Times Two

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Abstract: The nature and topology of time remain an open question in philosophy. Both tensed and tenseless concepts of time appear to have merit. Quantum mechanics demonstrates that both are instantiated, as complementary aspects of the time evolution of physical systems. The linear dynamics is tenseless. It defines the universe probabilistically throughout space-time, and can be seen as the definition of an unchanging block universe. All properties of the universe are defined for the whole extent of the linear time dimension of space-time. The collapse dynamics is the change to the linear dynamics: time evolution of the physical system in the quantum concept of time. This is tensed: different definitions of the probabilistic definition of the space-time universe exist from moment to moment in the quantum concept of time. Thus the linear time dimension of space-time is tenseless, while time in the quantum concept of time is tensed. Exercise of the linear dynamics is experienced as the passage of time, while the exercise of the collapse dynamics is experienced as change.

1 Introduction

The concept of tensed time is very attractive, as it makes sense of our apparent experience of the moving moment of now. Considerable philosophical argument has been presented both for this concept and for its opposite, tenseless time. However, on the view presented here, both sides of the debate would inevitably find evidence for their preferred mode, since both are present. Turning to physics to settle the dispute, it is clear that tensed time is incompatible with relativity. Any concept of tensed time must be based on a global simultaneity, the now that stands between past and future, but observers in different inertial frames of reference have different simultaneities. However, in relational quantum mechanics no such problem exists. The global frame of reference is always that of solely a specific observer, and tensed time is entirely feasible. In this context, it is straightforward to make a case for the collapse dynamics of a quantum system as the basis of tensed time. The linear dynamics meanwhile provides an ideal example of tenseless time. Taken overall it provides a static definition of the universe throughout space-time as defined by a specific global quantum state. Since the collapse dynamics is the time evolution of this global definition of the universe, giving rise to a sequence of different quantum states, these two different kinds of time evolution of physical systems are necessarily of different logical type. Thus both tenseless and tensed time exist as fundamental aspects of the quantum environment, coexisting in a manner akin to velocity and acceleration.

2 Two Kinds of Time Evolution

The standard von Neumann-Dirac formulation of quantum mechanics (1955) addresses the two different dynamics that apply to a physical system:

> Dynamics: (a) If no measurement is made, then a system S evolves continuously according to the linear, deterministic dynamics, which depends only on the energy properties of the system. (b) If a measurement is made, then the system S instantaneously and randomly jumps to a state where it either determinately has or determinately does not have the property being measured. (Barrett, 1998)

Dynamics (a) is the linear dynamics of the quantum wave equation, and dynamics (b) is the collapse dynamics, the 'collapse' of the probabilities defined by the quantum wave equation. After the discontinuous change of the probabilities of the linear dynamics to specificity upon measurement, the 'quantum jump', the system S is in a different quantum state and a new and different linear dynamics applies. Applying this to the universe as a whole, from the perspective of a specific observer, the linear dynamics is the time evolution of the overall system, defined by a specific quantum state. Since this defines the probability amplitudes for possible events, interactions of matter and energy, throughout four-dimensional space-time, this defines a block universe: here the quantum mechanical frame of reference. The collapse dynamics is the change in that four-dimensional definition, resulting in a different four-dimensional layout defined by a different quantum state: a change to the linear dynamics giving rise to a different block universe. The two dynamics are of different logical type.

3 Logical Types

Russell (1908) introduces the concept of logical types or ordinality: a member of a set is of different logical type to the set. An illustrative analogy in the current context is a movie film, a linear series of frames, each one a two dimensional arrays of pixels. Clearly a single frame of the movie film is of different logical type to the set of sequential frames on the film making up the whole movie. Similarly to the movie film, a quantum system in action can be considered as a sequence of four-dimensional 'frames', each one a four-dimensional array of probability amplitudes defined by a specific wave function.

The linear dynamics of a specific quantum state defines the probability amplitudes for possible events, throughout the four-dimensional space-time universe. With respect to the probability amplitudes of events, this is a four-dimensional frame of reference, here the quantum mechanical frame of reference. Collapse is the change of the linear dynamics, the transition from one such quantum mechanical frame of reference to another. The collapse dynamics involves a sequence of quantum mechanical frames of reference, and is thus of different logical type to a single frame of reference. While the linear dynamics is of the ordinality of a single state in the sequence, the collapse dynamics is of the ordinality of a set, the sequence of states. Thus the collapse dynamics is a process meta to the linear dynamics.

Applying this principle to the whole four-dimensional space-time physical environment, the quantum state of the universe defines the four-dimensional quantum mechanical frame of reference, a four-dimensional space-time block universe defined by the linear dynamics. The change of that block universe is the collapse dynamics giving rise to a sequence of block universes. This provides a simple implementation of Lockwood's suggestion that: "… the tensed and tenseless theories of time could both be true" (2005, p. 70). On this view, the linear time dimension of the four-dimensional space-time block universe is the tenseless view of time, and collapse is:

> … an overarching march of time, with respect to which this four-dimensional block universe itself undergoes change, in the same manner as is envisaged in the tensed view of ordinary time (Lockwood, 2005, p. 70)

Thus there is a sequence of definitions of the four-dimensional block universe, and the effect is of a four-dimensional space-time matter and energy movie.

4 Tensed and Tenseless Time

Although the linear dynamics defines change with linear time, with regard to the overall four-dimensional quantum mechanical frame of reference it is unchanging. Thus in the context of the quantum concept of time, the time evolution of the system with the exercise of the collapse dynamics, each linear dynamics is tenseless while the collapse dynamics itself is tensed. Markosian (2002) provides the following canonical statement of the terms tensed and tenseless:

The Tensed View of Semantics:

i. Propositions have truth values *at times* rather than just having truth values *simpliciter*.

The fundamental semantical locution is '*p* is *v* at *t*' (where the expression in place of '*p*' refers to a proposition, the expression in place of '*v*' refers to a truth value, and the expression in place of '*t*' refers to a time).

ii. It is possible for a proposition to have different truth values at different times.

The Tenseless View of Semantics:

i. Propositions have truth values *simpliciter* rather than having truth values *at times*.

The fundamental semantical locution is '*p* is *v*' (where the expression in place of '*p*' refers to a proposition and the expression in place of '*v*' refers to a truth value.

ii. It is not possible for a proposition to have different truth values at different times.

Throughout the four-dimensional quantum mechanical frame of reference, as defined by a specific quantum state with a specific linear dynamics, the definition of the probabilities of events is fixed and static. Thus with regard to the four-dimensional quantum mechanical frame of reference, the tenseless semantics applies: there is, for all points in space-time, a fixed truth value, the specific probabilities of events, given by a specific quantum state.

Within the context of a specific quantum mechanical frame of reference, the linear dynamics defines the time evolution of the three-dimensional spatial arrangement of matter and energy, with progression along the linear time dimension of space-time. Thus, within this context, the linear time dimension of space-time is tensed: the truth value for the three-dimensional spatial arrangement of matter and energy is different at different times along the linear time dimension of space-time.

Notwithstanding, this time evolution within the context of the linear dynamics is a fixed property of the linear dynamics, the four-dimensional truth value of the quantum state. Here the 'proposition' is the quantum state of the system, and the linear dynamics of the quantum state defines specific truth values for the probability amplitudes for possible events, for all positions throughout four-dimensional space-time. The truth value of this proposition does not vary with regard to linear time, since the the four-dimensional array of probability amplitudes does not change: the entire spread of values for different positions in linear time is subsumed by the specific four-dimensional truth value defined by a specific quantum state. Thus with respect to the four-dimensional proposition, the tenseless semantics applies. By contrast, with regard to the quantum concept of time, here 'collapse time', the tensed semantics applies, since the four-dimensional proposition has different truth values at different times in collapse time. A succession of different quantum states give rise to a succession of different values for the linear dynamics, each of which defines different truth values throughout the four-dimensional space-time matrix. As a result, the truth value of the probability amplitudes of events at a specific space-time location may vary with collapse time.

5 Relational Quantum Mechanics

Strong objections have been raised to accounting for a tensed view of time by attributing to the collapse dynamics an instantaneous change to the whole universe e.g. Callendar (2007). The central problem is the assumption of the validity of the concept of a global simultaneity for all observers, whereas relativity specifically demonstrates a relativity of simultaneity. This, however, depends on a specific, and entirely natural assumption, for which there is, however, no empirical justification in physics: namely a single quantum mechanical frame of reference for all observers. This is specifically refuted by Rovelli:

> … 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)

In relational quantum mechanics one is dealing with a frame of reference involving only a single observer, and thus there is no difficulty with the concept of a global simultaneity. The same applies to Everett's Relative State Formulation of Quantum Mechanics (1957).

5.1 Everett

Everett defines the functional identity of the observer as the state of the memory, defined in turn as the record of sensory observations and machine state. As shown elsewhere (Soltau, 2010a) this implies an effective physical environment determinate only where observed by this observer: the physical environment is otherwise indeterminate,[1] Thus the determinacy of the effective physical environment, the quantum mechanical frame of reference, is defined solely by the record of observations made: sensory observations of the external environment plus observations of machine state, in the human observer, proprioception, enteroception, thoughts, feelings etc..

Everett's formulation dispenses with the collapse dynamics as a physical process, thus resolving the measurement problem. He demonstrates that this is an unnecessary postulate, since there is the appearance of collapse to observers inherent in the linear dynamics. As he describes, in the unitary linear dynamics all possible outcomes are generated in the progression along the linear time dimension of space-time. Thus at the point in time when an observation is formulated, all possible versions of this observation take place, resulting in all possible versions of the observer. However, with respect to each functional identity of the observer only one specific version of the observation has taken place. This crucial distinction exists because the functional identity of the observer is a structure of information: the state of the memory, the record of observations and machine configuration.

To each such functional identity, there is the appearance of collapse: one specific version of the observation has been determinately made. The making of this observation changes the quantum state of the effective physical environment, thus giving rise to a new definition of the quantum mechanical frame of reference. In this quantum mechanical frame of reference the linear dynamics progresses, until there is a collapse, and the cycle recurs. Everett's formulation thus describes the time evolution of the effective physical environment of the observer, which alternates between the two quantum mechanical dynamics, linear and collapse, exactly as defined in the standard von Neumann-Dirac formulation of quantum mechanics (1955). This very clearly illustrates the two different types of time evolution of the physical environment effective for the observer.

1 This is strikingly similar to the holographic principle of t'Hooft's Dimensional Reduction in Quantum Gravity (1993), according to which there can be no more definition to the region beyond the interface than defined by the interface itself.

5.2 The Quantum Concept of Time

In the quantum concept of time, all possible states of the universe exist 'already'. Barbour makes exactly this point. He calls each specific state a 'Now', and this is what he is emphasising when he says that: “Every Now is a complete, self-contained, timeless, unchanging universe” (Folger, 2000). Each Now is a moment in the quantum concept of time. All the moments exist, complete, 'already', like the frames of a movie film. Thus Barbour: “... likens his view of reality to a strip of movie film. Each frame captures one possible Now” (Folger, 2000).

As Barbour (1994) Deutsch (1997) and Davies (2002) make clear, the movie does not run. As Deutsch states:

> ... the sequence of moments itself ... does not exist within the framework of time – it *is* the framework of time. (1997, p. 264)

As he describes, in the quantum concept of time, all possible variations of the block universe exist 'already'. Thus the no-collapse universe is effectively a multiverse of block universes. As he states:

> We exist in multiple versions, in universes called 'moments'. … Other times are just special cases of other universes. (1997, p. 278)

He goes on to comment that “This is the distinctive core of the quantum concept of time.” (p. 278).

For there to be any kind of progression in such a context, something would have to move from moment to moment, along the sequence. Naturally, this would give rise to the appearance of collapse. However, as Deutsch emphasises:

> *Nothing* can move from one moment to another. To exist at all at a particular moment means to exist there for ever. (1997, 263; his italics)

The puzzle is resolved very simply by Everett's formulation. To make an observation is to change the quantum mechanical frame of reference; thus the frame of reference of the observer changes from one moment to the next in the quantum concept of time. This is not a physical process, in the ordinary sense of the word. It is an information process, and a process meta to the linear dynamics of the physical environment. This appearance of collapse is an information process which takes place at a different logical level to the linear dynamics. It is literally a process taking place at a level meta to the physical. This is the elusive component of Everett's formulation.

5.3 Experiential Reality

Everett defines the functional identity of the observer as the record of sensory observations and machine state, which seems a far cry from the identity of a human observer as usually defined, as physical body-mind. However, what Everett defines is the experiential reality of the observer.

The record of observations, external and internal, is intensely familiar to every observer: this is the known world, the experiential reality one knows as 'the world'. This is a mental construct, and it is updated with each new observation. As described in some detail elsewhere (Soltau, 2010b), the record of observations, external and internal, is the actuality of the virtual reality each observer experiences, formulated in the physical brain. As Deutsch states:

> Imagination is a straightforward form of virtual reality. What may not be so obvious is that our 'direct' experience of the world through our senses is virtual reality too. (1997, p. 120)

In other words, not only is imagination an internal construct, as is the experiential reality, so too is the experience of the present moment, which is seamlessly blended into the experiential reality.

The physical brain, along with everything else in physical reality, evolves according to the linear dynamics, giving rise to a superposition-mixture of all possible experiential states. Each experiential state, however, is a specific version of the experiential reality. Hence the appearance of collapse. As Everett states, after observation:

> 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 (1973, p. 10)

While all possible pathways of this collapse dynamics are physically instantiated in the linear dynamics, the subjective passage from singular moment to singular moment is a process of a different logical type to the time evolution of the linear dynamics. This is an information process fundamentally different in kind, i.e. different in logical type, to the physical time evolution of the universe defined by the linear dynamics. 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)

Objectively, all possibilities take place in the linear dynamics. Subjectively, there is the appearance of collapse to a specific outcome, and a new, different, quantum state of the physical environment of the observer.

5.4 Inside and Outside

This difference between the objective and subjective viewpoints has been the cause of much difficulty in comprehending relational quantum mechanics in general and Everett in particular. This difference is explained by the difference between the outside view and the inside view of a quantum mechanical frame of reference, as explained by Tegmark (1997, 1998, 2007, 2010). This is very simply resolved by noticing that Everett defines the functional identity of the observer as a structure of information, the record of observations. Objectively, physically, as a new observation is made, all possible versions of the observation are made, resulting in all possible versions of the observer at the next moment. However, each new version of the functional identity of the observer is a new record of observations, a new structure of information. Moreover, each such structure of information exists, subjectively, in a slightly different version of the physical environment: one in which a specific version of the observation has been determinately made. There is thus a branching reality. As Everett states:

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

In each of the possible versions of the next moment, a different correlation formed with the environment results in a different version of the functional identity of the observer. Subjectively, in each specific version of the possible next configurations of the effective universe, one specific correlation has been formed. Objectively, all the different versions of the functional identity of the observer exist in a physical simultaneity, a superposition decohering almost instantly to a mixture. Subjectively, each record of observations exists in a slightly different version of the physical environment, that defined by the correlations established with that environment, and that alone. This is the difference between the inside and outside views of a quantum mechanical frame of reference, as explained by Tegmark.

Although the inside view seems to be merely a mental phenomenon, thus necessarily happening 'inside' the brain of the observer, it is, nonetheless, solely on this view that there is the change of quantum mechanical frame of reference, a process meta to the linear dynamics. This is Everett's central point.

This information process is utterly familiar to each observer, it is the change of the experiential reality, which, as Deutsch points out, is a virtual reality. The subjective reality experienced is a virtual reality constructed in the mind. In this virtual reality, every observation is a change, an update. Each observation gives rise to the next frame in the rendering of the virtual reality, the inner world, the subjective reality of this observer. This internal process appears to have little or nothing to do with physical reality at the quantum level. Nonetheless, it is meta to the physical. The crucial component of the concept is that the two different states of the experiential reality, the virtual reality before the observation is made, and the virtual reality after the observation is made, are instantiated in different physical environments. This is the basis of Everett's concept. This is why there is the appearance of collapse as an observation is made: the observation is the transition from one quantum state to another, the quantum jump.

5.5 Times Two

Thus, we have two kinds of time. One is the linear time dimension of space-time, the concept we are familiar with. This is the basis of the linear dynamics. Time passes in the linear dynamics, meaning simply that the position of the point of reference of reality moves along the linear time dimension of space-time[2]. As Penrose states:

> ... particles do not even move, being represented by “static” curves drawn in space–time’. Thus what we perceive as moving 3D objects are really successive cross-sections of immobile 4D objects past which our field of observation is sweeping. (1994, p. 389)

Subjectively, the passage of time occurs in the linear time dimension of space-time. In the experiential reality of the observer, the sensorium is constant for a brief moment, the specious present. During this time, the next observation is being formulated. As soon this formulation occurs, and the contents of the sensorium changes, the state of the memory, the record of observations, changes.

As each observation is made, the record of observations changes, and there is a new rendering of the sensorium, a new frame of the virtual reality movie in the brain, defined by a new record of observations. This is instantiated in a new and different version of physical reality. Thus to make an observation is to pass from one physical moment to another. This is the passage of time in the quantum concept of time. Thus there are two different kinds of time.

6 Two Kinds of Time

The two dynamics of quantum mechanics define two different types of time evolution of physical systems. The two different kinds of time are operational at different levels of logical type. Thus, as Lockwood suggests, “... the tensed and tenseless theories of time could both be true, but on different levels.” (2005, p. 70). These two kinds of time operate cyclically, as defined by the standard von Neumann-Dirac formulation of quantum mechanics (1955). Given a relational perspective, quantum mechanics forms a complete concept of the structure of time. This is what has been discovered, but not recognised.

2 At light-speed, as explained by Greene (1999, p. 48).

The linear dynamics defines the probability amplitudes, for possible events, throughout four-dimensional space-time. This is a static array, providing the probabilistic definition of block universe, as in relativity, which shows us that the past, and even the future, exist in the same way as the North and the South. As Deutsch states:

> Spacetime is sometimes referred to as the 'block universe', because within it the whole of physical reality – past present and future – is laid out once and for all, frozen in a single four-dimensional block. (1997, p, 268)

While objectively, linear time is tenseless, subjectively, as Penrose states (1994, p. 389), the passage of time is experienced as the field of observation sweeps past the immobile 4D objects of the block universe. This is the change of the physical or inertial frame of reference of the observer. Using Newtonian mechanics, and given the physical state and physical layout of objects in the world, future states and layouts can be calculated. Thus predictable changes to the inertial frame of reference can be computed. Newtonian mechanics is an approximation of the linear dynamics of quantum mechanics, thus the same principle applies. In other words, within the context of the block universe, changes in the perceptual frame of reference, Penrose's field of observation, the physical frame of reference of the observer, can be computed.

The collapse dynamics is the change of the linear dynamics, thus the two dynamics are of different logical types. These two different kinds of time evolution of physical systems are not only of different logical type, they operate with respect to two different kinds of frame of reference. The linear dynamics defines the change of the physical frame of reference, within the context of the physical environment defined by a specific quantum state: here the quantum mechanical frame of reference. The collapse dynamics defines the change of the four-dimensional physical environment with the change of the quantum state, the change of the quantum mechanical frame of reference. The collapse dynamics thus operates contextually to the linear dynamics. It is to a specific linear dynamics as the transition from frame to frame of a movie is to a specific frame of the movie.

In order to accommodate a dynamics of this logical type, the quantum concept of time is required. As Deutsch describes (1997, Chapter 11) the no-collapse universe is like a multiverse of snapshots, definitions of the state of the whole physical world. As Barbour states, all possible configurations of the complete universe simply exist:

> The Wheeler-DeWitt equation (WDE) of canonical quantum gravity is interpreted as being like a time-independent Schrödinger equation for one fixed energy, the solution of which simply gives, once and for all, relative probabilities for each possible static relative configuration of the complete universe. Each such configuration is

> identified with a possible instant of experienced time. These instants are not embedded in any kind of external or internal time and, if experienced, exist in their own right. (1994, abs)

The no-collapse universe is equivalent to a multiverse of these instants. This is the quantum concept of time. While all possible such instants exist in static array, each one a four-dimensional block universe defined by a specific linear dynamics, the making of observations is the subjective transition from moment to moment, as Everett explains. This is the appearance of collapse that he demonstrates is inevitable given only the linear dynamics in physical reality. This appearance of collapse is nonetheless a process 'outside of' or meta to the linear dynamics, just as the transition from one frame of the movie to another is a process 'outside of' or meta to an individual frame.

Everett states:

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

by this he means that:

> While our theory ultimately justifies the use of the probabilistic interpretation as an aid to making practical predictions, it forms a broader frame in which to understand the consistency of that interpretation. (p. 462)

By taking quantum mechanics at face value, the universe is defined by the unitary linear dynamics, giving rise to all possible configurations of matter and energy. Objectively, this array or simultaneity is unchanging. Moreover, as he also states, there is no change to the physical system on observation:

> *... it is not so much the system which is affected by an observation as the observer, who becomes correlated to the system.* (1973, p. 116; his italics)

The quantum jump is a purely subjective process. There is only the appearance of collapse. This view has no conflict with relativity. S ince the frame of reference is that of a specific, individual observer, a unique global simultaneity is inherent. It is the subjective 'now' in the functional frame of reference of a specific observer, with which every observer is so immediately familiar.

This 'now' is defined in differently in the kinds of time, since the two dynamics are of different logical type. With respect to the linear time dimension of space-time, the now is defined as a specific clock time, a specific position along the time dimension of space-time. With respect to Newtonian mechanics, relativistic mechanics, and the linear dynamics of quantum mechanics, this position on the time dimension of space-time defines a specific physical or inertial frame of reference. Change of this position on the time dimension of space-time results in change of the physical frame of reference, and correspondingly different three-dimensional spatial arrangements of matter and energy.

With respect to the quantum concept of time, the now is defined by the quantum state of the effective physical environment, the specific "... static relative configuration of the complete universe." (Barbour, 1994, abs). Change of the quantum state effective for the observer is the appearance of collapse, the transition of the functional frame of reference of the observer from one now, one 'static relative configuration of the complete universe', one quantum mechanical frame of reference, to another.

7 Conclusion

The nature of the collapse dynamics has been a paradoxical puzzle since the inception of quantum theory. Everett takes quantum mechanics at face value, and the paradoxes are dissolved. The time evolution of the physical universe unfolds in accordance with the linear dynamics. This is the progression of the now of the linear dynamics, along the linear time dimension of space-time. At the point in time along the linear time dimension of space-time at which a new observation is formulated, thus being added to the short-term memory of the observer, the record of observations changes. The new record of observations is instantiated in a new and different quantum mechanical frame of reference, as described in detail elsewhere (Soltau, 2010a). This is the change of the now of the collapse dynamics, from one quantum mechanical frame of reference to the next.

Each such now in the collapse dynamics is the specious present of this observer. This is the brief period of time during which the experiential reality, the contents of the sensorium, and, concomitantly, the effective quantum state of the physical environment, remains constant. During this specious present, this now in the quantum concept of time, the perceptual frame of reference progresses along the linear time dimension of space-time: the now in the linear dynamics progresses towards the future. As this progression takes place, a new observation is formulated in the sensorium of the observer. At the point in time, along the linear time dimension of space-time, at which this new observation is formulated, and thus added to short-term memory, the record of observations changes, and the cycle repeats. Thus, subjectively, the cyclical dynamics of the standard von Neumann-Dirac formulation of quantum mechanics (1955) is enacted.

The experience of the passage of time is the experience of the exercise of the linear dynamics, and the experience of change is the experience of the appearance of collapse, the subjective transition from one quantum mechanical frame of reference to another.

Given relativity as the prior and fundamental nature of the space-time universe, it is natural to expect the time evolution of the physical, as defined by quantum mechanics, to fit into this four-dimensional space-time framework. While this gives no problems with respect to the linear dynamics, this does not work for the collapse dynamics, hence a century of confusion and uncertainty about the nature of time in physics.

The great puzzle about quantum theory is that only the linear dynamics seems to be a physical dynamics; the collapse dynamics, has eluded comprehension. The linear dynamics of the overall system is laid out in the linear time dimension of space-time. In a no-collapse universe this defines all possible branching sequences of events, and all possible consequent states of a physical universe. This is the dynamics of the universe objectively and it cannot change: it subsumes all possibilities. Decoherence ensures that each possible variation of the state of the universe is determinate to a fine level of detail under most circumstances, but all such variations exist simultaneously in a mixture.

Objectively, the time evolution of the universe is linear time, progression along the time dimension of space-time. Subjectively, there is an additional process, the appearance of collapse, the sequential changing of the definition of the effective physical environment, as a succession of new correlations is made with the environment. Thus there are two different types of time evolution in the two different types of frame of reference.

Linear time, progression along the linear time dimension of space-time, is experienced as the passage of time, within the context of a specific quantum mechanical frame of reference. 'Collapse time', progression from one quantum mechanical frame of reference to another, is experienced as change.

Linear time can be understood as tenseless, since the entire progression of linear time is pre-existent in the block universe defined by the quantum state defining the linear dynamics: there is, for all points in space-time, a fixed truth value, the specific probabilities of events, given by a specific quantum state. Collapse time can be understood as tensed: the truth value of the probability amplitudes of events at a specific space-time location may vary with collapse time.

References

Barbour, J.: 1994, “The timelessness of quantum gravity: II. The appearance of dynamics in static configurations”, *Classical and Quantum Gravity*, Volume 11, Issue 12, pp. 2875-2897.

Barrett, J.: 1998, “Everett's Relative-State Formulation of Quantum Mechanics,” available online at http://plato.stanford.edu/entries/qm-everett/

Callendar, C.: 2007, “Finding 'Real' Time in Quantum Mechanics”, p ublished in Einstein, Relativity and Absolute Simultaneity. (Eds) W.L. Craig and Q. Smith. Routledge.

Davies, P.: 2002, “That Mysterious Flow”, *Scientific American Magazine*, September.

Everett, H.: 1957, “‘Relative State’ Formulation of Quantum Mechanics”, *Reviews of Modern Physics* 29: 454-462.

Deutsch, D.: 1997, *The Fabric of Reality*, Allen Lane The Penguin Press, London.

Folger, T.: 2000, “From Here to Eternity”, Discover Magazine (December 2000) interview with Julian Barbour.

Greene, B.: 1999, *The Elegant Universe*, Johnathon Cape, London.

Lockwood, M.: 2005, *The Labyrinth of Time*, Oxford University Press Inc., New York.

Markosian, N.: 2002, “Time”, available online at http://plato.stanford.edu/entries/time/

Penrose, R. 1994. *Shadows of the Mind*. Oxford: Oxford University Press.

Rovelli, C.: 1996, “Relational Quantum Mechanics”, available online at http://arxiv.org/abs/quant-ph/9609002/

Russell, B.: 1908, "Mathematical Logic as Based on the Theory of Types," American Journal of Mathematics, 30, 222-262. Repr. in Russell, Bertrand, Logic and Knowledge, London: Allen and Unwin, 1956, 59-102, and in van Heijenoort, Jean, From Frege to Gödel, Cambridge, Mass.: Harvard University Press, 1967, 152-182.

Soltau, A.: 2010a, “The Quantum Mechanical Frame of Reference”, available online at http://philsci-archive.pitt.edu/archive/00005544/

Soltau, A.: 2010b, “The World Hologram”, available online at http://philsci-archive.pitt.edu/archive/00005551/

Tegmark, M.: 1997, “The Interpretation of Quantum Mechanics: Many Worlds or Many Words?”, available online http://arxiv.org/abs/quant-ph/9709032v1

Tegmark, M.: 1998, “Is "the theory of everything" merely the ultimate ensemble theory?”, available online at http://arxiv.org/abs/gr-qc/9704009v2

Tegmark, M.: 2007, “Many lives in many worlds”, available online at http://arxiv.org/abs/0707.2593v1

Tegmark, M.: 2010, “Many Worlds in Context”, available online at http://arxiv.org/abs/0905.2182v2

t'Hooft, G.: 1973, “Dimensional Reduction in Quantum Gravity”, available online at http://arxiv.org/abs/gr-qc/9310026v2

von Neumann, J.: 1955, *Mathematical Foundations of Quantum Mechanics*, Princeton: Princeton University Press. (Translated by R. Beyer from Mathematische Grundlagen der Quantenmechanik, Springer: Berlin, 1932.)