# The Quantum Mechanical Frame of Reference

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Abstract: Everett demonstrates the appearance of collapse, within the context of the unitary linear dynamics. However, he does not state clearly how observers are to have determinate measurement records, hence 50 years of debate. This, however, is inherent. He defines the observer as the record of observations, which, naturally, is the record of correlations established with the physical environment. As in Rovelli's Relational Quantum Mechanics, the correlations record is the sole determinant of the effective physical environment, here the quantum mechanical frame of reference: due to multiple realisation of the functional identity of the observer, the physical environment is a simultaneity of all the physical environments in which it is instantiated, a 'universe superposition', in which only the environment correlated with the observer by observations is determinate. This effects a discrete and idiosyncratic physical environment for each version of an observer, in which determinate measurement records are recorded. Quantum mechanics is on this view fully relational, demonstrated as not only viable but necessary by Rovelli & Laudisa.

The quantum mechanical frame of reference is Everett's 'Relative State', and on Tegmark's 'inside view', the time evolution follows the standard von Neumann-Dirac formulation. Thus observers get precisely the measurement records predicted by the standard formulation, but since objectively there is only the appearance of collapse, there is neither a measurement problem nor a disparity with relativity. The linear dynamics and the collapse dynamics are directly experienced, as the passage of time and the making of observations, respectively.

# 1 Introduction

Everett, in his 'Relative State' Formulation of Quantum Mechanics (1957), resolves the measurement problem by demonstrating that it is not necessary to postulate physical collapse, since the appearance of collapse, to observers, is inherent in the linear dynamics. Everett's formulation seems incomplete, however, precisely because there seems to be no physical instantiation of this appearance of collapse as a specific and singular outcome. The difficulty lies primarily in the difference in the definition of the quantum state from different viewpoints. As Tegmark states:

> A key issue is to understand the relationship between two different ways of perceiving a mathematical structure. On one hand, there is what we will call the “view from outside” ... which is the way in which a mathematician views it. On the other hand, there is what we will call the “view from inside” ... which is the way it appears to a [Self Aware Substructure] in it. (1998, p. 9)

Everett's definition of the functional identity of the observer provides the basis on which to understand this difference, in quantum mechanical terms.

In Everett's formulation, the functional identity of the observer is defined by the record of observations and machine configuration (1957, p. 457). The record of observations is, naturally, the record of correlations established with the physical environment. This structure of information is multiply realised, being instantiated in a large number of different physical environments. Thus the effective physical environment is the simultaneity of all of them, a 'universe superposition'. While the effective physical environment, here the quantum mechanical frame of reference, is necessarily determinate where defined by this correlations record, it is otherwise indeterminate, since every possible variation of the rest of the physical environment is included in the effective superposition.

Within the context of a quantum mechanical frame of reference of this nature, on the inside view, it is obvious why there is the appearance of collapse. Whenever an observation is made, the correlations record defines a new universe superposition, thus there is a new and different quantum mechanical frame of reference effective for this observer. As Everett states, on observation:

> *... the observer-system state describes the observer as definitely perceiving that particular system state*. This correlation is what allows one to maintain the interpretation that a measurement has been performed. (1957, p. 459; his italics)

On the outside view, the linear dynamics produces all possible observations, and thus all possible functional identities of the observer in superposition or mixture. As Everett states:

> It is then an inescapable consequence that after the interaction has taken place there will not, generally, exist a single observer state. There will, however, be a superposition ... each element of which contains a definite observer state and a corresponding system state. (1973, p. 10)

From from the outside view, Wigner's view of his friend (1961), the outcome of the interaction is indeterminate. From the point of view of each resulting version of his friend, however, in each idiosyncratic quantum mechanical frame of reference of each such version, each Everettian 'relative state', a specific observation has taken place. Thus, following the interaction, for each of the different functional identities, one specific version of the interaction has determinately taken place, and a specific determinate observation record generated as a result.

On both inside and outside views, the time evolution of the system progresses in accordance with the linear dynamics. Whenever more than one observation is formulated in the neural system of the observer, the result is multiple functional identities, thus the functional identity fissions, as does the correlations record, and the quantum mechanical frame of reference. On the outside view, all exist in superposition or mixture. On the inside view, there is the discontinuous change brought about by observation. Thus, from the perspective of the friend, on Tegmark's inside view, there is an alternation of linear and collapse dynamics, exactly as specified in the standard von Neumann-Dirac formulation (1955). As Everett says, with reference to the standard formulation:

> ... we were able to show that all phenomena will *seem* to follow the predictions of this scheme to any observer. (1973, p. 110)

On the inside view, the state of the system is changed as each new observation is made. Each observation changes the correlations record, and thus the universe superposition, the quantum state of the physical environment. Everett's concept thus inherently invokes the quantum concept of time. In that concept, the no-collapse universe is equivalent to a static array of block universes.[1] Collapse, change to the quantum definition, is the transition from one block universe to another: the enactment of 'quantum time'. In principle, this concept is incompatible with relativity. For a universe with multiple observers, there can be no single definition of collapse, since different observers can have different definitions of temporal simultaneity. In Everett's formulation, however, since the appearance of collapse is specific and idiosyncratic to the observer, there is no conflict with relativity, and a simple, coherent explanation of the meaning of quantum theory is achieved. The universe evolves according to the linear dynamics; collapse is an inside view phenomenon.

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[1] The quantum state of the physical environment defines not only the state of the matter and energy at the present moment in space-time, but also the linear time evolution of that state along the time dimension of space-time, hence a block universe definition.

# 2 Everett's Observer

The linear dynamics is the fundamental nature of the universe according to quantum theory, and is not in question: the Schrödinger wave equation has now been derived from experimental findings (Granik, p. 2008). The problems with the interpretation of quantum theory arise when the collapse dynamics is included, giving rise to the measurement problem: the question of how, or even if, wave function collapse occurs. Everett resolves this problem very simply, by showing that physical wave function collapse is not necessary to explain observations of collapse, since there is the appearance of collapse to observers defined in the unitary linear dynamics.

He does so by analysis of the nature of observation. The observer is a physical entity, but to make an observation is to add the structure of information representing the observation, to memory. Everett therefore defines observers in the simplest possible way, as "... automatically functioning machines, possessing sensory apparatus and coupled to recording devices" (1957, p. 457) to serve as memory. Given an observer of this nature, he then defines the functional identity of the observer as the contents of the memory, a structure of information:

> If we consider that current sensory data, as well as machine configuration,[2] is immediately recorded in the memory, then the actions of the machine at a given instant can be regarded as a function of the memory contents only, and all relevant experience of the machine is contained in the memory. (p. 457)

He then shows that, with respect to the functional identity of the observer defined in this way, there is the appearance of collapse, given only the standard linear dynamics:

> 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. (p. 462)

In other words, the linear dynamics, Process 2 wave mechanics in the standard von Neumann-Dirac formulation (1955), without any collapse postulate, leads to the appearance of collapse: the apparent exercise of the collapse dynamics, and the probabilistic outcomes of experiments in accordance with the Born rule (1926), from the perspective of this functional identity of the observer. As he explains:

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[2] Human memory is a record of sensory experience, thus a cut in the von Neumann chain at the level of the sensorium is implicit in applying Everett's concept to the human observer. Similarly, the only records made of 'machine configuration', the state of the body-mind, are those internal sensory observations made of the state of the physical and mental system. Thus records of machine configuration are subsumed in the records of sensory data. (Records of sensory experience are integrated to form a concept of the world, while records of machine configuration are integrated to form the self-concept.)

> In other words, pure Process 2 wave mechanics, without any initial probability assertions, leads to all the probability concepts of the familiar formalism. (p. 462)

This, however, makes no sense unless there is a rationale that segregates this appearance of collapse from the standard linear time evolution, the Process 2 wave mechanics. What is required is a basis on which the collapse dynamics operates in a logical domain other than the domain of the linear dynamics, because at the logical level of the unitary linear dynamics there is, by definition, no collapse. As he prefaces the above statements:

> 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. (p. 462)

In summary, there is no physical instantiation of the process of collapse in the unitary linear dynamics. There is only the appearance of collapse, and that only with respect to the functional identity of the observer, the state of the memory defining the record of observations. The primary problem with comprehending Everett's formulation is that, since there is no physical instantiation of the collapse as a singular specific process, it is not clear how such a phenomenon can take place as such. It seems clear that he considers that this does take place, as he concludes:

> We have now completed the abstract treatment of measurement and observation, with the deduction that the statistical predictions of the usual form of quantum theory (Process 1) will appear to be valid to all observers. (1973, p. 85)

However, this would seem to require that the appearance of collapse operates in a different domain to the linear dynamics, and in some way segregated from it, but no rationale for this is provided. The concept thus appears incomplete. As Healey states “Everett's interpretation stands itself in need of an interpretation” (1984, p. 591). What is missing is a physical instantiation of a logical structure containing such a process as a sole, singular outcome. The structure required by Everett's formulation is naturally provided by the physical environment defined by the correlations record of each different functional identity of the observer, here the quantum mechanical frame of reference of that functional identity: Everett's 'relative state'.

## 3 Universe Superposition

Everett defines the functional identity of the observer as the record of observations. Naturally, this is also the record of correlations with the effective physical environment: the environment must be, and can only be, such as to give rise to these observations. The cumulative record of such correlations defines the determinacy of a specific physical environment effective for this observer. The record of observations is the record of observables defining the set of commuting operators which define the determinacy of the observed system. Thus it defines the established determinacy of the effective physical environment, the quantum mechanical frame of reference.

All else is indeterminate due to the multiple realisability of the identity. Every possible version of a world, meaning simply a possible physical environment, exists in the no-collapse universe. Thus the functional identity of the observer, a structure of information, is multiply realised: it is instantiated in every version of the physical environment commensurate with the existence of this structure of information. Since, in Everett's no-collapse universe, all these worlds exist simultaneously, the effective physical environment of this structure of information is the physical simultaneity of all of them, a 'universe superposition'.[3]

Naturally, that much of the physical environment correlated with the observer is necessarily present, and identically the same, in all these superimposed versions of a physical environment. Thus, the simultaneity of all of them, the universe superposition, is determinate with respect to that much of the physical environment correlated with the observer. Equally, since every possible variation of the physical environment concomitant with the existence of this correlations record is included in the simultaneity, the universe superposition is otherwise indeterminate: except where defined by the correlations record, the environment is necessarily a simultaneity of all possible, different, variations of the environment. Thus the effective physical environment of the observer is determinate where observed, and thus defined by the correlations record, and otherwise indeterminate.

This naturally produces a relativisation of the conventional view, since the definition of the physical environment is different for each observer of this type. Crucially, though, it produces a different definition of the physical environment for each functional identity of the observer, in each element of the objectively effective superposition, or more correctly mixture, following observation in Everett's example quoted in Section 2. Thus, while in the overall objective context of the unitary wave function, there is nothing to select one of the elements of the superposition / mixture rather than another. Subjectively, meaning from the perspective of the functional identity of the observer, in each element in the superposition / mixture, the effective physical environment is specifically, and idiosyncratically, defined. In other words, subjectively, meaning from the inside view perspective of each identity, Tegmark's Self Aware Substructure, there is an idiosyncratic quantum mechanical frame of reference, in which observations are determinately made, giving rise to determinate measurement records.

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[3] Considering the time evolution of the unitary linear dynamics, these worlds exist in a decoherent mixture of states, rather than a quantum superposition.

# 4 Inside and Outside

There are, therefore, two different quantum definitions of the system, depending on the viewpoint taken, objective and subjective. This distinction is the same as made between the outside and the inside view of the world, by Tegmark (1998, p. 9-10). These correspond to Wigner and Wigner's friend's, different viewpoints on the friend's world. On the objective view of the quantum mechanical frame of reference of the observer, following the making of an observation with more than one possible outcome, there is:

> ... a superposition of states, each element of which assigns a different state to the memory of the observer." (Everett, 1957, p. 462)

On the subjective view, however, meaning from the point of view of the observer within the context of the quantum mechanical frame of reference of the observer, for each different version of the functional identity of the observer, there is a different, specific, quantum state of the environment. As Everett states:

> ... each element of the resulting superposition describes an observer who perceived a definite and generally different result (1973, p. 10)

This is the appearance of collapse, and leads directly to many worlds, each one the effective physical environment of a specific version of the observer.

This is directly borne out by an example given by Mitra:

> If an initial state
>
> $$|\psi \text{ initial}\rangle = |O_1\rangle\,|U_1\rangle \tag{4}$$
>
> evolves in time to become a superposition of the form
>
> $$|\psi \text{ a while later}\rangle = |O_2\rangle\,|U_2\rangle + |O_3\rangle\,|U_3\rangle \tag{5}$$
>
> We then interpret this as two parallel universes, one containing the observer in state $|O_2\rangle$, the other containing the observer in the state $|O_3\rangle$. (2008, p. 2)

The experiential state of the observer, which he refers to as the state the observer's consciousness is in, is assumed to be identified with a classically describable macrostate of the observer. Initially, $|O_1\rangle$ is the macrostate of the observer, defining her state of consciousness: here defining the state of the memory of the observer, the record of observations. Initially, $|U_1\rangle$ is the generic form of a quantum state of the universe containing this observer. The superposition of two different functional identities generated in the time evolution of the linear dynamics, defined by the quantum state $|\psi \text{ initial}\rangle$, gives rise to two different versions of the observer $|O_2\rangle$, $|O_3\rangle$, and, two different states of the rest of the universe, $|U_2\rangle$, $|U_3\rangle$ respectively: two parallel realities. As he states:

> ... as explained in the previous section, the ket vectors describing the observer only describes whatever the observer is aware of. If we expand the entangled state describing the observer and the rest of the universe in the tensor products of the states $|O_n\rangle$ and the states describing the rest of the universe (which will include parts of the observer that the observer has no direct knowledge of), then the coefficient of each $|O_n\rangle$ will be a superposition of states describing the rest of universe. (2008, p. 3)

Thus his example shows two different versions of the observer, each with a specific and idiosyncratic 'superposition of states describing the rest of universe' or universe superposition: parallel realities. In Everett's formulation, since the record of observations is idiosyncratic, so too is the quantum mechanical frame of reference on the inside view, the effective physical environment of the observer, the 'relative state'.

# 5 The Quantum Concept of Time

The quantum state of a physical system defines a specific linear dynamics, while the collapse dynamics defines the change of the quantum state, with the concomitant change to the linear dynamics. This, the fundamental quantum mechanics, extrapolates to define the dynamics of a complete physical environment, in the quantum concept of time.

As Deutsch (1997, pp. 258-287) explains, the no-collapse universe can be understood as a multiverse of moments or 'snapshots': definitions of a specific arrangement of matter and energy in the universe. Each such snapshot must necessarily have a specific quantum definition, which in turn defines the probabilistic layout of possible events, interactions of matter and energy, throughout the four-dimensional matrix of space-time: a specific linear dynamics. Thus each snapshot is a specific quantum mechanical frame of reference. This is a specific moment in 'quantum time'. As Deutsch also explains:

> The snapshots which we call 'other times in our universe' are distinguished from 'other universes' only from our perspective, and only in that they are closely related to ours by the laws of physics. (1997, p. 278)

In other words, all possible snapshots exist, each one a moment in quantum time, and certain special cases of such moments are possible pasts and possible futures of our current snapshot, our universe at the present moment in quantum time. This is to emphasise his previous statement “Other times are just special cases of other universes.” (p. 278), of which he says “This is the distinctive core of the quantum concept of time.” (p. 278).

The collapse dynamics defines the relationship between these moments, or snapshots. For any given collapse of the quantum state, a different specific quantum state with a different linear dynamics, a different quantum mechanical frame of reference, a different moment in quantum time, is the result. The linear dynamics defines how the state of the matter and energy in the universe changes, going forward along the linear time dimension of space-time. At each point in this time dimension, there is a specific, largely probabilistic, arrangement of matter and energy in the three dimensions of space. Going forward along the linear time dimension of space-time, the three-dimensional configuration of matter and energy in space, changes: the inertial frame of reference changes. This whole four-dimensional layout, subsuming the time evolution of the physical environment, defined by a specific linear dynamics, is defined by a specific quantum state.

The collapse of the quantum state results in a different quantum state, defining a different linear dynamics, a different four-dimensional layout. Thus, while the linear dynamics is the change to the physical *within* the four-dimensional layout defined by a specific quantum state, a specific quantum mechanical frame of reference, the collapse dynamics is the change *to* the physical four-dimensional layout defined by a specific quantum state, the change of the quantum mechanical frame of reference. This is the logical structure of the universe in the quantum concept of time, a straightforward implementation of the fundamental quantum mechanical dynamics. The linear dynamics is an expression of a specific quantum state, and the collapse dynamics defines the change of the quantum state.

As a global phenomenon applicable to all observers and viewpoints in space-time, this concept of the collapse dynamics is directly incompatible with relativity. Since in relativity, the different inertial frames of reference of different observers have different temporal simultaneities, there cannot be a collapse that applies to all inertial frames of reference at once. However, in Everett's formulation this problem does not arise. The appearance of collapse is always with respect to a specific functional identity of a specific observer. In this context, since the frame of reference is always that of a specific observer, there is no conflict between the quantum concept of time and relativity.

With each observation, the correlations record changes, as the functional identity changes, and as a result the universe superposition changes. Thus the appearance of collapse in Everett's formulation is an exact description of the quantum concept of time. With each observation, the quantum state defining the effective physical environment changes, thus the quantum mechanical frame of reference changes. In the no-collapse universe, all possible quantum mechanical frames of reference, moments in quantum time, exist, and the appearance of collapse is simply the effective transition from one specific quantum mechanical frame of reference to another. This collapse dynamics is idiosyncratic to the individual observer, which renders the quantum concept of time in agreement with relativity.

# 6 Dynamics

The quantum state of the system defines the linear dynamics, and the collapse dynamics is the change to the quantum state. If the quantum state defines a physical environment, then this is the change to the physical environment. Here the effective physical environment of the functional identity of the observer is considered to be the quantum mechanical frame of reference, defined by the record of observations, the record of correlations with the environment. This quantum mechanical frame of reference is subject, alternately, to both linear and collapse dynamics, as described by the standard von Neumann-Dirac formulation (1955).

## 6.1 Linear

The quantum state of the system is defined solely by the record of observations made by the observer, the correlations record. This defines a specific linear dynamics. In between observations, the system evolves continuously according to the linear, deterministic dynamics. This is the change of the three-dimensional spatial configuration of matter and energy, in the progression along the linear time dimension of space-time, as defined by the linear dynamics of the quantum state.

## 6.2 Collapse

At the point in the linear time dimension of space-time where an observation is made, the functional identity changes. This is the point at which there is subjective collapse. With each observation, the correlations record changes, as the functional identity changes, and as a result the quantum mechanical frame of reference changes. Thus, the making of the observation, the addition of the observation to the record of observations, changes the effective physical environment of this observer. Subjectively, meaning within the context of this quantum mechanical frame of reference, from the perspective of the Self Aware Substructure within it, to make an observation is to make the transition from one quantum mechanical frame of reference to the next: a progression in quantum time. In the new quantum mechanical frame of reference, a specific observation is determinately defined, whereas in the moment before, the outcome of this observation was indeterminate. Hence, while objectively there is only the appearance of collapse, subjectively, on the inside view, in the quantum mechanical frame of reference of the observer, collapse effectively takes place. This change is, in each case, the transition from one quantum mechanical frame of reference to the next, one block universe moment to the next.

## 6.3 The Cycle

The two quantum mechanical dynamics alternate, exactly as in the standard von Neumann-Dirac formulation (1955)[4]:

> Process 1: The discontinuous change brought about by the observation of a quantity with eigenstates $\varphi 1$, $\varphi 2$, , in which the state $\psi$ will be changed to the state $\varphi j$ with probability $|(\psi, \varphi j)|^2$.
>
> Process 2: The continuous, deterministic change of state of an isolated system with time according to a wave equation $\partial\psi/\partial t = U\psi$, where U is a linear operator.

The quantum state of the system, $\psi$, is here considered to be the quantum state of the quantum mechanical frame of reference, the effective physical environment of the functional identity of the observer, defined by the correlations record. On collapse, Process 1, this quantum mechanical frame of reference changes, while the inertial space-time frame of reference remains constant. This change is instantaneous with regard to linear time, the time dimension of space-time, thus at the point of transition, the clock time in the two quantum mechanical frames of reference (before and after in 'quantum time') is identical. In Process 2, the quantum mechanical frame of reference remains constant, while the time evolution of the linear dynamics progresses, time elapsed in the linear time dimension of space-time increases, and the inertial space-time frame of reference changes as a result.

Objectively, in the unitary linear dynamics, as in the reality of Wigner's friend from Wigner's perspective, there is only the linear dynamics, Process 2. Subjectively, however, inside the quantum mechanical frame of reference of each observer, Process 1 occurs on observation. Each collapse, each 'quantum jump', is a purely subjective transition to a new quantum state, meaning that it applies solely to the inside view of the quantum mechanical frame of reference, which undergoes time evolution in quantum time, while the inertial space-time frame of reference remains constant. The probability of a specific quantum jump is given by the quantum state of the quantum mechanical frame of reference, the eigenstates being the different possible quantum mechanical frames of reference, each resulting from the addition of a specific observation to the correlations record of the observer.

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[4] If the definition of the quantum state of the effective physical environment is to be taken as a density matrix rather than a wave function, the time evolution of the linear dynamics in Process 2 is defined by the linear dynamics of the density matrix: as Jordan states “... it is proved that the maps of density matrices in time are linear” (2009, p. 2). In Process 1, the density matrix is assumed to define the same probabilistic expectation values for observables as the eigenstates.

## 6.4 The Specious Present

The quantum mechanical frame of reference is defined by the correlations record, the record of observations, which changes only with the new addition of an observation. The formulation of an observation is dependent on neural processes, and takes a certain amount of time. Thus, as the linear dynamics progresses, there is a period of time, in the linear time dimension of space-time, during which a specific record of observations is constant, while the next observation is being formulated in the neural system. This period of time is here considered to be the specious present, the period of time during which no change to the record of observations takes place, and a specific experiential state of the world, inner and outer, remains constant for the observer. This is the period of time between one collapse and the next. Effectively, this is also the duration of a moment, being the period of linear time that elapses within the context of a specific quantum mechanical frame of reference, defined by a specific quantum state: a specific moment in the sequence of moments in quantum time.

The specious present was originally defined as "... delusively given as being a time that intervenes between the past and the future." (1893, p. 509). However, in regard to moments in quantum time, it is, in reality, just such a time: this is the duration, in the linear time dimension of space-time, of a specific quantum state of the environment. As the time evolution of the linear dynamics progresses, there is an overall progression along the linear time dimension of space-time. For the functional identity of the observer, this progression is punctuated by a series of 'quantum jumps', each one an instantaneous transition to a different quantum mechanical frame of reference, upon the making of an observation. Each period of linear time between jumps is a new instance of the specious present.

## 6.5 Many Worlds

During the period of the specious present, since this is a linear quantum system, all possible variations of events in the physical environment are simultaneously present, in superposition or mixture. Similarly, all possible variations of observations, which the physical body-mind of this observer, in this environment, could be in the process of formulating, are simultaneously present in this system. At the point in time where the next observation is formulated in the neural network, and thus added to the record of observations, all possible variations of such an addition take place in the linear dynamics. In the quantum mechanical frame of reference of each, individual, new, functional identity of the observer, a different specific observation is defined as determinately made.

For each addition of a different observation to the record of observations, a different functional identity of the observer is produced. As Everett states:

> ... with each succeeding observation (or interaction), the observer state "branches" into a number of different states. (1957, p. 459)

Each individual new observer state defines a new observer-system state: each new functional identity of the observer defines a new record of correlations with the physical environment, and thus a new quantum mechanical frame of reference, a new relative object-system state. As Everett states:

> ... each element of the resulting superposition describes an observer who perceived a definite and generally different result, and to whom it appears that the object-system state has been transformed into the corresponding eigenstate. (1973, p. 10)

Each eigenstate, each new quantum mechanical frame of reference, is the discrete and idiosyncratic world of that specific version of the observer.

## 7 The Quantum Mechanical Frame of Reference

The time evolution of the quantum mechanical frame of reference is different viewed objectively and subjectively. As stated by Laudisa & Rovelli:

> ... a variable (of a system *S*) can have a well determined value *q* for one observer (*O*) and at the same time fail to have a determined value for another observer (*O′*). (2005)

To illustrate this, Barrett's classic example (1998) is examined from both perspectives. When an observer (*O*), here Wigner's friend, goes to measure the x-spin of a physical system *S* that begins in a superposition of x-spin eigenstates, the initial condition of the physical system to be measured is indeterminate.

$$|\text{“ready”}\rangle_O \, (\alpha \, |\text{x-spin up}\rangle_S + \beta \, |\text{x-spin down}\rangle_S)$$

Wigner's friend performs the experiment. Objectively, in Wigner's (*O′* above) quantum mechanical frame of reference, no collapse has occurred. This is the time evolution of the overall linear dynamics in the the objective view of the quantum mechanical frame of reference.

$$\alpha \, |\text{“spin up”}\rangle_O \; |\text{x-spin up}\rangle_S + \beta \, |\text{“spin down”}\rangle_O \; |\text{x-spin down}\rangle_S$$

Subjectively, however, meaning from the perspective of the experimenter, Wigner's friend, a specific observation has just taken place. This provides exactly the outcome predicted by the standard von Neumann-Dirac collapse formulation, which is that the quantum-mechanical state of the system will collapse either to

$$|\text{“spin up”}\rangle_O \; |\text{x-spin up}\rangle_S \quad \text{or to} \quad |\text{“spin down”}\rangle_O \; |\text{x-spin down}\rangle_S$$

which, subjectively, is exactly what happens. Subjectively, meaning simply on the inside view, inside the quantum mechanical frame of reference of the observer, one or the other happens, as the observer defined by the correlations record fissions. As the correlations record fissions, so too does the quantum mechanical frame of reference, viewed subjectively.

Everett's formulation hinges on this distinction. As Tegmark states:

> Everett's brilliant insight was that the MWI *does* explain why we perceive randomness even though the Schr ödinger equation itself is completely causal. To avoid linguistic confusion, it is crucial that we distinguish between
>
> - the outside view of the world (the way a mathematician thinks of it, i.e., as an evolving wavefunction), and
> - the inside view, the way it is perceived from the subjective ... perspective of an observer in it.
>
> (1997, p. 2; his italics)

As he goes on to describe, while the objective view is of a superposition of possible states of the observer, which evolves in time maintaining the strict causality of the linear dynamics, the subjective view is of a random series of observations.

On the outside view of the quantum mechanical frame of reference, the post-measurement quantum-mechanical state of a system, such as Wigner's definition of his friend, is not an eigenstate of there being a single determinate record, while on the inside view, it is. As Everett himself describes:

> It is then an inescapable consequence that after the interaction has taken place there will not, generally, exist a single observer state. There will, however, be a superposition of the composite system states, each element of which contains a definite observer state and a definite relative object-system state. ( 1973,p. 10)

This is the difference between outside and inside views of the quantum mechanical state, as explained by Tegmark (1997).

The concept of universe superposition provides a solid rationale for this difference. On the outside view, the quantum state of a subsystem is defined by the correlations with that subsystem. Observations made within the subsystem do not affect the quantum state on the outside view, since these do not alter those correlations: all possible versions of events within the subsystem are aspects of the simultaneity of versions of the environment defining the quantum mechanical frame of reference of the observer outside the subsystem. On the inside view, in the quantum mechanical frame of reference of each functional identity, observations made within the subsystem result in determinate measurement records, since the effective physical environment is, inevitably, determinate where observed, in all possible variations of the physical environment in which this specific observation is determinately made. Thus, the simultaneity of all such versions of the environment is also determinate with respect to the outcome of this observation. On the outside view, an observation made inside that quantum mechanical frame of reference produces a simultaneity of all possible outcomes, and concomitant versions of the functional identity.

Viewed solely from the outside point of view, Everett's formulation of the appearance of collapse does not make sense. As he shows, however, it is only subjectively, meaning on the inside view of the quantum mechanical frame of reference, inside the effective physical environment defined by the correlations record defining the observer, that there is collapse. We have evidence only for this subjective appearance of collapse. Given Everett's explanation, it would seem that no further explanation is needed. There is no measurement problem. The collapse dynamics is a step in quantum time, a change in the quantum mechanical frame of reference of the observer, induced by the progression of linear time, the time evolution of the linear dynamics. Each observer in their specific quantum mechanical frame of reference, on making an observation, experiences a specific version of the observation being made, as their functional identity changes, and thus the quantum mechanical frame of reference changes. On the outside objective view, there is only the appearance of collapse, and only in so far as an observer on the inside view will report collapse. On the outside view, the linear dynamics gives rise to a simultaneity of all possible physical environments for an observer inside the quantum mechanical frame of reference.

Given that different observers have different quantum mechanical frames of reference, it is clear that, on the inside view, these different relative observer-system states to which Everett refers are not only logically, but also physically, discrete, segregated domains: many worlds. The result is the time evolution of multiple, branching, transtemporal, quantum mechanical frames of reference, within the context of the unitary linear dynamics.

## 8 Transformations

As Merriam states:

> Each quantum system "carries" around a local spacetime in whose terms other quantum systems may take on nonlocal states. Each quantum system forms a physically valid coordinate frame. (2005, p. 1)

It is in order to capture this sense of idiosyncratic uniqueness to each quantum system that the term quantum mechanical frame of reference is used here, as distinct from the term quantum reference frame, a derivative of the inertial frame of reference.

Just as in relativity, where different observers in the same space-time system have different inertial frames of reference, different observers in the same unitary quantum mechanical system can have different quantum mechanical definitions of the effective physical environment. In other words, the different observers have different quantum mechanical frames of reference. This is exactly what Everett is saying:

> Thus we are faced with a fundamental relativity of states, which is implied by the formalism of composite systems. It is meaningless to ask the absolute state of a subsystem - one can only ask the state relative to a given state of the remainder of the system. (1973, p. 43)

Thus Everett is stating that the same identical principle central to relativity applies equally to quantum theory. As he states, the formalism of quantum systems dictates that the quantum state of a subsystem in the system is relative, exactly as applies to position and velocity in relativity. While this is a somewhat challenging idea, Rovelli also sees it as directly required by quantum mechanics:

> ... quantum mechanics indicates that the notion of a universal description of the state of the world, shared by all observers, is a concept which is physically untenable, on experimental ground. (1996, p. 7)

As he states, in an exact parallel with the relativity of inertial frames of reference:

> ... a quantum mechanical description of a certain system (state and/or values of physical quantities) cannot be taken as an "absolute" (observer independent) description of reality, but rather as a formalization, or codification, of properties of a system relative to a given observer. (1996, p. 6)

In relativity, the abstract mathematical structure of the Lorenz transformations defines the change of the frame of reference from one inertial position in space-time to another. In quantum mechanics, the time evolution of the linear dynamics defines the way the spatial configuration of matter and energy changes with progression along the linear time dimension of space-time. As Tegmark states, the position representation is uniquely special:

> Essentially, the position basis gets singled out by the dynamics because the field equations of physics are local in this basis, not in any other basis. (1997, p. 3)

Thus the time evolution of the inertial frame of reference of an observer is defined, within the context of a specific quantum mechanical frame of reference. The collapse dynamics defines the change of the quantum mechanical frame of reference, the change of view from one point in quantum time to another.

The standard formulation defines the alternating operation of these two dynamics. The progression of the linear dynamics gives rise to the generation of a new observation in the neural network of the observer. This changes the correlations record, resulting in the progression of the collapse dynamics, in the quantum mechanical frame of reference of this observer. This gives rise to a new quantum mechanical frame of reference, and a concomitant new linear dynamics, and the cycle begins again. Like relativity, quantum mechanics is fundamentally the physics of frames of reference, and the relevant operations on the frame of reference defining the nature of the physical environment and the way it operates.

On the outside view, there is only the linear dynamics, the time evolution of the physical, giving rise to all possible configurations of the world. On the inside view, that of the observer inside the quantum mechanical frame of reference, this is simply the time evolution of 'the real world'. The linear dynamics is experienced as the passage of time, the change to the inertial frame of reference, while the collapse dynamics is experienced as the making of observations, the change to the quantum mechanical frame of reference. This is the transtemporal reality defined by Everett's formulation.

Multiple versions of the functional identity are produced whenever there is more than one possible observation. Thus the quantum mechanical frame of reference fissions, with all possible states of the system being made real, experientially, hence the 'many worlds' attributed to Everett's formulation. Each quantum mechanical frame of reference is idiosyncratic to that observer, hence parallel, but often overlapping, effective physical realities for each observer.

# 9 Conclusion

Due to multiple realisability, the effective physical environment of the observer, here the quantum mechanical frame of reference, is indeterminate except where defined by the record of correlations established with the physical environment by observations. This provides Everett's formulation with a concrete difference between the inside and outside views of the quantum mechanical frame of reference. As Tegmark states, illustrating the significance of the difference between these two views, in regard to quantum mechanics:

> Here the difficulty of relating the two viewpoints reached a new record high, manifested in the fact that physicists still argue about how to interpret the theory today, 70 years after its inception. Here one choice of outside view is that of a Hilbert space where a wave function evolves deterministically, whereas the inside view is that of a world where things happen seemingly at random, with probability distributions that can be computed to great accuracy from the wave function. It took over 30 years from the birth of quantum mechanics until Everett [1957] showed how the inside view could be related with this outside view. (1998, p. 10)

What is missing from Everett's formulation in its original form is the overt clarification of this distinction. On the inside view, from the perspective of the observer within the quantum mechanical frame of reference, there is the enactment of collapse, the change of the quantum mechanical frame of reference. On the outside view, there is only the appearance of collapse, the observer reporting collapse on the inside view.

From the point of view of an observer outside of a quantum mechanical system, the dynamics of that quantum mechanical frame of reference is different to that of an observer within the system, as described in the concept of Wigner's friend. For the observer within the system, quantum mechanical collapse gives rise to determinacy of the outcome of an experiment, while for the observer outside of the system, the system evolves according to the linear dynamics, giving rise to superposed / mixed versions of both experiment and experimenter. Thus there are two different views of a quantum mechanical frame of reference, outside and inside, objective and subjective.

The subjective view is Tegmark's 'view from inside', the view of an observer inside the reality of the quantum mechanical frame of reference, that of Wigner's friend who does the experiment and gets a determinate result. On this view, the record of correlations with the environment established by observations defines the sole determinacy of the effective physical environment for that observer, the quantum mechanical frame of reference. Since the determinacy of the quantum mechanical frame of reference is different for different observers, an observer observing this subsystem from outside has a different quantum defintion of the subsystem to that of the observer inside it. This objective view is Tegmark's 'outside view' of the same quantum mechanical frame of reference, that of Wigner, in which the outcome of the experiment is indeterminate, as is the state of the friend.

On the outside view, the time evolution of a quantum system is always that of the linear dynamics. On the inside view, that of an observer within the context of a specific quantum system, there is an additional collapse dynamics. T his is the quantum mechanical difference between 'objective' and 'subjective'. We have taken the term subjective to mean simply and solely the experiential, assuming, very naturally, that the experiential is simply the experience of the objective. Which, of course, it is. But the crucial distinction is that this is only true of the linear dynamics. When it comes to collapse, the experiential is not simply the experience of the objective physical world defined by the quantum state, it is the experience of the change of the quantum state. This is the logical nature of the addition of an observation to the definition of the functional identity of the observer. This is Everett's genius at work. As he states:

> ... [our theory] can be said to form a metatheory for the standard theory. (1957, p. 462).

While the linear dynamics is the logical operation of the physical system, this system also produces a phenomenon effectively meta to this dynamics, the change to the quantum state effective for the functional identity of the observer: progression from moment to moment in the quantum concept of time discovered by Page & Wooters (1983) and described by Deutsch (1997, pp. 258-287).

On both inside and outside views, the time evolution of the linear dynamics causes the inertial frame of reference to change, while the quantum mechanical frame of reference remains constant. On observation, on the inside view, there is instantaneous collapse, and the quantum mechanical frame of reference changes, while the inertial frame of reference remains constant. Both dynamics are intensely familiar to a conscious observer: the time evolution of the physical in the linear dynamics is the passage of time, while the collapse dynamics is the making of observations that happens in the context of the passage of time. Quantum theory is complete, but collapse is purely subjective, meaning that it applies solely to the inside view of the quantum mechanical frame of reference.

As is the case with Einstein's relativity, the physical environment defined in quantum mechanics is relative to the frame of reference of the observer, as Rovelli proposes is essential to make sense of the experimental findings. On the inside view, the quantum mechanical frame of reference follows the time evolution of a quantum system as defined by the standard von Neumann-Dirac formulation. This is the nature of the reality of each observer, in the context of Everett's no-collapse universe.

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