle_1$. Although there are two terms in the complete wave function, Everett claims that each individual term is a reality caused by a branching process in which there are now two universes. In Reality or Universe 1, the spin ½ particle is measured up and there is a separate reality or Universe 2 in which the spin ½ particle is measured down. After the first branching process occurs, the state of the device-spin 1-spin 2 in the first reality is given by

$$|\psi_{\mathcal{U}_{2,1}}\rangle = |\uparrow\rangle_{M_1}\,|\uparrow\rangle_1\left(\sqrt{a}|\uparrow\rangle_2 + \sqrt{1-a}|\downarrow\rangle_2\right)$$

and in the second universe a spin down is observed:

$$|\psi_{\mathcal{U}_{2,2}}\rangle = |\downarrow\rangle_{M_1}|\downarrow\rangle_1\left(\sqrt{a}|\uparrow\rangle_2 + \sqrt{1-a}|\downarrow\rangle_2\right).$$

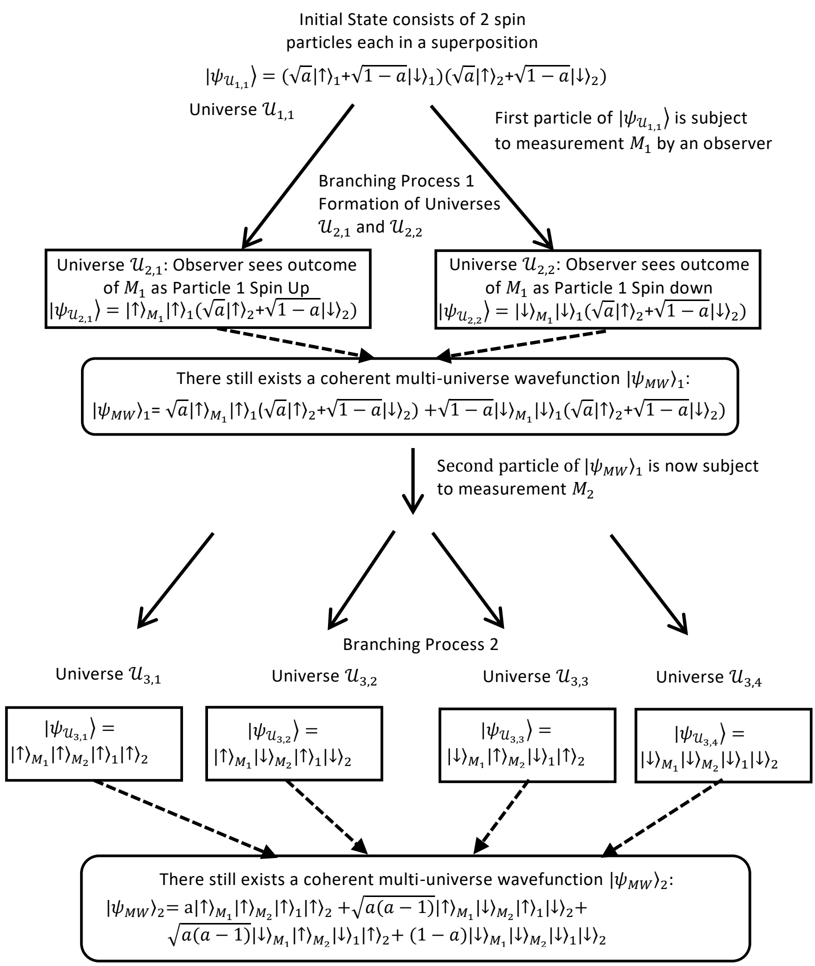

Figure 4.1: Universe formation in the Multiple Worlds Interpretation illustrated via sequential measurement of two spin ½ particles each initially in a superposition.

In addition, there still exists a fully coherent wave function that agrees with Schrödinger's equation given by:

$$|\psi_{MW_1}\rangle = \sqrt{a}|\uparrow\rangle_{M_1}\,|\uparrow\rangle_1\big(\sqrt{a}|\uparrow\rangle_2 + \sqrt{1-a}|\downarrow\rangle_2\big) + \sqrt{1-a}|\downarrow\rangle_{M_1}|\downarrow\rangle_1\big(\sqrt{a}|\uparrow\rangle_2 + \sqrt{1-a}|\downarrow\rangle_2\big).$$

The individual terms such as $|\psi_{\mathcal{U}_{2,1}}\rangle$ are considered by Everett to be relative states, all of which make up the overall absolute state $|\psi_{MW_1}\rangle$. An observer that has a particular relative state is termed a relative observer. Now, consider the case when the second particle of $|\psi_{MW_1}\rangle$ is now subject to a measurement M_2. This results in the further branching of the wave function for which there are four possible outcomes as shown in Figure 4.1, which are:

$$\begin{aligned}
|\psi_{\mathcal{U}_{3,1}}\rangle &= |\uparrow\rangle_{M_1}|\uparrow\rangle_{M_2}|\uparrow\rangle_1|\uparrow\rangle_2\\
|\psi_{\mathcal{U}_{3,2}}\rangle &= |\uparrow\rangle_{M_1}|\downarrow\rangle_{M_2}|\uparrow\rangle_1|\downarrow\rangle_2\\
|\psi_{\mathcal{U}_{3,3}}\rangle &= |\downarrow\rangle_{M_1}|\uparrow\rangle_{M_2}|\downarrow\rangle_1|\uparrow\rangle_2\\
|\psi_{\mathcal{U}_{3,4}}\rangle &= |\downarrow\rangle_{M_1}|\downarrow\rangle_{M_2}|\downarrow\rangle_1|\downarrow\rangle_2.
\end{aligned}$$

Still, in MWI there continues to exist a coherent wave function that is given by:

$$|\psi_{MW}\rangle_2 = \mathrm{a}|\uparrow\rangle_{M_1}|\uparrow\rangle_{M_2}|\uparrow\rangle_1|\uparrow\rangle_2 + \sqrt{a(a-1)}|\uparrow\rangle_{M_1}|\downarrow\rangle_{M_2}|\uparrow\rangle_1|\downarrow\rangle_2 + \sqrt{a(a-1)}|\downarrow\rangle_{M_1}|\uparrow\rangle_{M_2}|\downarrow\rangle_1|\uparrow\rangle_2 + (1-a)|\downarrow\rangle_{M_1}|\downarrow\rangle_{M_2}|\downarrow\rangle_1|\downarrow\rangle_2.$$

Everett's MWI and Born's Rule

Now there remains the issue of the mechanics of universe splitting. Essentially how does one branch from $|\psi_{MW_1}\rangle$ to either $|\psi_{\mathcal{U}_{2,1}}\rangle$ or $|\psi_{\mathcal{U}_{2,2}}\rangle$? This issue is important in terms of how the probability interpretation in Everett's procedure can be fully reconciled with Born's rule. For a thorough discussion on this issue, the reader is referred to Barrett [141]. One problem with Everett's version of MWI is that Everett desired to derive Born's law as a consequence of deterministic pure wave function dynamics. Everett's theory proposes that if a measurement of an observable with N possible outcomes is made, there will exist only N branches of the universe for which each outcome occurs. These branches or worlds all simultaneously exist and are independent of the coefficients of the superposition which are needed to derive the Born law. Since the branches are independent of the coefficients of the superposition, it is not clear how Born's law can come about. Everett added an *additional* requirement that branches are to be measured by a mathematical measure that is equivalent to the coefficient squared of the corresponding term of the superposition. This at once gives the Born rule for the typical observer. Now, the probability of occurrence of Universe $\mathcal{U}_{3,1}$ after the second branch in Figure 4.1 is given by $\mathrm{P}(\mathcal{U}_{3,1}) = a^2$, and as well probabilities of the remaining universes now correspond with Born's law. However, as all branches physically exist in Everett's theory, it has been argued by Graham [140, p. 236] that the rationale of such a measure is inappropriate, and rather a methodology in which the universes are measured by a simple count should be applied. Deutsch also makes the point in that Everett derives the Born rule by depending on a probabilistic mechanism, which he was hoping to avoid. To rectify this possibility, Deutsch [142] added the following axiom to Everett's theory:

> *See the print edition of The Quantum Measurement Problem for quotation.*

Furthermore, Deutsch stipulates that when a superposition occurs as in Equation (4.2) the set of universes then form a disjoint set of N elements, each set of universes corresponding to a given outcome. The size (or measure) of the set of universes that correspond to the r th outcome is $|c_r|^2$. In this manner, one can ensure that outcomes occur with the correct probability. Even with this modification, MWI as a Category 1 theory does not provide the conditions for which the Chapter 3 UMDT experiment would verify a product state that is demanded by the measurement postulate.

Analysis of MWI with UMDT

Let us now critically examine this theory via the UMDT of Chapter 3. First suppose that the devices that are observers consist of quantum controlled-not (CNOT) gates that flip a bit in the device should the device interact with a photon. Basic quantum logic devices have long been the subject of experimental investigation and have already been realized in a fully unitary manner, for example, [143] [144] [145] [146]. Such devices clearly satisfy Everett's requirement for an observer as quantum CNOT gates that are automatically functioning machines that possess sensory apparatus and are coupled to recording devices capable of registering past sensory data via the flipping of the ancilla qubit. Everett expects that there is a branching that would occur for which the two devices are in a product state, "with complete indifference to the presence of absence of any other elements." If the quantum CNOT gates were in a product state, the CHSH result would be $\sqrt{2}$. However, this can be tested and will almost certainly be found to be false. As quantum CNOT gates are unitary, the value would be expected to be $2\sqrt{2}$.

One might ask if there are other types of memories that act non-unitarily. It may be, however it was also found that when a photon was slowed and stored in a slow light medium, entanglement was found to be maintained and not destroyed [147]. Hence it does not appear that Everett's requirement of automatic functioning machines possessing sensory apparatus and are coupled to recording devices capable of registering past sensory data, can be considered to be a necessary condition for a bona fide measurement device.

A problem with Everett's theory in solving the measurement problem as we have defined it, is that Everett concludes that there is a "splitting" process of which no observer will be aware:

> *This total lack of effect of one branch on another also implies that no observer will ever be aware of any "splitting" process.*

This splitting process is what many refer to as a *many minds* theory. That is, the act of observation demands many observers that possess a memory, to exist simultaneously with no observer aware of the other observers. The problem is that entanglement between the two devices in the UMDT can still be experimentally distinguished from a product state of the two devices within the current formalism. If Everett is to be in full agreement with unitary theory, the result of the UMDT CHSH must always be $2\sqrt{2}$. It would have to then come as a surprise if particular configurations of particles were found for the detectors for which the UMDT CHSH is only $\sqrt{2}$. And we already know that memory is not a necessary condition for the UMDT CHSH to yield the value of $\sqrt{2}$. Hence there does not appear to be any particularly helpful resolution of the physical measurement problem in Everett's theory so far. On the other hand, Everett states in [148, p. 98]:

> *The irreversibility of the measuring process is therefore, within our framework, simply a subjective manifestation reflecting the fact that in observation processes the state of the observer is transformed into a superposition of observer states, each element of which describes an observer who is irrevocably cut off from the remaining elements. While it is conceivable that some outside agency could reverse the total wave function, such a change cannot be brought about by any observer which is represented by a single element of a superposition, since he is entirely powerless to have any influence on any other elements.*

In this sense, Everett seems to be claiming that the superposition terms do exist, but one is powerless to have any influence. If Everett claimed that it is impossible to reverse the total wave function, then Everett's theory would be a Category 2 theory.

The theory of Bell's inequality, which showed a difference between two-qubit product states and entangled states, was not developed until 1964 and was not known to Everett in 1957. As well, the development of a unitary CNOT gate was not begun until the 1990s. At some point, when a bona fide measurement device is utilized, the UMDT Chapter 3 test is expected to show a value of $\sqrt{2}$ within the current formalism if the resolution to the measurement problem is a Category 1 theory. On the other hand, a unitary CNOT gate would be expected to give the CHSH sum of $2\sqrt{2}$. Everett's formulation falls significantly short of predicting the physical conditions under which a configuration of particles constitutes a bona fide measurement device, which is a requirement of any Category 1 theory.

Decoherence

Zurek proposed that environmental decoherence can be utilized along with MWI. Note that once one has a composite state of two particles, it is always possible to rewrite the superposition in another basis for which it becomes a superposition. Hence the actual basis for which measurement occurs is called the basis selection problem. The basis selection problem is required for Category 1 theories via Requirement 1.3. Zurek states [149]:

> *If the quantum laws are universally valid, very nonclassical Schrödinger cat–like states should be commonplace for an apparatus that measures a quantum system and, indeed, for run-of-the-mill macroscopic systems in general Everett and other followers of the MWI philosophy tried to occasionally bypass this question by insisting that one should only discuss correlations. Correlations are indeed at the heart of the problem, but it is not enough to explain how to compute them; for that, quantum formalism is straightforward enough. What is needed instead is an explanation of why some states retain correlations, but most of them do not, in spite of the arbitrariness in basis selection that is implied.*
>
> *http://doi.org/10.1103/PhysRevD.26.1862*

Zurek proposes that the pointer basis results largely from the interaction Hamiltonian formulation of device and environment. *Einselection*, a decoherence-imposed selection of preferred pointer states that remain stable in the presence of the environment, establishes stable states in which the apparatus can exist and for which the system is diagonal [149] :

> *Only the einselected pointer states will persist for long enough to retain useful (stable) correlations with—say— the memories of the observers, or, more generally, with other stable states. By contrast, their superpositions will degrade into mixtures that are diagonal in the pointer basis.*

Zurek further claims in [149] that environmental decoherence and pointer states provides the missing elements for defining the branches of Everett:

> *Decoherence and einselection are, however, rapidly becoming a part of a standard lore. Where expected, they deliver classical states, and —as we have seen above— guard against violations of the correspondence principle. The answers that emerge may not be to everyone's liking, and do not really discriminate between the Copenhagen Interpretation and the Many Worlds approach. Rather, they fit within either mold, effectively providing the missing elements —delineating the quantum-classical border postulated by Bohr (decoherence time fast or slow compared to the dynamical timescales on the two sides of the "border"), and supplying the scheme for*

> *defining distinct branches required by Everett (overlap of the branches is eliminated by decoherence).*

Zurek's environmental decoherence does indeed augment MWI by the proposal of addressing the basis selection problem of Requirement R1.3. A stable pointer basis found via the interaction Hamiltonian may very well be related to the measurement problem. This is similar to the theory of external orthogonalization and environmental decoherence which has already been presented. Zurek's theory at this time can be considered a hypothesis (as it has not been experimentally verified) of how Requirement R1.3 is met via the pointer basis selection for which MWI branches. However, it is not a sufficiently developed theoretical solution to Requirement R1.1 of the measurement problem because it is very possible that a system undergoes external orthogonalization and yet one finds that the result of the Chapter 3 CHSH test is $2\sqrt{2}$. Only when the CHSH test is $\sqrt{2}$ can a measurement be said to have occurred in a Category 1 theory. That is, a pointer basis could be established for example with the example of a CNOT gate, yet it is known that such a gate is not a bona fide measurement device. Hence environmental decoherence does not appear to be a sufficient condition for measurement in regards to Requirement R1.1. Precise conditions under which either a device or a device plus its environment constitute a bona fide measurement device must be proposed theoretically and confirmed experimentally in order to meet Requirement R1.1.

Although we would agree that "*decoherence is rapidly becoming a part of a standard lore,"* we argue that this is due to a general lack of understanding in the scientific community of the measurement problem and its requirements for solution, for which it is the intent of this book to rectify. Decoherence certainly can occur and is commonplace in unitary theory. Decoherence does provide a working hypothesis in addressing Requirement R1.3. However, decoherence as proposed by Zurek fails as a sufficient condition to meet Requirement R1.1. Zurek believes that decoherence is a necessary condition for Requirement R1.1 [150]

> *"The environment induces, in effect, a superselection rule that prevents certain superpositions from being observed. Only states that survive this process become classical."*
>
>

However, this claim is a statement with no scientific proof; environmental decoherence may or may not be a necessary condition. Certainly, it would be significant if it were rigorously established to be a necessary condition for Requirement R1.1. However, further theory and substantial experimentation would be needed to validate this claim.

Although there have been other proposed modifications to Everett's initial proposal, there is no theoretical nor experimental evidence at this time that we are aware of that establishes any of these MWIs as either a necessary condition or a sufficient condition for measurement. However, if a new theory is found which provides a physical reason that measurements are forming and this can be predicted via a new theory, then whether or not there are multiple universes and/or minds formed seems inconsequential and an interpretational issue that has no bearing on predictability.