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Clocks and Time

Arlen Anderson*
Dept. Physics
UNC-Chapel Hill
Chapel Hill NC 27599-3255

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Abstract

A general definition of a clock is proposed, and the role of clocks in establishing temporal pre-conditions in quantum mechanical questions is critically discussed. The different status of clocks as used by theorists external to a system and as used by participant-observers within a system is emphasized. It is shown that the foliation of spacetime into instants of time is necessary to correctly interpret the readings of clocks and that clocks are thus insufficient to reconstruct time in the absence of such a foliation.

*arley@physics.unc.edu

"How does one know what time it is?" The standard retort is, "by consulting a clock!" This answer is probably as old as the quantum theory itself, but is that answer glib, or does it withstand scrutiny? What is a clock, and does it faithfully reflect time?

This question, how one knows what time it is, is a central challenge in quantum gravity and underlies many of the problems of time and the proposals to resolve them[1, 2, 3]. Recently Kuchař[4] has criticized Rovelli's "evolving constants of motion"[5] with a question closely related to this, and this is discussed in [6]. The prominent need to identify time arising in Wheeler's program[7] of the "3-geometry as the carrier of time" is well known, but a discussion focussing on the Wheeler-DeWitt equation is subject to unnecessary technical distraction. On the other hand, virtually all questions in quantum mechanics implicitly carry time preconditions, so the need to "know" time is ubiquitous. In view of the broad significance of this question and recent interest in clocks (e.g. [8]), a general discussion of the relation between clocks and time is called for.

1 The Nature of Clocks

When one asks, "what is the position of particle-a?", one implicitly assumes "at time t." But how does one know what time it is? By consulting a clock? Consider the question, "what time does the clock show?" Necessarily the question again implicitly assumes "at time t," but one cannot now answer that one knows the time t by consulting the clock. Instead one relies on a primitive immediacy[9] in the understanding that it is "at this moment as I ask the question," which becomes "at this moment as I make the observation" when one seeks the answer.

When talking about time in quantum physics, it is prudent to distinguish two points of view about time which are wont to be conflated. One is the time of the theorist who has access to the full wavefunction of the universe. The other is the time of a participant-observer who must make measurement-observations of other subsystems to obtain markers of particular instants. It is the participant-observer who must rely on primitive immediacy, or the sense of "now." The theorist can look at a map of the spacetime history of a system and, pointing with a finger, ask, "what time does the clock show—here?" Neither can answer in any absolute sense what time t it is, not at that moment "now" nor at that place in spacetime, but then they don't need to. Time itself is not being measured because no value for t is returned by a measurement-interaction. One does not need to know t to be able to measure an observable: one can measure the self-adjoint operators which are convenient to measure, and these are necessarily instances of observables[6].

One of the challenges of dealing with time in quantum cosmology is to reconcile these two points of view. As theorists, our goal is to find the map which is the spacetime history of the wavefunction of the universe. And, as participant-observers within the universe, our desire is to translate that map into an understanding of what we may experience. We must be able to move back and forth between the two points of view comfortably.

There are cautionary difficulties however. We are far more limited in our observational capacity as participant-observers than we are as theorists. Given the full wavefunction of a system, it is easy to see the details of the states of its component subsystems. As one of those subsystems, it is far more difficult to deduce that information through measurement-observations. In particular, there are limitations on the nature of couplings that we are allowed as observing subsystems. Furthermore, it is in the nature of theorists to idealize component subsystems to their "essential" elements and in particular to minimize their numbers of degrees of freedom. These features of the different realms run at cross purposes.

For instance, there is a danger of confusing the difficulty of the participant-observer to learn some piece of information that is obvious to the theorist with the absence of that information. In the participatory realm, one must remember that not all observers are physicists and they have no need to "know" more than it takes them to evolve properly under the dynamics. Thus, suppose one has a system consisting of a clock-subsystem and subsystems -a and -b. Subsystem-a does not have to have the necessary couplings to be able to measure the clock's state in order to interact with subsystem-b nor for time to pass. When the theorist speaks of subsystem-a as the observer, and says that it makes a measurement when the clock reads, say 2:00, subsystem-a does not have to verify (or be able to verify) the truth of that statement when it makes the measurement.

When discussing time, it has become popular to insert clocks into systems to label time or to speak of certain subsystems as being "the clock." This is an unnecessary device of convenience to aid the theorist. Time does not become any more real because there are readily identifiable clocks present in a system. This will become clearer when clocks are defined and discussed below.

Turning the situation around, the theorist must be wary of the fact that models with few degrees of freedom may impose limitations that are not present in larger systems. For instance, suppose that the theorist is concerned that the observer-subsystem be able to read the state of a clock many times to observe the passage of time. If the full system is not sufficiently complicated, the theorist may find that the interaction between the observer and the clock "saturates" so that no further distinct measurements are possible. This is an artifact of the idealized nature of the system. It should be a concern whenever one insists on modelling all interactions.

Following these general remarks, it should not be disturbing that there are theorems that time cannot be observed by measuring a self-adjoint operator[10, 11, 12]. More precisely, there is no self-adjoint operator whose expectation value increases monotonically in correlation with time for quantum systems whose Hamiltonian is bounded from below. Generally one finds that there is a non-vanishing amplitude that the putative time will run backwards. Since we have no great direct need as participant-observers to measure time itself, our inability to do so is not an insurmountable loss.

Our desire to measure time is driven by our perception of dynamics as theorists. We think of dynamics as parametrized by a time t, and we want to coordinate this time with the flow of (participatory) physical time in order to translate our theoretical considerations into practical predictions. Our access to time even as theorists is more limited than we may be accustomed to believe. This is because our experience with Newtonian dynamics creates an intuition about a rigidity to time and spacetime slicing which is not present in a time-reparametrization and diffeomorphism invariant theory like general relativity. Of course we recognize that an easy way to deal with this is to look for diffeomorphism invariant markers, that is, for correlations amongst physical states. This is how clocks are often used: they are time-markers. One can identify where one is in the time continuum by specifying one's position in relation to a sequence of clock readings.

In the context of quantum theory, one does not even need to "know" one's relation to the time-markers or clock states; it appears sufficient for there to be a condition of correlation. The idea here[13] is that much of quantum mechanics is based on conditional statements like "if spin-b is down, then spin-a is up with certainty." Such statements are the post-Everett interpretation of the meaning of product states like $|\uparrow\rangle_a |\downarrow\rangle_b$. If our knowledge of time is simply through condition of correlation, then statements involving time reduce to familiar conditional statements of quantum mechanics: "if the clock reads 2 o'clock, the particle is at position x."

In the conditional probability interpretation, one does not measure time by computing the expectation value of a self-adjoint operator against the state of the clock (as assumed in the no-go theorems). Rather one understands in the post-

Everett sense that such measurement has implicitly taken place when "a correlation is established through interaction." The conditional statement "if the clock reads 2 o'clock, the particle is at x with certainty" is the interpretation of the product state $|x\rangle|2{:}00\rangle$. Admittedly, the status of conditional statements in quantum mechanics is not universally agreed upon, with a large segment of the community holding that a major part of the measurement problem in quantum mechanics is to explain how one establishes the truth of pre-conditions in conditional statements. But, at least one hopes that statements referring to time are no worse than any other conditional statements. This is what we will investigate.

Let us examine this picture of conditional correlation more closely. In the correlation of a pair of spin one-half states, one can pose and answer the linguistically symmetric questions "what is the state of the first spin given that the second is down?" and "what is the state of the second spin given that the first is down?" These questions are on an equal footing physically. Contrast this with the questions "where is the particle at time t?" and "when is the particle at position x?" These questions are linguistically symmetric, but they are not on an equal footing physically. The former question can be answered by giving a probability distribution, but it isn't clear what answer if any can be given to the second in conventional quantum mechanics.

In quantum mechanics, it is the existence of exhaustive and exclusive sets of alternatives that allows us to give probability distributions as answers to questions, or more precisely as predictions of the outcomes of experiments to answer questions. With spin one-half states, when the spin is measured in the z-direction, it can either be up or down but not both. In each measurement, some alternative must occur, but no more than one does occur. For a particle position at a given time, the following statements are satisfied

- Every object is somewhere.
- No object is in more than one place.

The first statement assures that position at a moment of time is exhaustive and the second that it is exclusive. The analogous statements about position in time at a given spatial location are not generally satisfied. An object need never be at a particular place or it may be there many times.

That alternatives in temporal location at a given place do not form an exhaustive and exclusive set indicates a fundamental asymmetry between space and time in conventional quantum mechanics. It is easy to trace this asymmetry to the fact that states are essentially superpositions of alternatives at moments of time (or on spacelike hypersurfaces, which correspond to the notion of a moment of time in curved spacetime). This reveals something about the correlation picture of clocks. Since conditional statements about a pair of physical states are symmetric, statements about a system and its clock are symmetric. This is because the possible states of the clock and the states of the system both come from exhaustive and exclusive sets. The implication is again that a clock is not a direct reflection of time.

As a precise and general definition of a clock, I propose the following: a clock is any subsystem with whose motion another subsystem may be correlated. In what sense does this definition describe a clock? Perhaps the most fundamental feature of time[14] is the uniqueness and distinguishability of different moments of time. Unruh and Wald[10] refer to this as the Heraclitian nature of time. In product states representing the correlation of one subsystem with another, in so far as the motion of one subsystem passes through distinct states, these reflect distinguishable moments of time. The subsystem acts as a clock in that it allows moments of time to be distinguished.

By this definition, almost everything is a clock. There is however a difference between how a clock is viewed by a theorist and by a participant-observer. A glass of water standing on a table serves as a clock because its internal quantum state varies from moment to moment. From my perspective, looking at it with my eyes, I cannot perceive the differences between these states. I can only appreciate the glass of water as a clock on the much longer time scale when there are changes of water level through evaporation. This leads to the conclusion: to a theorist, anything can serve as a clock, but an observer won't necessarily be able to read it!

Interestingly, in conflict with the desire to distinguish instants, we are accustomed to associate "good" clocks with periodicity, in which a given physical state of a clock refers to a sequence of times. I would argue that periodicity is important for a secondary function of clocks, namely for measuring uniform intervals of time. Uniform periodicity is useful in synchronizing and in verifying accuracy of clocks. It is by observing other factors that periodicity is broken and distinct moments are recognized: the minute hand advances after each cycle of the second hand; the date changes each time midnight comes again. If one were not concerned with measuring intervals of time, but only with distinguishing moments, periodicity would not be important and indeed might be a negative feature.

Another attribute widely expected of clocks is the ordering of the instants of time. This is not implied by the definition of clock given here. In so far as a subsystem can be seen as moving through a sequence of states under deterministic evolution, this motion provides an ordering to that sequence of states and hence to the moments of time they label. Independent of this motion however, there is not generally an ordering on the possible states of the clock subsystem. This is important for example in (classical) general relativity where each spacelike slice through a 4-manifold solution of the Einstein field equations is an instant of time, the clock-state being the 3-metric and its conjugate momentum on that slice. There is at best a partial ordering of these spacelike slices. One can choose to focus on foliations which have a definite ordering, but clock-states are defined by every spacelike slice.

Returning to the issue of periodicity, consider the correlation question, "where is the particle when the clock reads 2 o'clock?" The answer to this question is a member of a set of exhaustive and exclusive alternatives only if one implicitly assumes that one means one of the unique moments when the clock reads two o'clock. If the unique moment is not identified, the particle may be in more than one place. The problem is the same as that above when asking "when is the particle at position x?" This is important because it undercuts the conditional correlation picture. The conditional is only meaningful when identification of the unique moment is assured. Then one is guaranteed that there are an exhaustive and exclusive set of alternatives.

Ultimately, the uniqueness of each moment of time is reflected only in the uniqueness of the state of the full system, including all its clocks. Because the equations of motion for states are deterministic, if the initial data for the full system reoccur, the exact evolution of the system repeats, and in such case time is truly periodic. Suppose however that attention is restricted to a subsystem, as it usually is in practice. It is always possible to arrange, by adding appropriate degrees of freedom external to the subsystem and controlling their interaction with the subsystem, that the subsystem repeats its state without the state of the full system repeating. Time itself does not repeat, but one cannot use the subsystem to confirm this. Thus, no subsystem in isolation can be wholly reliable as an indicator of the passage of time.

By introducing the notion of clocks, one has made the measurement of time and space seem more symmetric, but the apparent progress only reveals further trouble. The measurement situation is indeed symmetric, but where before there once was a problem with conditionals based at a position in space, now there is a problem with conditionals specified at a moment of time because subsystem clocks do not always successfully identify unique moments. The original question stands only mildly modified: how does one identify the unique moment of time? I have given the answer above: the unique moment of time is only unambiguously identified by the full state of the system. This is not something one can set out to measure from within. There is no Great Clock Variable that is present in all situations which we as participant-observers can consult to see what time it is. We are forced to accept that our ability to measure time is not absolute.

Is this really a problem? No. As participant-observers, we have a perception of unique moments and we use that perception to improve on our clocks. Truly we may only be consulting a biomechanical system with a large number of degrees of freedom which is not locally periodic, but that stands adequately as a representative of the full state of the universe. That it is possible in principle for any subsystem to repeat its state without the full system doing so, and that therefore no subsystem can be assured of being a perfect clock, is of no concern—if we are not looking for a Great Clock Variable! We are working within a small spacetime domain and we only require that our measurement of time is adequate within that domain.

This argues that we should be satisfied with our clocks even though we can construct mathematical examples in which models of them are inadequate. The impudent answer by a participant-observer to the question of how one knows what time it is, is that "I *know* what time it is when I consult a clock." I know this in the sense that I have the perception that I can distinguish that moment from other moments. A theory of consciousness is not needed, only a non-periodic subsystem with sufficiently large numbers of degrees of freedom to distinguish between the different periodic moments of the clock. Does something have to explicitly keep track for the moments to be different? No, it is sufficient that the state of the full system is different. If you like, the state of the environment is what guarantees that clocks refer to unique moments. Our internal perceptions are simply a symptom that the environment of the clock is different each time it repeats its state.

One might even be tempted to say that the environment decoheres the different instants of time, or more accurately that it decoheres the different clock readings so that they distinguish different moments of time. This is an intriguing picture, but one must be careful if one tries to take it literally. Different clock states occur at different moments of time and while one may compute matrix elements between them, this is not what one would do in the usual (Zurek) density matrix decoherence picture.

By inspecting the evolution of a particular full system, one may determine that the state of some subsystem does not repeat. That subsystem then serves as a clock to distinguish instants for the full evolution, but it is only known to be adequate because the full evolution has been consulted. The point here is that there is no single Great Clock Variable that will serve as a clock in all systems. It is futile then to look for such a time variable, be it an intrinsic or extrinsic time, to interpret the wavefunction of the universe obtained from the Wheeler-DeWitt equation. I emphasize that this is not to say that time does not exist on super-phase space (the space of 3-metrics and their conjugate momenta). It does, but it is not so easily captured as to admit representation in a single functional combination of the 3-metric and its conjugate momentum for all spacetimes. It seems entirely plausible given the freedom in initial data that any such functional combination can be made to repeat by suitable choice of initial data.

2 A *Gedanken* Experiment

To illustrate the distinction between a theorist's clock and one of a participant-observer, consider a free particle-a and a subsystem-b, described by the Hamiltonian H_b, which do not interact. The super-Hamiltonian is

$$\mathcal{H} = p_0 + \frac{1}{2}p^2 + H_b. \tag{1}$$

Since particle-a is free and uncoupled from subsystem-b, it can be prepared at $t = 0$ as a normalized Gaussian, $\psi_a(q,0) = \pi^{-1/4}\exp(-q^2/2)$. The variance of this Gaussian will grow as the state evolves. The full system can be prepared as a product of this state and the evolving state of subsystem-b

$$\Psi(q,x,t) = \psi_a(q,t)\phi_b(x,t). \tag{2}$$

The point is that, by the definition above, particle-a acts as a clock because its state distinguishes moments of time. It is however a clock which is never physically read by subsystem-b. It is a theorist's clock. One can use it to pose conditional questions: "what is the state of subsystem-b when the clock-state (particle-a) is $\psi_a(q,t_0)$?" Note that it is a perfect clock even though it is described by a Hamiltonian which is bounded from below. This does not violate the theorems quoted above because no self-adjoint operator is introduced to attempt to read the time by taking expectation values.

This clock is used differently than one might naively expect. One doesn't compute the conditional by projecting $\psi_a(q,t_0)$ on $\Psi(q,x,t)$—there would be nonzero overlap for all t. In a very real sense, the sequence of states $\psi_a(q,t)$ are the moments of time. They are the only readings the clock is allowed to take and they uniquely correspond to temporal locations in the evolution of the full system.

Consider the situation when subsystem-b is not in a product state with the clock. Take the simple superposition

$$\Psi'(q,x,t) = \psi_a(q,t)\phi_b(x,t) + \psi_a(q,t+\Delta)\phi'_b(x,t). \tag{3}$$

The clock-state associated to the second term in the superposition is the same as in the first term only advanced by time Δ. Here, the full system state denotes a unique moment of time, but the clock subsystem seems to refer to more than one instant. Suppose one asks what the state of subsystem-b is when the clock-state is $\psi_a(q,t_0)$. This question only makes sense if it is completed by the information of what time t it is! If the time were $t = t_0$, the state would be $\phi_b(x,t_0)$. If the time were $t = t_0 - \Delta$, the state would be $\phi'_b(x,t_0-\Delta)$. One needs sufficient additional information to determine which eventuality occurs. This hints at an essential inadequacy of clocks as surrogates for time.

To amplify on this, consider a *gedanken* experiment in which this situation could arise. Let an observer-scientist experience the experiment as part of a subsystem-a. Suppose that subsystem-a (the scientist and her equipment) is initially coupled to both subsystem-b and clock-c so that it can monitor both. For definiteness, let clock-c be an ordinary (nearly classical) mechanical clock, and take subsystem-b to be a spin one-half particle precessing in a magnetic field. Assign the rest of the universe to subsystem-e (the "environment").

As an element of subsystem-a, the scientist has a sense of "Now." Occasionally she looks at clock-c, and she observes a sequence of readings with which she chooses to label the sequence of "Now" instants. She also inspects subsystem-b and prepares it in an initial state. At this moment, the initial state of the full system is a product state of the states of clock-c and subsystems-a, -b and -e.

The scientist puts subsystem-b and clock-c in a rocket and then closes herself in her lab-bunker—which does not contain a clock—preparatory to doing a Schrodinger-cat-like experiment. Her experiment consists of a trigger (consider it to be part of subsystem-e) which takes the form of a spin one-half particle with spin up in the z-direction entering a Stern-Gerlach apparatus with magnetic field in the x-direction. If the spin leaves to the right (spin up in the x-direction), nothing happens. If it leaves to the left, clock-c and subsystem-b are launched in the rocket and later return to the lab. The rocket completes its journey sufficiently fast for its clock to be 1 minute behind what a clock would read that did not make the journey (i.e. a twin-paradox effect).

The scientist waits a sufficiently long, but unknown, time, and leaves her lab. Prior to opening the rocket, the state of the full system is

$$2^{-1/2}|S;t\rangle_a(|\omega t\rangle_b|t\rangle_c|+x,\mathcal{E}\rangle_e+|\omega(t-1)\rangle_b|t-1\rangle_c|-x,\mathcal{E}'\rangle_e). \qquad (4)$$

When the scientist opens the rocket and looks at clock-c, she predicts the precession of the spin in subsystem-b. She then verifies that she is correct. Even though she can make this conditional probability calculation correctly, she cannot determine whether the rocket took the journey or not without looking at subsystem-e. Therefore she has no way to determine how much laboratory time has elapsed. As one expects from special relativity, clock-time is not an absolute measure of time. Clock-c has a known correlation with the motion of subsystem-b and is therefore sufficient to determine that the time-precondition of a quantum mechanical question is satisfied. Clock-c does not have a known correlation with subsystem-a, the laboratory, and cannot be used to establish time-preconditions.

Note that the scientist's sense of "Now" is also not a measure of time—it distinguishes instants, but it does not measure intervals. The measure of time is one of the attributes of clocks beyond merely distinguishing instants.

Consider a second scenario. The scientist leaves her bunker, inspects subsystem-e and determines that the rocket took its journey. Then knowing the path of that journey, she computes the twin-paradox effect. When she looks at the clock, she can deduce how much laboratory time has passed. Clock-c becomes sufficient as a measure of laboratory time because she knows how its motion correlates to the motion of the laboratory. One concludes that in order to use a clock to establish the time pre-condition of a quantum mechanical question it is necessary that the motion of the clock have a known correlation with the subsystem of interest.

As the final and most revealing scenario, suppose that during the rocket's journey, it flies through a magnetic field which perturbs the spin-precession experiment. The scientist does not know about this because it is an unmodelled consequence of interaction between subsystem-b and subsystem-e. For definiteness, suppose that at 2:00 in the rocket which did not make the journey, the spin is up in the z-direction while at 2:00 in the rocket which did make the journey, it is down. Because of the twin paradox delay, there are two spacetime events involved, say t_1 and t_2 in terms of an external labelling by a theorist. The state of the clock, spin and scientist at these times are

$$
\begin{array}{lll}
t_1 & : & 2^{-1/2}(|S_1;t_1\rangle_a|\uparrow\rangle_b|2{:}00\rangle_c|\mathcal{E}_1\rangle_e + |S_1';t_1\rangle_a|\downarrow -\epsilon\rangle_b|1{:}59\rangle_c|\mathcal{E}_1'\rangle_e) \\
t_2 & : & 2^{-1/2}(|S_2;t_2\rangle_a|\uparrow +\epsilon\rangle_b|2{:}01\rangle_c|\mathcal{E}_2\rangle_e + |S_2';t_2\rangle_a|\downarrow\rangle_b|2{:}00\rangle_c|\mathcal{E}_2'\rangle_e)
\end{array}
\tag{5}
$$

As outsiders who are privy to the wavefunction of the full system and to an external time labelling, we can pose and answer the question, what is the probability, after the scientist looks at the clock, that she will correctly predict the spin-precession? The answer of course is that it equals the probability that the rocket did not take the journey.

Suppose she looks at clock-c, but not at subsystem-b. We pose the conditional question, "what is the state of subsystem-b when she sees that clock-c reads 2:00?" This is the same peculiar situation as above where there was a superposition state containing a free particle-clock at two readings. She will see clock-c read 2:00 at two different spacetime locations, depending on whether the rocket made its journey or not. This is not a conditional question posed at a single instant of time. The clock does not act effectively to specify a moment of time.

I emphasize that this has happened even though the clock is, for all intents, perfect. The clock is effectively classical, and nothing disturbs it during the course of the experiment. Any trouble cannot be attributed to the clock itself. Clearly, a similar outcome could be achieved with a defective clock or a clock whose evolution is disturbed by some quantum evolution, but then one might argue that the situation reflects some failure in the clock. Here, there is no such failing and yet the clock does not fulfill its function from the perspective of one outside the system.

Certainly, within the system, the scientist can perform her experiment of reading the clock and checking the spin, and she will find definite outcomes. She will be surprised that the clock is not correlated with the spin in the branch where the rocket made its journey, but that is the extent of it. If she repeats the experiment many times, she will discover that the correlation of clock and spin is broken half of the time. By measuring other directions of the spin, she can determine that the state of the spin is incoherent. As a participant in the time flow of the universe who therefore has a sense of the passage of time, nothing especially unusual about this situation is apparent to her. It is in the attempt to inspect the full system from outside that there are potential difficulties.

3 The Inadequacy of Clocks

To comprehend the significance of this situation, consider the situation as analogous to what one confronts in a traditional Wheeler-DeWitt approach to canonical quantum gravity. One is given a super-Hamiltonian constraint. This argument is not really about gravity, so the super-momentum constraints can be ignored. For definiteness, suppose the super-Hamiltonian describes an experiment similar to the *gedanken* experiment above. There is a clock correlated to a spin, and there is a quantum event which produces a motion leaving the clock-spin subsystem in a superposition with the same clock reading occuring at different spacetime locations. Suppose that one succeeds in solving the super-Hamiltonian constraint corresponding to the described experiment to obtain the wavefunction of the universe. The difficulty one faces is that one does not know which variable or combination of variables in configuration space is time. More particularly, one doesn't know what constitutes an instant of time, so one doesn't know how to foliate spacetime into spacelike slices. This means that one doesn't know how to classify alternatives into exhaustive and exclusive sets.

One turns to the notion of a clock. The proposal has been made to inspect the state of the full system and identify the state of subsystem-c, the clock. Because of the dynamics of the system, this state is correlated to the state of subsystem-b and seems a likely surrogate for time. Inspecting the wavefunction of the universe, one sees that there are two events where clock-c reads 2:00 and that at these events the state of the spin is up in one and down in the other. One wants to know what this says about the state of the spin when the clock reads 2:00. Is the state "$2^{-1/2}(|\uparrow\rangle_b + |\downarrow\rangle_b)$" or is it "$|\uparrow\rangle_b$ or $|\downarrow\rangle_b$ with probability 50%"? One cannot answer this unless one knows whether the events labeled by 2:00 occur on the same spacelike hypersurface or on different hypersurfaces. But one doesn't know this, and the clock can't help!

One is forced to conclude that clocks cannot stand in place of the knowledge of the spacelike foliation on which exhaustive and exclusive alternatives are defined. A clock can have the same reading at more than one spacetime event. If the events are spacelike separated, one expects a coherent superposition of alternatives, given a clock reading. If the events are timelike separated, one expects an incoherent collection of alternatives. It may even be that when there are an infinite number of timelike separated events with the same clock reading, one cannot normalize a probability distribution for the outcomes correlated to that reading.

A clock is a useful device for distinguishing moments of time for participant-observers who have an "experiential" sense of time. This is in the sense that by virtue of distinctions in their own state, they can distinguish moments, even if they are not "consciously" self-aware. The usefulness of clocks in interpreting the wavefunction of the universe is more limited. In particular, it relies crucially on knowledge of the Hilbert space structure and the associated foliation of spacetime into instants of time. Knowledge of the instants of time is necessary to collect alternatives in exhaustive and exclusive sets. It is also necessary to determine whether the correlation with a given clock reading is coherent or not. Clocks cannot be used to deduce the Hilbert space structure or the foliation of spacetime into instants of time.

4 Quantum Spacetime Events

An alternative worth considering is whether conventional quantum mechanics can be modified in such a way that conditional statements involving time always have well-defined answers. This would restore the symmetry between space and time. This could be accomplished if there were exhaustive and exclusive sets of alternatives that refer to time. It was mentioned above that the temporal analog of the statements about positions in space are untrue. If one deals with events in spacetime as the analog of positions in space, then one can formulate an exhaustive and complete set of alternatives. One has the statements

- Every event is somewhere in spacetime.
- No event is in more than one location in spacetime.

By virtue of these, one can assign a probability distribution to the location of events in a spacetime manifold.

Comparison with the spatial analog shows that working with these is equivalent to quantizing the location of the spacetime events in a manifold. Because every event must be somewhere and can't be in more than one place, one can assign an amplitude to the location of events. To formulate a quantum theory of this amplitude, one can associate four spacetime "coordinate" variables and their conjugate momenta with each event. These can be taken to satisfy canonical commutation relations (at least in the simplest case). The eigenvalues of the coordinate variables would refer to the location of their event in spacetime. This is in analogy to the spatial case where three spatial coordinate variables refer to the spatial location of each particle.

A simple model illustrating this is a discrete lattice model of spacetime. Each point of the lattice is an event. Because each event is quantized, there is a wavefunction describing the displacement of the actual event in the manifold from its lattice site. The wavefunction of the full lattice is the product of the wavefunctions at each site. This gives one a truly quantum spacetime geometry. One can pose questions asking about the location of a given event and there will be a *bona fide* probability distribution as an answer. The details of the wavefunction of the lattice ("wavefunction of the universe") will of course depend on the equation which relates the wavefunctions at different sites.

It is not difficult in this picture to imagine how time slices and quasiclassical geometry arise when the fluctuations of events around their lattice sites is small. It is more difficult to imagine how matter degrees of freedom could be put into this dynamical background and be made to evolve. While quantizing the location of events makes the interpretation of the quantum spacetime picture tractable from the outside, one is faced with the issue of how it would appear from within the system. One does not expect that there are operators which measure the location of particular spacetime events. To other subsystems, then, spacetime events should appear as identical particles, possibly fermions so that no two events can occupy the same location in the manifold. A correlation picture seems natural in which matter states are correlated with states for collections (regions?) of events. This is admittedly vague, and further work is obviously needed to make these ideas precise.

Such a picture could not be elaborated into a realistic toy model of quantum gravity unless one were able to meet two serious criteria. First one requires that when quantum fluctuations are turned off and events lie in the equilibrium positions of some quantum potential, they take positions such that the lattice corresponds to a solution of Einstein's field equations. The ability to do this is difficult because of the second problem: the theory should not depend on an *a priori* background. In particular, one should not measure displacement of an event from its lattice site in a fixed background, else the final structure will depend on this background. The requirement of a background independent formulation is a serious obstacle to parlaying this picture into a model of quantum gravity, even at the level of Regge calculus.

At the level of a toy model however, the idea of quantizing spacetime events is attractive because it fits naturally with the goal of being able to ask questions in quantum theory which involve the time. A similar conclusion was reached independently in recent work of Isham and Linden[15]. They were studying quantum temporal logic in connection with Gell-Mann and Hartle's consistent histories formalism. They found that putting a quantum logic structure on propositions about histories led to the idea of imposing independent commutation relations on variables at each spacetime event. While they have not elaborated on the meaning of such a quantization, it is clearly related to the situation described here.

5 Conclusion

Time is a central feature of our experience as participant-observers in the universe, yet we do not measure it directly. We are accustomed to confirming our sense of the passage of time by observing the changing state of various dynamical systems, and we recognize these systems as clocks. Indeed it is this observation of change which constitutes our recognition of the passage of time, and in a general sense, any subsystem whose motion we may correlate with is a clock: by its changing state, we may distinguish instants of time.

From an external vantage as a theorist inspecting the full wave function of a system, any subsystem whose motion is correlated with that of another subsystem serves as a clock for that subsystem, whether the capacity to observe the correlation is present or not. Generally, non-trivial correlation indicates some interaction between the subsystems, so there is a form of observation between them, but correlation can be built in through the initial state. A theorist detects the passage of time by noting the changing collection of correlations amongst the subsystems of the full system as the slice on which states are defined is moved through spacetime.

A subtlety arises when the theorist attempts to reconcile his conception of time with the perception of the participant-observer. The theorist requires a knowledge of the foliation of spacetime in order to view change among subsystem states. The participant-observer has a sense of "now" but has no direct knowledge of the foliation. The common folklore is that the theorist can use clocks to determine a foliation of spacetime from which to predict possible experiences by the participant-observer. This is false because quantum theory allows for superpositions of clock states, each correlated with different subsystem states. When one tries to assert temporal preconditions to a quantum question by saying "when the clock reads –," there is a potential ambiguity because a clock may have the same reading at different spacetime events. One needs to know the hypersurface on which to read the clock state to determine if these different occurences of the precondition contribute to the same amplitude or to incoherent probabilities. This cannot be decided on the basis of the clock state alone.

Fortunately, one is not left without options. A crucial element that is missing in the picture of the theorist is the involvement of the participant-observer. The theorist must coordinate his foliation with the experience of the participant-observer. This may help to resolve ambiguities, but further investigation is needed.

A more radical alternative is to consider a modification of quantum theory which treats space and time uniformly. By quantizing spacetime events, one is capable as a theorist of posing well-defined questions involving time—time and space are put on an equal footing. The situation from the perspective of the participant-observer is less clear and needs to be studied. This approach while clearly speculative seems to offer hope of a novel direction in quantum geometry which redresses the traditional unequal treatment of space and time in the quantum theory.

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[9] This primitive immediacy may not be satisfying to everyone because it suggests the personal involvement of some observer, but I submit that ultimately it underlies any discussion of time as it is experienced, be it by people or by inanimate objects. There is a tendency to anthropomorphize observers which associates with them a connotation of awareness. This connotation is wholly undeserved, and unnecessarily complicates the language of measurement and observation. I shall speak of observers even in the absence of human beings. An observer is simply a subsystem whose state we choose to focus on as it interacts with other subsystems.

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directly treated by Rovelli but seems most closely related to his "existence of the Present."

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