2 Finding "real" time in quantum mechanics

Craig Callender

Quantum mechanics seemingly offers something to everyone. Some find free will in quantum mechanics. Others discover consciousness and value. Still others locate the hand of God in the quantum wave function. It may come as no surprise, therefore, to hear that many believe quantum mechanics implies or at least makes the world more hospitable to the tensed theory of time.[1] Quantum mechanics rescues the significance of the present moment, the mutability of the future and possibly even the whoosh of time's flow. It allegedly does so in at least two different ways:

A. Quantum non-locality is said to make a preferred foliation of space-time into space and time scientifically respectable again. Tensers need worry no longer about "no-go" theorems proving the incompatibility of the tensed theory with special relativity. Quantum non-locality provides the foliation they need.
B. Wave function collapse injects temporal "becoming" into the world.

The aim of this paper is to show that the kind of reasoning underlying these claims is at least as desperate as that finding freedom, value, the mind and God in quantum mechanics – which is pretty desperate. The bulk of the paper concentrates on A; discussion of B is reserved for the Appendix. After setting things up in the first three sections, the next section develops what I call the "coordination problem" for tensers. The upshot of this problem is that if tensers escape the threat of relativity, they do so only by embracing conflict with the branch of physics they believed saved them, quantum mechanics. The following section entitled "Quantum gravity to the rescue?" briefly considers what lessons we might draw for tenses from quantum gravity. Finally, in the concluding section I step back from the fray and examine some methodological issues, concluding that scientific methodology will always be "against" tenses as they are currently conceived.

Special relativity against tenses

The argument from special relativity against tenses is familiar, so I will be brief. The basic idea begins with the relativity of simultaneity in Minkowski space-time, the space-time appropriate to special relativity. A special relativistic world is a 4-dimensional manifold of space-time events endowed with Minkowski metric and matter fields. A foliation of this manifold carves up space-time into space and time via an equivalence relation, simultaneity, and time is the 1-dimensional linearly ordered quotient set induced by this relation. The famous relativity of simultaneity implies that there are many different foliations of space-time into space and time. Though a tension between relativity and common sense conceptions of time was recognized very early on, Putnam (1967) and Rietdijk (1966) were perhaps the first to set out the argument against tenses from relativity explicitly.

The basic idea is as follows (see Figure 2.1): consider two inertial observers, A and B, traveling in opposite directions but intersecting at some event e, and some distant inertial observer C. Simply put, using the standard Einstein-Poincaré synchronization, A has a different hyperplane of simultaneity than B does. Hence A and B will disagree about what events on C's history are simultaneous with e. A will declare that event C_1 is simultaneous with e whereas B will declare that event C_2 is simultaneous with e. In typical terrestrial situations, C_1 and C_2 may be so close together that their difference is not subsequently noticeable to A or B. For Cs that are very far away

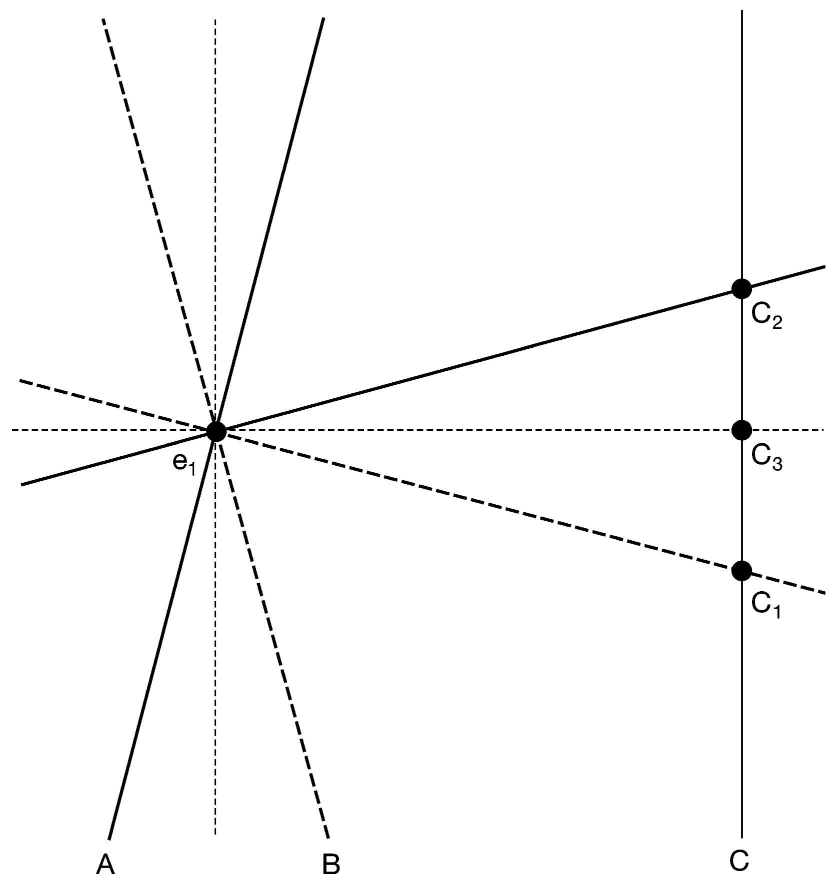

Figure 2.1 Relativity of simultaneity.

(or for As and Bs with very high relative velocity with respect to one another), however, there can be great disagreement. Now take some event C_3 such that $C_1 < C_3 < C_2$. Since one's simultaneity hyperplane divides the world into the future and past – and on any tensed view this has ontological repercussions – C_3 is in A's past but B's future. Furthermore, the so-called "principle of relativity" asserts that neither A nor B is privileged in any way. If the future is ontologically unlike the past or present (i.e. non-existent, indefinite, etc.), as the tensed theory demands, then A judges C_3 ontologically different than B judges C_3. But why should C_3's *ontological* status be relative to one's state of motion?

Scores of papers respond to this argument. I won't summarize them all here, but let me comment on a few strategies of reply (see Savitt 2002). Some tensers have bitten the bullet and suggested relativizing existence to one's state of motion. Others have flatly denounced special relativity as false (which it is, but they mean even if gravitational and quantum effects are negligible). These claims are obviously very radical. Others, like Stein (1991), have claimed that Putnam's argument is wrong, that a "becoming" relation is perfectly well definable on Minkowski space-time. The trouble with this claim is that Stein's "tensed" theory is not remotely close to any tensed theory ever devised and lacks any philosophical virtues apart from having a relation definable on (temporally oriented) Minkowski space-time (see Callender 2000; Saunders 2002). Callender (2000), furthermore, argues that if one uses a relation remotely like those found in tensed theories (that is, where at least two events can be co-present), then one can invert Stein's theorem and prove a "no go" theorem showing that becoming is incompatible with Minkowski space-time (see also Clifton and Hogarth 1995; Dorato 1996; Rakic 1997).

In my opinion, by far the best way for the tenser to respond to Putnam *et al.* is to adopt the Lorentz 1915 interpretation of time dilation and Fitzgerald contraction.[2] Lorentz attributed these effects (and hence the famous null results regarding an aether) to the Lorentz invariance of the dynamical laws governing matter and radiation, not to space-time structure. On this view, Lorentz invariance is not a space-time symmetry but a dynamical symmetry, and the special relativistic effects of dilation and contraction are not purely kinematical. The background space-time is Newtonian or neo-Newtonian, not Minkowskian. Both Newtonian and neo-Newtonian space-time include a global absolute simultaneity among their invariant structures (with Newtonian space-time singling out one of neo-Newtonian space-time's many preferred inertial frames as the rest frame). On this picture, there is no relativity of simultaneity and space-time is uniquely decomposable into space and time. Nonetheless, because matter and radiation transform between different frames via the Lorentz transformations, the theory is empirically adequate. Putnam's argument has no purchase here because Lorentz invariance has no repercussions for the structure of space and time. Moreover, the theory shouldn't be viewed as a desperate attempt to save absolute simultaneity in the face of the phenomena, but it should rather be viewed as a natural extension of the well-known Lorentz invariance of the free Maxwell equations. The reason why some tensers have sought all manner of strange replacements for special relativity when this comparatively elegant theory exists is baffling.

The main concern about the Lorentzian theory is that dynamical symmetries do not mirror space-time symmetries on this view, or as Einstein said, "there are asymmetries in the theory not found in the phenomena" (Janssen 2002). The matter fields are Lorentz invariant but the space-time is not. For this reason, all else being equal, one ought to prefer the Einstein-Minkowski interpretation to the Lorentzian interpretation. Positing otherwise unnecessary unobservable structure – absolute simultaneity – does violence to Ockham's razor. But is all else equal? If the case for tenses is elsewhere strong, that may tip the balance over to the Lorentzian interpretation. The Lorentzian picture is logically consistent and empirically adequate, after all. What are a few lost explanatory virtues in contrast to ________ (fill in the blank with whatever tenses explain)? There are many assumptions in our overall world picture, and we know from Quine-Duhem that there are many ways of organizing them. The no-go theorems focus on only a small piece of this theorizing and are only as good as their assumptions. In particular, what symmetries one takes a space-time to have depends on prior assumptions about what one takes to be in the space-time in the first place. If quantum non-locality spoils the Lorentz invariance of Minkowski space-time, then this would override the explanatory deficit of the Lorentzian view. Does quantum mechanics help tip the balance toward a space-time structure more friendly to tenses?

The quantum challenge

Sir Karl Popper, reflecting on recent experiments violating Bell's inequality, writes:

> It is only now, in the light of the new experiments stemming from Bell's work, that the suggestion of replacing Einstein's interpretation by Lorentz's can be made. If there is action at a distance, then there is something like absolute space. If we now have theoretical reasons from quantum theory for introducing absolute simultaneity, then we would have to go back to Lorentz's interpretation.
>
> (1982: 30)

According to Popper, the underdetermination between Lorentz and Einstein, which had persisted for more than sixty years, was finally broken with an *experimentis crucis.* Quantum non-locality, experimentally vindicated by Aspect's violation of Bell's inequality, demands absolute simultaneity. For the would-be tenser, Popper's reasoning to a physically preferred foliation of space-time is precisely what one wants. But why would Popper, or anyone, think quantum non-locality entails absolute simultaneity?

To answer this question we must take a detour through the philosophical foundations of quantum mechanics. In brief, the idea is as follows. Experiments in the late twentieth century revealed robust correlations between space-like separated events, i.e. events that are not connectable by a light signal. Quantum mechanics must explain these correlations. Different interpretations of quantum mechanics explain the space-like correlations differently, but the thought is that however this is done, it will entail picking out a preferred foliation of space-time. Quantum mechanics, once interpreted plausibly, must posit a mechanism requiring absolute simultaneity if it is to explain the Bell correlations. Let's flesh this out slightly and briefly evaluate the claim. For more details, see Bell (1987) and Maudlin (1994, 1996).

To begin, start with the now canonical spin ½ version of the famous 1935 Einstein-Podolsky-Rosen (EPR) paradox by Bohm. A pair of electrons, 1 and 2, in the spin singlet state:

$$\frac{1}{\sqrt{2}}(|\uparrow_x>^1 |\downarrow_x>^2 - |\downarrow_x>^1 |\uparrow_x>^2)$$

emerge from a common source and are sent in opposite directions. Each electron is then measured by a Stern-Gerlach device that sorts spins, up or down, in the x-direction. In the singlet state, thanks to spin conservation, the probability of the measurements on systems 1 and 2 disagreeing is one for any measurement orientation. Upon measuring electron 1 and finding a definitely spin up or down state, therefore, we know with certainty the result on electron 2. Assuming locality, that is, that the measurement of 1 didn't affect the state of 2, EPR reason that it must be that 2 already had a definite spin state – even when it was in the singlet state, which doesn't have a definite spin state. Hence we have EPR's dilemma: either quantum mechanics is non-local or it is incomplete.

Later, Bell derived in 1964 an inequality from the distant correlations encoded by the singlet state and some natural locality assumptions. For various orientations quantum theory predicts the violation of this inequality; and in a host of experiments since systems have vindicated this prediction. Though there remain theoretical and experimental loopholes still to close, these loopholes are increasingly desperate. There is now wide consensus that theory and experiment have discovered space-like correlations not attributable to any local hidden variable theory. Complete or not, quantum mechanics is non-local.

Does this non-locality conflict with the relativity of simultaneity? In the absence of an interpretation of quantum mechanics, it is impossible to answer this question. The mechanism responsible for enforcing the space-like correlations varies with interpretation. Not including the mechanism in the discussion of conflict is like leaving the guest of honor at a party uninvited. We need to know how different interpretations understand the space-like correlations and then we need to ask if the physics posited is Lorentz invariant. To answer these questions, we need a quick survey of the measurement problem and reactions to it. As we will see, Popper's reasoning has some purchase with *some but not all* solutions to the measurement problem.

Here is a quick and simplistic description of the measurement problem (for more details, see Albert 1992.) First, suppose that the governing equation for the quantum state is linear. The equations are in fact linear in both non-relativistic and relativistic quantum theory. Second, suppose we have a reliable measuring device. For our spin ½ system, "reliable" means that if the state of the electron is spin up (down), then the measuring device will register a spin up (down) outcome. Together these assumptions entail that if we let the measuring device M measure an electron in the superposed state $\psi = \frac{1}{\sqrt{2}}(|\uparrow_x> + |\downarrow_x>)$ then we get a macroscopic measuring device in a superposed state too. In other words, the initial state

$$\Psi = |ready>_M \frac{1}{\sqrt{2}}(|\uparrow_x> + |\downarrow_x>) \text{ at time } t_1$$

will evolve into

$$(1) \qquad \Psi = \frac{1}{\sqrt{2}}(|''up''>_M |\uparrow_x> + |''down''>_M |\downarrow_x>) \quad \text{at time } t_2.$$

We then have a macroscopic state that is not reading "up," "down" or anything in between. What does this mean? We never see anything suspended between distinct macroscopic properties. And of course, if *everything* is governed by the linear quantum equation, then we are also in a superposition, suspended between myriad distinct macroscopic states; and so is the Earth, the solar system, and anything else entangled (even to a small degree) with the superposed system.

Since measurements seem to have determinate outcomes, something has gone badly wrong. To have an empirically adequate physics, the measurement problem must be solved. How do we solve it? The lack of determinate outcomes is largely a result of holding two theses:

a. Ψ is representationally complete (i.e. the so-called eigenvalue-eigenstate link holds).
b. Ψ always evolves according to a linear dynamical equation.

To solve the measurement problem, we must deny one of these or explain away the mismatch between the macroscopic superposition and experience. The denial should be part of a full-blown theory that is empirically adequate and logically consistent. These theories are called "interpretations" of quantum mechanics. There are scores of interpretations, but they fall naturally into one of three classes (see Albert 1992 and Barrett 1999 for discussion and references).

The first class is called "collapse" interpretations. What makes a theory a collapse interpretation is its denial of proposition b above. The "standard" Copenhagen interpretation states that upon measurement there is an instantaneous wave function collapse from a superposition to an eigenstate (when the state is expanded in the relevant basis for the observable being measured). Other collapse theories rewrite the dynamical equation so that it is sensitive to the mass density or the particle number; when a certain threshold is reached a collapse is triggered. The most developed theory of this kind is known as GRW, after Ghirardi, Rimini, and Weber (1986).

The second class is sometimes called "hidden variable" interpretations. These theories deny proposition a. In addition to the wave function evolving according to some linear equation, these theories add what Bell (1987) calls "beables" (typically a particle or field ontology) and a separate dynamics for these beables. The ontology is dualistic: interpreted realistically, there are both beables and wave functions in the world. By claiming the Ψ description to be incomplete, they can say, for instance, that a macroscopic pointer is in a definite position because its beables are definitely located – even if the quantum state description is a superposition of distinct positions as in (1). In these theories measurement-like situations stimulate what are sometimes called "effective collapses" – events such that only one component of the superposed wave function becomes non-negligible for the subsequent evolution of the beable. Bohmian mechanics and modal interpretations are the best-known versions of this kind of reaction.

The third class forms a heterogeneous group. These theories neither supplement the wave function description of the world nor interrupt its evolution. What unifies them, if anything, is that they seek to explain away the mismatch between (1) and experience. Advocates of relative-state interpretations claim that (1) does describe our experiences accurately, but that the way our experience supervenes upon (1) is more complicated than one normally thinks. They often speak of (1) as corresponding to different worlds, different branches, or different observers, with one world branch or observer seeing the pointer pointing up and another with the pointer pointing down. Decoherence effects are often invoked as being crucial. Another very different group, which for our purposes we might include in group three because they don't supplement or modify quantum mechanics, is one that treats quantum mechanics instrumentally. These thinkers consider the wave function an epistemic device and see collapse as a kind of Bayesian conditionalization. We learn new information about the system and change our credences accordingly, but collapse is not a real physical process nor is the dynamics supplemented with hidden variables.

We are finally in a position to ask our question, namely, do all interpretations that solve the measurement problem (or purport to) enforce Bell's space-like correlations in a way that conflicts with Lorentz invariance? The answer is straightforwardly "no," for we don't get a conflict on the "epistemic" treatment of the wave function mentioned in class three. Also, depending on how one understands the metaphysics of branches, observers and worlds, it *may* be possible to escape conflict with a relative-state interpretation (Bacciagaluppi 2002). So interpretations in class three hold out hope of not conflicting with Lorentz invariance. It is also possible that hidden variable theories be Lorentz invariant, in the sense that no proof to the contrary has ever stood up. Some hidden variable theorists are also reluctant to posit a dynamics for their beable; not doing so can make it unclear as to whether the theory is Lorentz invariant or not. At any rate, it is clearly contentious whether all interpretations that solve the measurement problem also entail a violation of Lorentz invariance. In addition, there are non-standard ways of understanding Lorentz invariance ("hyperplane dependence"). If successful, this understanding would allow any of our interpretations to be Lorentz invariant. With all these qualifications now in place, we can only say that Popper's conclusion threatens most if one adopts a standard collapse or hidden variable interpretation of quantum mechanics as well as a standard reading of Lorentz invariance.

To get a sense of the trouble, consider real collapses in Minkowski spacetime (for more see Aharanov and Albert 1981). We'll consider no-collapse dynamics later. Consider two spin-1/2 particles in the singlet state. Both particles emerge from a common source, with particle 1 traveling to the left in the diagram and particle 2 traveling right (see Figure 2.2). At event L

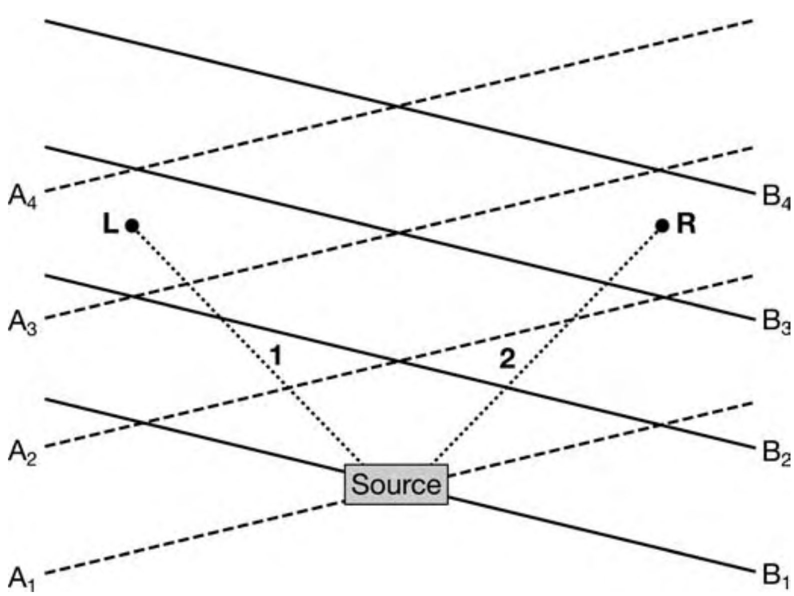

Figure 2.2 Measurement of the singlet state.

particle 1 is measured for its value of x-spin; at event R, which is space-like related to L, particle 2 is measured for its value of z-spin. Now consider two foliations of space-time, A, wherein R happens first, and B, wherein L happens first. What is going on in the world according to inertial observers to whom B is appropriate is as follows.

Start off in the singlet state

$$\frac{1}{\sqrt{2}}(|\uparrow_x>_1 |\downarrow_x>_2 - |\downarrow_x>_1 |\uparrow_x>_2)$$

at time B_1. Then by B_3 an x-spin measurement happens at L. Suppose the result at L is x-spin-up. Then the quantum state instantaneously reduces to:

$$|\uparrow_x>_1 |\downarrow_x>_2 .$$

By time B_4, R has occurred and the scientist at the right finds particle 2 to be z-spin-up:

$$|\uparrow_x>_1 |\uparrow_z>_2 .$$

But from the perspective of an inertial observer to whom A is the appropriate foliation, we instead get the sequence:

A1: $\frac{1}{\sqrt{2}}(|\uparrow_x>^1 |\downarrow_x>^2 - |\downarrow_x>^1 |\uparrow_x>^2)$

A3: $|\downarrow_z>^1 |\uparrow_z>^2$

A4: $|\uparrow_x>^1 |\uparrow_z>^2$

by parallel reasoning. The two histories are very different. History A says R collapsed the singlet state into a factorizable state; history B says L did. History A says that R measured particle 2 to be x-down; history B says it measured the singlet state. History A says that L measured the singlet state; history B says it measured particle 1 to be z-down. History A and B also disagree on which measurements results were determined and which ones were chancy.

If we take the wave function at all seriously – that is, as a real entity in the world rather than a summary of information – disagreements like this will not do. If real wave functions really collapse, then either A's story is right or B's story is right. The same goes for no-collapse hidden variable theories. Hidden variable theories will have the beables behaving one way if A's story is right and behaving another way if B's story is right (see Section 4 below). Again, since the beables represent the fundamental ontological furniture of the world in these theories, disagreements like that between A and B won't do there either.

Hence, on two large and natural classes of interpretation, the mechanism responsible for explaining the Bell correlations does require a preferred frame. Since I am personally partial to these types of interpretation, I have some sympathy with tensers claiming quantum non-locality lends some pressure to believe again in a preferred frame.

Whether a quantum preferred frame would actually push us all the way back to the Newtonian or neo-Newtonian space-time of Lorentz is yet another question. As Maudlin (1996) points out, another option would be to retain Minkowski space-time but add a physically preferred foliation (see also Dürr *et al.* 1999). Like the Newtonian options, it would introduce an asymmetry in the theory not fond in the phenomena. All three space-times, Newtonian, neo-Newtonian and Minkowskian-with-preferred-frame, would be hospitable to tensers hoping to re-introduce a global simultaneity hyperplane.

Quantum preferred frames

To one defending the Putnam argument against tenses, the situation regarding quantum mechanics is nothing less than embarrassing. By adopting the principle of relativity Putnam claims that there can't be anything in the world that doesn't "commute" with the symmetries of Minkowski space-time. But the speculations of the previous section suggest that physics itself – indeed, arguably our best scientific theory ever – violates Putnam's reasoning! Putnam's argument, run on quantum mechanics rather than tenses, would prohibit good interpretations of quantum mechanics from reproducing and enforcing violations of Bell's inequality.

Here is Lucas (1998) savoring the irony:

> But physics goes further. It not only defeats the would-be defeaters of the tense theory, but offers positive support. Quantum mechanics, if it is to be interpreted realistically, distinguishes a probabilistic future of superimposed eigen-states from a definite past in which each dynamical variable is in one definite eigen-state, with the present being the moment at which – to change the metaphor – the indeterminate ripple of multitudinous wave-functions collapses into a single definite wave. Admittedly, many of those who think about quantum mechanics are not realists, and admittedly again, there are horrendous difficulties in the way of giving a coherent account of the collapse of the wave-function. But an obstinate realism, as well as a slight sympathy for our feline friends, precludes my envisaging any long period in which Schrödinger's cat could be half-dead and half alive, and this whether she be in a laboratory in Europe or on some planet circling Betelgeuse. There is a definite fact of the matter, there as much as here, whether or not we are dealing with a superposition of functions or one definite eigen-function. And hence there is a unique hyperplane advancing throughout the whole universe of collapse into eigen-ness.

Lucas finds at least two attractive elements in quantum mechanics. One is the unique hyperplane presumably corresponding to the tensed now advancing through history. Another is that what is to the future of this hyperplane is genuinely open. For many who find tense in quantum mechanics, it is quantum mechanics' alleged probabilistic future that make tense so attractive. One should point out, of course, that the two features, preferred frames and stochastic dynamics, do not go hand in hand. Bohm's theory requires a preferred frame, for instance, but does not need a probabilistic dynamics for its hidden variables (though it usually has such in its field theoretic extensions). So if it's a genuinely "open" future that attracts you, preferred frames don't necessarily get you that. We'll turn to the idea of quantum becoming in the Appendix.

I want to argue that even if quantum mechanics does imply a preferred frame, matters are hardly rosy for tensers. In fact, one can argue that there is a real in principle problem for tensers. What I want to do is consider the foliation from the perspective of Bohmian mechanics and GRW. The former is the best worked out "realistic" no-collapse interpretation of quantum mechanics; the latter perhaps the best worked out "realistic" collapse interpretation. Assuming neither can be modified and made fundamentally Lorentz invariant, then quantum phenomena plus a solution to the measurement problem may demand a preferred frame. I want to concentrate on these theories since, for the tenser seeking to escape Putnam, things will get *no better* than if one or the other of these interpretations is true.

The coordination problem

Quantum mechanics is not the answer to the tenser's prayers. Even if we charitably assume quantum non-locality does require a preferred frame, there is a Putnam-like argument lurking nearby in quantum mechanics. Let's run the argument with the Bohm interpretation and then briefly point out the slight differences that we obtain when working with GRW instead.

The basic idea of non-relativistic Bohmian mechanics is that there is, in addition to the wave function, particles. Relativistic versions of Bohmian mechanics have been developed for some fields and are in the process of being developed for others.[3] The basic structure is the same, however. There is the wave function and there are the beables; the wave function evolves according to the relevant linear dynamical equation (Schrödinger equation, Dirac equation, Klein-Gordon equation, etc.) and the beables have a velocity that takes the wave function as input. In the non-relativistic particle version, the particles evolve according to:

$$\mathbf{p} = \frac{\partial \mathbf{S}}{\partial \mathbf{X}}$$

where **p** is the canonical momentum equal to md**X**/dt, **X** is a point in configuration space, and S is the phase of the wave function (S = ImlnΨ). In the non-relativistic case, the Schrödinger equation and this guidance equation are the two fundamental laws of nature according to the Bohmian. One often makes another assumption, namely, that the initial probability density of particles is given by the absolute value of the initial wave function squared, $|\Psi|^2$. Call this assumption the *distribution postulate*; some Bohmians view it as a law of nature. The amazing thing is that if you assume the distribution postulate and that the beables and wave function evolve according to the above equations, you will find that the particles' predicted statistics precisely match those of "standard" quantum mechanics.

Consider our earlier experiment with two spin ½ particles in the singlet state. Stern-Gerlach devices essentially split the regions of positive wave function support into two disjoint sections, an upper and lower section as measured along the vertical axis of the magnet. In the version of Bohm's theory under consideration, spin is not fundamental. The value of spin is contextual, meaning that it depends on the initial location of the particle in the wave packet and the kind of device it meets. If the Bohm particle starts off in the upper half of the wave packet (along the i-th dimension, where i = x, y, or z), then the dynamics will evolve it to the region we call spin-up in the i-th dimension; if the Bohm particle begins in the lower half of the wave packet, then it will evolve to the position we call spin-down in the i-th dimension. There is *no* possibility of a transition from low to high, or vice versa. This impossibility is due to the fact that the Bohmian dynamics is first-order and deterministic; the combination means that trajectories can't cross in configuration space.

Suppose the wave function is in our singlet state above and that the configuration point representing the two-particle system is located in the upper left half of the wave packet before the system is measured. (See Figure 2.3, fashioned after Barrett, 1999: 142.) Suppose also that the measurements occur at space-like separation, so that the measurement events occur in different orders in at least two different foliations of space-time. According to one foliation, A measures first; according to another foliation, B measures first. Let it be the case that A measures first. Since the particle is in the upper half of the wave packet, A will find the particle to be x-spin up; when the observer corresponding to B's foliation subsequently measures, the observer must find the particle to be x-spin down. That is, A's measurement will have effectively collapsed the state to $|\uparrow_x>^A\ |\downarrow_x>^B$. Now let it be the case that B measures first. If B measures first, B will find the particle to be x-spin up and therefore A will find the particle to be x-spin down, i.e. B's measurement would have effectively collapsed the state to $|\downarrow_x>^A\ |\uparrow_x>^B$. So in Bohm's theory, the *actual outcome* of the measurements depends on who measured first!

But "first" is not a relativistic invariant for space-like separated events. There shouldn't be a fact of the matter about who measured first, yet on

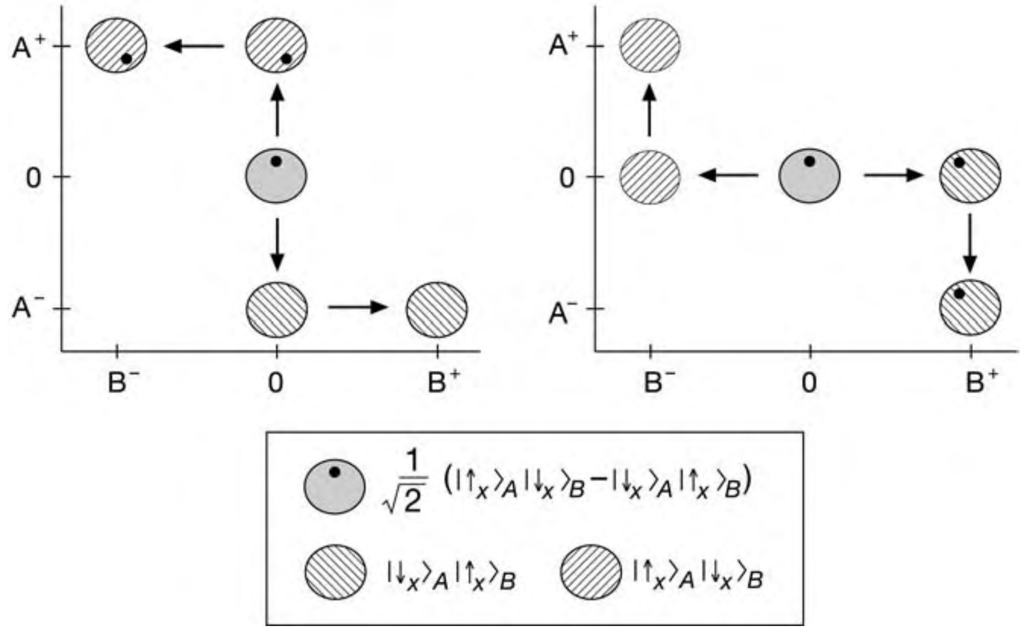

Figure 2.3 The preferred frame in Bohm's theory.

Bohm's theory there is. Since there is a fact of the matter about the outcomes there must be a fact of the matter about who measured first. Hence one foliation must be preferred over the others.

You may be curious why the above reasoning doesn't simply show that Bohm's theory is observationally incompatible with known relativistic facts. Doesn't the above reasoning demonstrate that Bohm's theory is false? Recall the distribution postulate. We don't know where the representative particle point is. If we get spin-down, we know it was in the lower half of the initial wave packet; but there is no way to know this beforehand. Moreover, it can be shown that if the distribution postulate is satisfied, then we can in principle never find out (see Albert 1992). Intuitively, finding out the point is in the upper half in the x-direction doesn't allow a reliable inference about whether it is in the upper or lower half of the y-direction. In any case, because the distribution postulate ensures that Bohmian mechanics reproduces exactly the predictions of ordinary Copenhagen quantum mechanics, the so-called "no signaling theorem" holds in Bohmian mechanics too. That is, one can show that it's impossible in Bohmian mechanics to exploit these space-like correlations for communication. At the statistical level, special relativity holds. It is only at the sub-quantum level that the outcomes pick out a preferred frame. But since we, in principle, don't have access to the initial location of particles in wave packets, we can never tell which of the indefinitely many possible inertial frames is the preferred one.

We now have enough background to make a very simple point. There is an, in principle, irresolvable *coordination problem* between the two preferred foliations, the metaphysically preferred foliation posited by the tenser and the physically preferred one by Bohmian mechanics. There is simply no reason to think the two are the same. Only blind faith leads one to expect that the two are coordinated. In our above experiment, A might measure first and then B measure second according to the Bohm frame, yet according to the temporal becoming frame B measures first and A second. Assuming the becoming frame is primary, we would say B really happened before A; meanwhile fundamental physics would say that A happened before B. Since it would be a miracle if the two frames coincided exactly, with near certainty this will be the case for *some* pairs of events. *Hence the tenser is committed to asserting that with near certainty fundamental physics gets the order of some events the wrong way round.* Far be it from quantum mechanics saving tenses, the tenser merely trades one conflict with fundamental physics for another. And since the distribution postulate prohibits in principle us from finding out the preferred frame, the coordination problem is in principle irresolvable.

This situation also seems to undermine many of the reasons motivating the tenser. For suppose – as an act of blind faith – that the Bohm frame and tense frame were one and the same. Well, it's still true that *you* are a Bohmian system corresponding to a piece of the universal wave function and a bunch of Bohmian particles. So whenever you experience anything or even introspect, *you* are making a Bohmian "measurement". The same general limitations on Bohmian measurements hold for you too. If the distribution postulate is a law of nature, then the laws of nature in a Bohmian world prevent you from having any *reliable* feeling or impression or introspective reflection that could at all indicate which frame is the becoming frame. Unlike in Putnam's argument, there *is* a fact of the matter about which foliation is the foliation needed by physics (i.e. Bohmian mechanics). But Bohmian mechanics makes it in principle impossible to determine via any interaction whatsoever which one this is. *Your intuitions, introspections, etc., all being species of interactions, can be in principle no guide to which foliation is the true foliation or even whether there is one.* If the world becomes or enjoys an objectively privileged present, then it is not something at all connected to experience (assuming physicalism). Since tensers regularly appeal to experience to support their theory (whether they should is another matter, see Callender (ms)), this conclusion cannot be congenial to the tenser. Hence the tenser faces a dilemma: either the becoming frame and preferred quantum frame are one and the same, in which case Bohmian mechanics implies that no physical experience could be a reliable guide to this frame, or they differ, and then the tensed theory conflicts with physics over the order of some events. Since there aren't any good reasons to endorse the former horn of the dilemma, it appears that the tenser is stuck with the latter, as depicted in Figure 2.4.

Matters change only slightly when we switch to the GRW interpretation. Again we will have a preferred foliation (the collapse dynamics is not Lorentz invariant), and again there will be no reason to think the foliation matches the one produced by becoming. So again the tenser will be postulating a

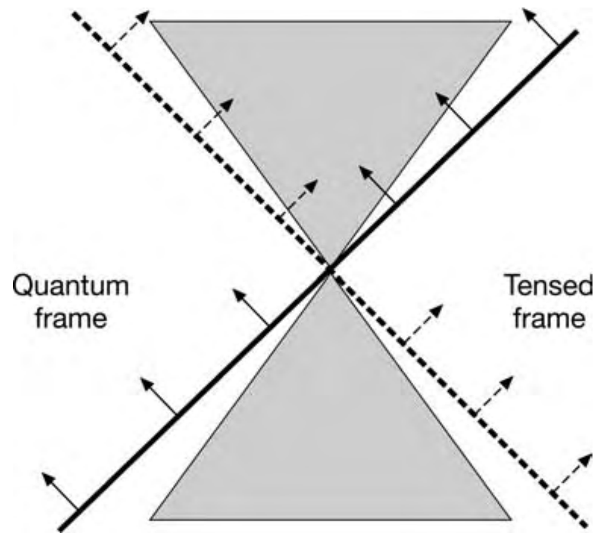

Figure 2.4 The coordination problem.

new coincidence into our world system. The only significant difference between the case of Bohm and of GRW regarding the present discussion is that, unlike in Bohm's theory, a relativistic version of GRW does at least in principle allow one to find the quantum preferred foliation (see Albert 2000). Second quantized GRW may predict slight observable violations of Lorentz invariance, in which case sophisticated experimental investigation of Lorentz invariance may pick out GRW's preferred frame. But since there is absolutely no reason to suspect that our brains are already doing the experiments in Albert (2000), there is no reason to think our experience in any way is a reliable guide to where the preferred frame is.

One might respond to the coordination argument as follows. We sense becoming or flow or what-have-you. Making sense of this experience entails the existence of a preferred frame. But the experience itself doesn't tell us *which* frame is preferred – it just tells us that one is needed. Monton (2005) makes a claim similar to this one. My reply is that our experiences aren't so unselective. What could our experience of becoming be if it is so startlingly insensitive? For all we know, the quantum foliation might be one that treats events in what we call the very early universe as "present". Don't confuse my argument with one merely pointing out that due to our necessarily coarse terrestrial measurements (arising from our being clumsy macroscopic creatures) we'll have trouble finding the preferred frame. If that were the argument, then one could imagine coarser measurements that might give us some estimate of the foliation. But my argument is that no measurement whatsoever will even remotely narrow down the preferred foliation. Contrast this case with the following one in cognitive science. In some circumstances, subjects will report that they experience two events (for instance, two flashes on a computer screen) even though they cannot tell which happened first (for discussion and references, see Callender (ms)). These subjects would be quite right to say that the experience entails various propositions, yet it does not entail knowing which event happened first. Notice, however, that many other experiments will reveal which events happened first. As we separate our events in time, we'll begin to experience one after another. Or if we leave the events the same temporal distance apart, we can devise mechanisms we might experience that tell which came first. Not so in the present case. No experiment whatsoever will even give us a hint about the true location of this foliation.

Far from being out of the woods thanks to a preferred foliation, a quantum foliation only serves to embarrass the tenser.

Quantum gravity to the rescue?

One feature all of the theories we have discussed have in common is the fact that they are false. Special relativity gives way to general relativity, non-relativistic quantum mechanics to relativistic quantum field theory; furthermore, there are reasons for thinking general relativity and quantum field theory are mutually incompatible and must themselves give way to quantum gravity. Perhaps quantum gravity can rescue preferred frames? This is the hope expressed by Monton (2005).

There are already sketches of theories of quantum gravity that yield a preferred foliation, including some to which I'm partial (e.g. Callender and Weingard 1995). But it must immediately be acknowledged that there are also sketches of those that do not require a preferred foliation, e.g. loop quantum gravity, and probably there are more of the latter than the former. None of these theories is at all well developed. Most are constitutionally unable to make predictions. Some, like topological quantum field theory, have no "local physics" whatsoever. Some turn out to be mathematically incoherent. Some are under-funded; others perhaps over-funded. Who should we bet on? At this stage it's way too early to glean anything. The tenser is right: relativity will be superseded. But with what, when, how and why are all up in the air.

Tensers can always cross their fingers and hope. If quantum gravity lets them down, perhaps then the next theory will accommodate. If science is a state of permanent revolution, as Popper thought, there is always hope, if nothing else. In the conclusion we return to this issue, where I hope to dash even this thin reed of hope.

Conclusion

This paper has argued that even if tensers get what they want from quantum mechanics, i.e. a preferred foliation, there is no reason to think it will serve the tensers' purposes. The foliation preferred by quantum mechanics may not be that preferred by metaphysics. Indeed, there is no reason to think it will be.

The same argument can be made with respect to tensers replying to the threat from general relativity. In general relativity, tensers find the cosmic time definable in a certain class of "realistic" solutions to Einstein's field equations congenial to their purposes. These cosmic times are defined in various ways, but usually they hang on various averaging procedures to determine the center of mass frame. The matter distribution picks out a preferred foliation. But why think that the psychological lapse of time or our perceived present marches in step with the foliation dictated by the center of mass frame? There is no reason to link the two.[4]

Why are tensers having such trouble connecting their theories to what they find in physics? I claim that it is no accident. Let's step back and reflect on what is happening. If we believe physics is time translation invariant, then we believe that whether an experiment is done at 2 p.m. or 3 p.m. doesn't matter, so long as the experimental procedure is the same in both cases. If for some reason we thought the property of happening at 2 p.m. were physically relevant, then we wouldn't be inclined to think physics is time translation invariant. If our reasons are good, then we are justified in denying time translation invariance; if our reasons don't stand up, nor do they for any other time, then time translation invariance looks plausible. If, as is in fact the case, its obtaining helps explain other phenomena as well, such as energy and energy conservation, then we have a strong case for time translation invariance. For why should science posit a fundamental property that doesn't do any work and whose existence would adversely affect science's simplicity? What symmetries and laws we take to hold of the world hangs on what things we take to be real. But also, if there is a great deal of motivation for certain symmetries and laws, then what things we take to be real hangs in part on what symmetries and laws we take to hold.

We ought to think of the arguments against the tensed theory of time in this same light.

The argument from special relativity against tenses was never just a matter of one physical theory implying the rejection or acceptance of tenses. Putnam's argument and the other no-go arguments arrange an inconsistent set of propositions so that Lorentz invariance is a premise and the denial of the tensed theory of time is a conclusion. Of course, any inconsistent set can be re-arranged; one might instead take objective tenses (a now, becoming, etc.) as real and turn the argument over, making tense a premise and the violation of Lorentz invariance a conclusion. As we know from Quine-Duhem, how we arrange the premises and conclusions depends upon background assumptions. Putnam's argument assumes that physics gets along perfectly well without tenses, just as our argument for time translation invariance assumes physics can manage without "2 p.m.-ness". This claim is contentious, to be sure, but it is there behind the scenes. The Minkowski space-time structure explains away asymmetries in the theory not found in the phenomena. Giving it up for neo-Newtonian space-time or Minkowski space-time with a preferred foliation introduces otherwise unnecessary unobservable structure to the theory.

From the Minkowskian perspective, it also introduces unexplained coincidences: why do those rods and clocks keep contracting and dilating, respectively? As a kinematical effect in Minkowski space-time, Minkowski space-time is a common cause of this behavior, which is otherwise brute in the Lorentzian framework.

Unobservable theoretical entities and unexplained coincidences are found throughout science, and there is often nothing wrong with that. Quarks are examples of the former. The unexplained equivalences among passive, active and gravitational masses in Newtonian gravitational theory are an example of the latter. Though replete with such entities and coincidences, science accepts them reluctantly: only if their cost is compensated for elsewhere and the alternative is worse. Do the benefits of accepting a coincidence among types of mass outweigh the costs? Given the astounding success of Newtonian gravitational theory, the coincidences more than pay their weight. By contrast, tensers have a stock of arguments about temporal indexicals that also apply to spatial and personal indexicals, dubious appeals to experience, and ordinary language analysis. Since this is not a fair trade for coincidences or extra unobservable structure, the balance tips and we claim special relativity rules out tenses rather than tenses rule out special relativity.

The same goes with my coordination argument against tenses. It desires to eliminate otherwise unexplained coincidences from science. The same goes also with Gödel's famous argument against tenses from general relativity. Belot (forthcoming) faults Gödel for assuming the symmetries of the general relativistic laws are more important than the matters of fact that support a preferred foliation of space-time. However, Gödel's argument assumed, again as a kind of background assumption, the idea that science could operate perfectly well without privileging a particular foliation. Why posit this structure if it's not needed?

Tensers are wasting their time trying to find an image of the tensed theory in physics. Specific physical theories will be more or less hostile to tenses, but in general they will be against tenses so long as there is no clear need for them. Show physics a need for tenses and it will quickly accommodate them. Until then, merely as a by-product of scientific methodology, physics will not accommodate them. Those hoping to rescue tenses will do best by returning to the fundamentals and showing that we can't do without them. But since most of these fundamental reasons arise solely from ordinary language analysis – a mostly bankrupt enterprise in my opinion – I, for one, will not hold my breath. From this perspective, physics – and science itself – will always be against tenses because scientific methodology is always against superfluous pomp.

Appendix: Quantum becoming

Tensers sometimes find vindication or inspiration for their views from objective wave function collapse. We met this view in Lucas (1998) above and it is found in Stapp (1977), Whitrow (1980), Popper (1982), Shimony (1993, 1998), Lucas (1999), and elsewhere. Quantum mechanics is supposed to require wave function collapse, and wave function collapse is supposed not only to pick out a preferred frame but also to make the future open, indeterminate or mutable. Here is Lucas (1999):

> There is a worldwide tide of actualization – collapse into eigenness – constituting a preferred foliation by hyperplanes (not necessarily flat) of co-presentness sweeping through the universe – a tide which determines an absolute present . . . Quantum mechanics . . . not only insists on the arrow being kept in time, but distinguishes a present as the boundary between an alterable future and an unalterable past.
>
> (1999: 10)

The collapse of the wave function, interpreted realistically, suggests a picture of a fixed past (wave functions collapsed to the eigenstates of the relevant observable) and an open future (wave functions as superpositions of such eigenstates). In fact, the path from objective collapses to tenses is a two-way street. While some reason to tenses from collapses, others reason to collapse interpretations from a prior commitment to tenses. Here is Christian (2001) on his motivation for pursuing Penrose's collapse theory:

> [It] implicitly takes *temporal transience* in the world – the incessant fading away of the specious present into the indubitable past – not as a merely phenomenological appearance, but as a *bona fide* ontological attribute of the world [. . .] For, clearly, any gravity-induced or other intrinsic mechanism, which purports to actualize – as a *real* physical process – a genuine multiplicity of quantum mechanical potentialities to a specific choice among them, evidently captures transiency, and thereby not only goes beyond the symmetric temporality of quantum theory, but also acknowledges the temporal transience as a fundamental and objective attribute of the physical world
>
> (2001: 308)

Many who crave a tensed time find just what they need in objective wave function collapse and vice versa.

Let us first consider whether quantum mechanics, on a collapse interpretation, supports one's pre-theoretical views of the openness or mutability of the future, as Lucas suggests. I do not believe it does. We can approach this question by asking whether the open/fixed distinction maps at all neatly into the superposition/eigenstate distinction? The answer is "no". To begin with, the symmetry of Hilbert space implies that we can expand our wave function in any of an indefinite number of bases, e.g. position, momentum, spin. A wave function that is a superposition in one basis may not be a superposition in another; for instance, the wave function of x-spin down is a superposition of up and down spins in the z-spin direction. Now, if we believe collapses are real physical mechanisms, then we must decide in what basis they occur. A natural choice might be position basis, as in GRW. A preferred position basis will entail (if it solves the measurement problem) the absence of superpositions of distinct *macroscopic* properties in other bases too, but it does not entail the absence of superpositions in these bases. Eigenstates in position space still correspond to non-eigenstates in momentum space. For the topic at hand, this fact raises the natural question: is the momenta of past objects "still" open? Or do we care only about macroscopic openness? Either view would represent a significant departure from the ordinary conception of an open future. Furthermore, how should we view the future measurement of systems already in eigenstates of the relevant observable? These measurements aren't open in the sense of a superposition collapsing to the eigenstate of the relevant observable. Are the outcomes nonetheless open because of the future or are they fixed because of eigenstates? If the former, then quantum mechanics has little to do with openness; if the latter, then again we have a drastic departure from our pretheoretic intuitions of openness. The actualization Lucas gets from quantum mechanics is more a series of partial drips and splashes than a worldwide surge.

Perhaps the link with openness and transience arises instead from the single-case objective probabilities needed for a collapse theory? Shimony and Popper stress throughout their work the benefits of a truly probabilistic process, seeing in it an open future, the flow of time, and even freedom. The intuitions underlying these links are clear enough. Suppose at time t there is an objective chance of 0.5 that a radium atom will decay tomorrow. For this to be true, some believe, there must not "already" at t be a unique determinate future with (say) a decayed radium atom in it tomorrow. That would entail, in one way of understanding objective chances, an objective probability of 1, not 0.5. Since the tenseless theory of time entails that there is a unique determinate future – in a sense – the existence of non-trivial objective probabilities requires the tensed theory of time (see Shanks 1991).

Here I only want to point out that the inferences in this reasoning are more tenuous than is usually acknowledged. First, if the reasoning goes through at all, it does so only for some interpretations of chance and not others. The reasoning is perhaps most natural on a Popperian propensity interpretation, but there exist other (and I would argue, better) interpretations of objective single-case chances that won't yield the desired conclusion. On Lewis' 1994 theory of chance, for instance, non-trivial chances are compatible with a tenseless theory of time. Lewis views chance as a theoretical entity that increases the overall strength and simplicity of the best systematization of nature. Crucially, on this theory information about whether or not a radium atom decayed after t is "inadmissible" at t and therefore doesn't affect the value of the chance at t. Second, and at least as important, the justification for the line that a "fixed" future implies trivial values of objective chance is similar if not identical to the famous argument for fatalism. The sea battle tomorrow spoils freedom today just as the radium atom's decay tomorrow spoils non-trivial values of chance today. But if one believes, as I do, that the argument for fatalism is flawed (see Sobel 1998 for a penetrating critique) then the existence of the sea battle tomorrow doesn't undermine freedom today; one therefore needn't see the tenseless view and its implications of either a sea battle or not tomorrow as a threat to freedom. Nor need it be a threat to non-trivial chances. The actual world may contain our radium atom in it decayed tomorrow, yet today it still may have a one-half chance of decaying.

Notes

1 Throughout I assume familiarity with tensed theories of time. For clear introductions see Dainton (2001) and Savitt (2002). In what follows I make no attempt to disentangle the various distinct theses classified as "tensed theories". Primarily I have in mind the theories commonly referred to as presentism and possibilism (or the "growing block" view).

2 See Bell (1987: 67–80) and Janssen (2002) for discussion and references. Craig (2001) is the first tenser I know of who adopts a Lorentzian perspective to defend the tensed theory. Arguably, he uses the wrong version of Lorentz's theory (see Balashov and Janssen 2003).

3 For some philosophical discussion of Bohmian field theories, see Callender and Weingard (1997). For the latest Bohmian quantum field theory, see Dürr *et al.* (2003). For an attempt to write a Bohm theory that wouldn't pick out a preferred frame, *in asense*, see Dürr *et al.* (1999).

4 Tensers in general have a problem linking the phenomenon they want to explain to the ontology they believe explains it, even when the ontology is their own metaphysics. See Dainton (2001: 75) for an argument that there is no necessary coordination between the becoming arrow and the memory arrow, and see Callender (2005) for a generalization of this objection.

References

Aharonov, Y. and Albert, D. (1981) 'Can We Make Sense out of the Measurement Process in Relativistic Quantum Mechanics?' *Physical Review D* 24, 359–70.

Albert, D.Z. (2000) 'Special Relativity as an Open Question', in Heinz-Peter Breuer and Francesco Petruccione (eds.) *Relativistic Quantum Measurement and Decoherence*, Berlin: Springer, pp. 3–13.

Albert, D. (1992) *Quantum Mechanics and Experience*, Cambridge: Harvard University Press.

Bacciagaluppi, G. (2002) 'Remarks on Space-time and Locality in Everett's Interpretation', in T. Placek and J. Butterfield (eds.), *Non-Locality and Modality*, Dordrecht: Kluwer Academic, pp. 105–22.

Balashov, Y. and Janssen, M. (2003) 'Presentism and Relativity: A Critical Notice', *British Journal for the Philosophy of Science* 54, 327–46.

Barrett, J.A. (1999) *The Quantum Mechanics of Minds and Worlds*, NY: Oxford University Press.

Bell, J.S. (1987) *Speakable and Unspeakable in Quantum Mechanics*, Cambridge: Cambridge University Press.

Belot, G. (forthcoming) 'Dust, Time and Symmetry', *British Journal for the Philosophy of Science*.
Callender, C. (2000) 'Shedding Light on Time', *Philosophy of Science*, 67, S587–S599.
Callender, C. and Weingard, R. (1997) 'Trouble in Paradise? Problems for Bohm's Theory', *Monist*, 80 (1), 24–43.
—— (1995) 'A Bohmian Model of Quantum Cosmology', *Philosophy of Science (Proceedings)*, 1, 228–37.
Clifton, R. and Hogarth, M. (1995) 'The Definability of Objective Becoming in Minkowski Spacetime', *Synthese*, 103, 355–87.
Christian, J. (2001) 'Why the Quantum Must Yield to Gravity' in Callender, C. and Huggett, N. (eds.) *Physics Meets Philosophy at the Planck Length*, Cambridge: Cambridge University Press, pp. 305–38.
Craig, W.L. (2001) *Time and the Metaphysics of Relativity*, Dordrecht: Kluwer Academic Publishers.
Dainton, B. (2001) *Time and Space*, Montreal: McGill Press.
Dorato, M. (1996) 'On Becoming, Relativity, and Nonseparability', *Philosophy of Science*, 64, 585–604.
Dürr, D., Goldstein, S., Tumulka, R. and Zanghì, N. (2003) 'Bohmian Mechanics and Quantum Field Theory', *Physical Review Letters*, 93, 090402, 1–4.
Dürr, D., Goldstein, S., Münch-Berndl, K. and Zanghì, N. (1999) 'Hypersurface Bohm-Dirac Models', *Physical Review A*, 60, 2729–36.
Ghirardi, G.C., Rimini, A. and Weber, T. (1986) 'Unified Dynamics for Microscopic and Macroscopic Systems', *Physical Review D*, 34, 440–91.
Jansen, M. (2002) 'Reconsidering a Scientific Revolution: The Case of Einstein Versus Lorentz', *Physics in Perspective*, 4, 421–46.
Lewis, D. (1994) 'Humean Supervenience Debugged', *Mind*, 103, 473–90.
Lucas, J.R. (1998) 'Transcendental Tense II', *Aristotelian Society Supplementary Volume*, 72, 29–43.
—— (1999) 'A Century of Time' in Jeremy Butterfield (ed.) *The Arguments of Time*, NY: Oxford University Press, pp. 1–20.
Maudlin, T. (1994) *Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics*, Cambridge, MA: Blackwell.
—— (1996) 'Space-Time in the Quantum World', in J. Cushing, A. Fine and S. Goldstein (eds.) *Bohmian Mechanics and Quantum Theory: An Appraisal*, Dordrecht: Kluwer, pp. 285–307.
Monton, B. (2005) 'Presentism and Quantum Gravity', *The Ontology of Spacetime*, edited by Dennis Dieks, forthcoming.
Popper, K. (1982) *Quantum Theory and the Schism in Physics*, Hutchison: London.
Putnam, H. (1967) 'Time and Physical Geometry', *Journal of Philosophy*, 64, 240–47.
Rakic, N. (1997) 'Past, Present and Future and Special Relativity', *British Journal for the Philosophy of Science*, 48, 257–80.
Rietdijk, C. (1966) 'A Rigorous Proof of Determinism Derived From the Special Theory of Relativity', *Philosophy of Science*, 33, 341–44.
Savitt, S. (2002) 'Being and Becoming in Modern Physics', in Edward N. Zalta (ed.) *The Stanford Encyclopedia of Philosophy (Spring Edition)*, available online at: http://plato.stanford.edu/archives/spr2002/entries/spacetime-bebecome/
Saunders, S. (2002) 'How Relativity Contradicts Presentism', in C. Callender (ed.) *Time, Reality and Experience*, Cambridge: Cambridge University Press.

Shanks, N. (1991) 'Probabilistic Physics and the Metaphysics of Time,' *The South African Journal of Philosophy*, 10 (2), 37–43.

Shimony, A. (1993) *Search for a Naturalistic World View*, Vol. II, Cambridge: Cambridge University Press.

—— (1998) 'Implications of Transience for Spacetime Structure' in S.A. Huggett, L.J. Mason, K.P. Tod, S.T. Tsou, and N.M.J. Woodhouse (eds.) *The Geometric Universe: Science, Geometry and the Work of Roger Penrose*, Oxford: Oxford University Press, pp. 161–72.

Sobel, J.H. (1998) *Puzzles for the Will*, Toronto: University of Toronto Press.

Stapp, H.P. (1977) 'Quantum Mechanics, Local Causality, and Process Philosophy', edited by William B. Jones, *Process Studies* 7/3, pp. 173–82.

Stein, H. (1991) 'On Relativity Theory and Openness of the Future', *Philosophy of Science*, 58, 147–67.

Whitrow, G. (1980) *The Natural Philosophy of Time*, Oxford: Oxford University Press.