EPR and the ‘Passage’of Time

> Temporality does not come from mechanics but statistical mechanics..... C. Rovelli, The Disappearance of Space and Time, in D. Dieks (ed.), *The Ontology of Space-time* (2006), §3

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Abstract

The essay revisits the puzzle of the ‘passage’ of time in relation to EPR-type measurements and asks what philosophical consequences can be drawn from them. Some argue that the lack of invariance of temporal order in the measurement of a space-like related EPR pair, under relativistic motion, casts serious doubts on the ‘reality’ of the lapse of time. Others argue that certain features of quantum mechanics establish a tensed theory of time – understood here as Possibilism or the growing block universe. The paper analyzes the employment of frame-invariant entropic clocks in a relativistic setting and argues that tenselessness does not imply timelessness. But this conclusion does not support a tensed theory of time, which requires a preferred foliation. It is argued that the only reliable inference from the EPR example and the use of entropic clocks is an inference not just to a Leibnizian order of the succession of events but a frame-invariant order according to some selected clocks.

Der vorliegende Aufsatz fragt, welche Konsequenzen für das Rätsel des Zeitpfeils aus der Betrachtung von relativistischen EPR-Paaren gezogen werden können. Die fehlende Invarianz der Zeitordnung bei raumartig getrennten relativistischen EPR-Paaren scheint einerseits Zweifel an der ‚Realität‘ des Zeitablaufs aufkommen zu lassen. Andererseits scheinen gewisse Mermale der Quantenmechanik, wie der Kollaps der Wellenfunktion, eine temporale Zeittheorie – hier im Sinne des Possibilismus oder des wachsenden Blockuniversums – zu erlauben. Der Aufsatz untersucht den Einsatz von bezugssystem-unabhängigen entropischen Uhren, bei relativistischen Geschwindigkeiten, und zeigt daß das Fehlen von temporalen Formen keinen Schluß auf Zeitlosigkeit bedeutet. Der Schluß unterstützt jedoch keine temporale Zeittheorie, die eine ausgezeichnete Schichtung der Ebenen der Raum-Zeit erfordert. Der Einsatz von entropischen Uhren bei relativistischen EPR-Paaren erlaubt als einzige Folgerung eine (Leibnizsche) bezugssystem-unabhängige Zeitordnung, zufolge ausgewählter Uhren.

EPR and the ‘Passage’ of Time

I. Introduction

Over the years researchers have proposed a number of physical criteria to characterize temporal asymmetry in a physical sense, e.g. statistical-mechanical entropy, quantum measurements, the collapse of the wave-function, decoherence and the expansion of the universe. At the same time a debate in the metaphysics of time between Eternalism (Block Universe), Presentism (Moving Now) and Possibilism (fixed past, open future) has tried to muster the results of scientific theories (quantum mechanics, theory of relativity, thermodynamics) in support of these rival conceptions. According to Eternalism, past, present and future equally exist, while Presentism will accord existence only to the momentary moving Now. Possibilism requires the past to be fixed, the present moment to be distinguished and the future to be open. (Savitt 2001) The motion of the present Now constitutes temporal becoming. The significance of the present seems to imply that there must be a unique Now, on which all observers can agree. In the language of space-time physics this claim amounts to the demand of a ‘unique hyperplane’ or ‘preferred foliation’. These requirements also mean that the ‘passage’ of time cannot simply be a psychological affair – an impression of flow confined to the minds of individual observers. As space-time does not depend on the existence of observers, the impression of ‘flow’ must correspond to some passage of physical events in the real world, from which the ‘passage’ of time is inferred. The question to be considered is whether Possibilism is compatible with the measurement of relativistic EPR-pairs.[1]

Whilst these discussions seem to have reached a certain stalemate, there is nevertheless some agreement between the opposite views. Firstly, it is agreed that philosophical positions should be sensitive to scientific development. (Cf. Dieks 1988; Callender 2007; Dorato 2006) Secondly, the opponents seem to share the assumption that these divergent and incompatible metaphysical positionsare *deductive* consequences of the respective

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[1] Callender’s 2007 paper, which will be the focus of Section III, is concerned with ‘tensed theories of time’ by which he means the metaphysical positions of Presentism and Possibilism (or the growing block universe). Callender (2000, S 587) describes Presentism as picturing the ‘four-manifold as foliated via an equivalence relation, simultaneity, and time as the one-dimensional linearly ordered quotient set induced by simultaneity. Three-dimensional leaves of simultaneous events successively flash into and out of being….’.

scientific theories. In the present paper ‘deductive consequences’ means that they can be deduced from the principles of the respective theories. For instance, it follows from the principles of relativity that coordinate systems in relative motion with respect to each other may not agree on the simultaneity of events but it does not follow from these principles that the world is a four-dimensional static block universe. Notions like stasis or flux, Eternalism and Possibilism are philosophical implications of these principles. However, the very fact that these opposite standpoints can be inferred from scientific theories suggests that it may be more appropriate to regard metaphysical positions as *philosophical* consequences of scientific theories. Such a viewpoint means that they are at best compatible or incompatible with scientific results – and hence more or less plausible in the light of scientific theories.

Whilst the above-mentioned physical criteria have been well explored in the literature with respect to the ‘passage’ of time, the Einstein-Podolsky-Rosen (EPR) correlations in a relativistic context have received less attention but are equally puzzling in the quest for the anisotropy of time. (See Aharonov *et al.*1964; 1981; 1980; Callender 2007; Penrose 1989; 1994; 2004) The EPR correlations are a further example, as discussed in this paper, of how mutually incompatible philosophical consequences are inferred from relevant scientific theories.

The measurement of entangled spin-½ particles from the point of view of relativistically moving observers encounters the well-known problem of the relativity of simultaneity, a phenomenon, from which a long list of physicists had already inferred either the ‘unreality’ of time or at least the ‘flow’ of time along a world line, i.e. proper time. (Cf. Dieks 1988; Harrington 2008; Rakić 1997) However, such inferences are often drawn without due care to *all* the factors, which should be taken into account to make reasonable statements about the ‘nature’ of time. It is not immediately obvious why the non-coincidence of the simultaneity hyperplanes of two observers, moving at relativistic speeds with respect to each other, should lead to the often-reached Parmenidean conclusion that time is unreal. If it is correct that these philosophical positions are to be inferred from scientific theories, then the argument should focus on physical parameters – like the behaviour of clocks or the measurement of spin-½ particles – without presupposing such notions as ‘becoming’, ‘stasis’ or Heraclitean ‘flux’ – and draw plausible conclusions regarding the nature of time from such results. (Cf. Dorato 2006) If metaphysical positions, like Eternalism and Presentism, Parmenidean stasis and Heraclitean flux, are merely philosophical (rather than deductive) consequences of scientific theories, then the relevant questions should be: a) Given observers, attached to inertial systems in relativistic motion with respect to each other, how do they register, say, the EPR correlations and b) what plausible consequences regarding the 'passage' of time would they be allowed to infer? The aim of the present paper is to re-examine the question of the 'passage' of time with respect to the EPR correlations in a relativistic setting and to take both physical and philosophical criteria into consideration; and in particular to draw attention to covariant and invariant relationships. The question, then, is what philosophical consequences regarding the lapse of time follow from this approach. The analysis in this paper results in the view that the EPR correlations, if considered from the point of view of the use of frame-invariant entropic clocks, support an inference to a tenseless 'passage' of time but that even an invariant 'passage' of time, as indicated by a pair of entropic clocks, falls short of the required criteria for a tensed theory of time.

II. Quantum Measurement and the 'Passage' of Time

Consider, first then, the ordinary non-relativistic case of a measurement process on an EPR pair. (Cf. Penrose 2004, 606; 1994, 294) In such a case only one coordinate system is relevant – the one in which the measurement occurs. The temporal ordering of events poses no problem. When the spin state of one member of the EPR pair, say +½, is measured the other instantaneously 'collapses' to -½ and a later measurement on the second member unambiguously finds a reduced or unentangled state. This reduction occurs irrespective of the distance between them. Let two observers be space-like separated.[2] Experimenter *A* performs a measurement on an EPR pair, which reduces the entangled state to an unentangled state. Experimenter *B* may be so far away from *A*'s laboratory that some time, *t*, elapses before *B* can be informed of the measurement result. *B* is space-like separated from *A*. *A* may perform a subsequent measurement on the unentangled state but *B* will not be confused about the temporal ordering of these events, as *A* and *B* are taken to be at rest with respect to each other. A third observer, *C*, also at rest with respect to *A* and *B* will

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[2] 'Space-like' separation means that the observers are close enough in time but too far apart in space for finite signals to connect them at the moment of detection.

regard *A*'s measurement of the spin states of the EPR pair as effecting the disentanglement, while *A*, according to *C*, may perform a later measurement with a disentangled component of the pair. (Figure I)

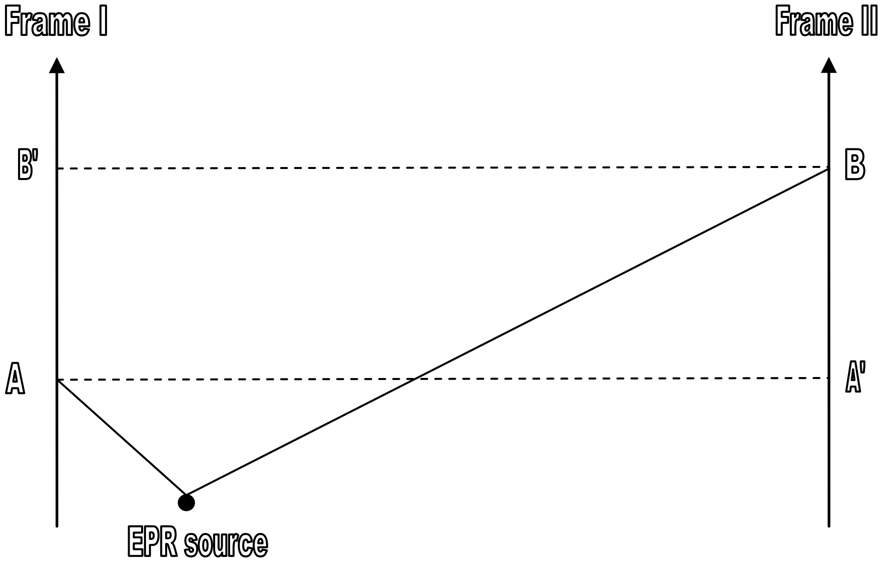

Figure I: From the point of view of an inertial frame, the detector A registers first, which simultaneously reduces the state at A', which lies outside of A's light cone. The reduced state is detected later, at B, in frame II, a point, which is simultaneous with B' in frame I.

If relativistically moving frames are brought into consideration, the agreement on the unique temporal succession of events is upset and encounters the 'relative simultaneity' problem. Let one experimenter, *B*, move at relativistic speeds, with respect to another experimenter, *A*. (Figure II) If the two experimenters are in relativistic motion with respect to each other, there will be disagreement about the moments of measurement and detection. In frame I measuring event A (measuring +½) is simultaneous with B (the jump to -½) but in frame II A is simultaneous with A' and B is simultaneous with B', so that adetector in frame II will experience the reduced, unentangled state at B', which is prior to A, the measurement act, in frame I. This situation is often labelled a 'paradox' in the literature (Aharonov/Albert 1981; Penrose 2004; Callender 2007). What seems paradoxical is that, if the 'collapse' of the wave function is 'real' or at least if the detection event is real then it seems that it is not possible for both observers in their respective frames to be correct about the temporal order of events. These observers may reasonably ask themselves what

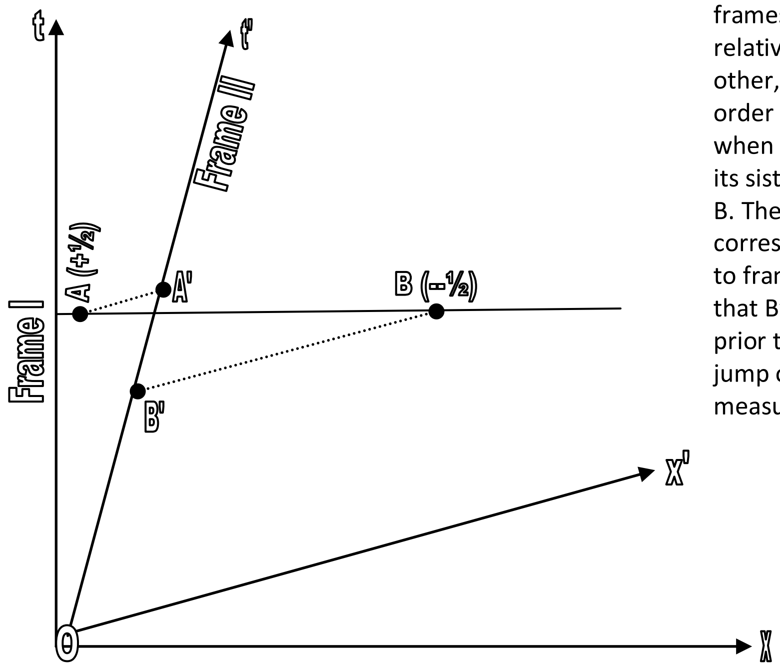

Figure II: According to the Special theory of relativity the two observers, in frames I and II respectively, in relativistic motion with respect to each other, disagree about the temporal order of events. According to frame I, when the photon is measured at A (+½) its sister jumps instantaneously to -½ at B. The act of measurement, A, corresponds to A' in frame II. According to frame II A' is simultaneous with A so that B', simultaneous with B, occurs prior to A. According to frame II, the jump occurs (at B') before the measurement act at A.

implication this paradoxical situation has for the understanding of the lapse of time. What inferences regarding the nature of time are to be drawn from this version of relative simultaneity? It will be convenient to start with a brief review of the physics literature before addressing Callender's argument, in terms of relativistic EPR pairs, against a tensed theory of time. This review shows that the problem is essentially due to the 'relativity of simultaneity', which also affects the EPR-correlations, but does not depend on any particular interpretation of the measurement process in quantum mechanics.

III. What Physics says.

According to the physics literature several conclusions can be drawn from this situation.

1. It is a requirement of relativistic quantum field theory that the temporal ordering of space-like related events is irrelevant, which means that the two measurements commute, and that the invariant features are the joint probabilities.

> The local observables of any relativistic quantum field theory are required to commute at spacelike separations, and therefore the results of two spacelike-separated local experiments will not depend upon the order in which these experiments are carried out.

> (…) If (…) each observer applies the postulate of instantaneous reduction to his *own* frame, all will nonetheless derive identical (i.e., covariant) experimental predictions for *local* observables. (Aharonov/Albert 1981, 369; italics in original)

Similarly, Penrose states that

> (…) this kind of symmetry is a necessary feature of EPR measurements in order that they be consistent with the observational consequences of special relativity. Measurements that are performed at space-like separated events (i.e. events lying outside each other's light cones (…) must necessarily commute and it is indeed immaterial which measurement is considered to occur 'first' – according to the firm principles of special relativity. (Penrose 1994, 294-5)

2. A consequence of the requirement that 'local measurements must commute at space-like separations' (Aharonov/Albert 1980, 3322) is that, whilst 'collapse' along equal time hypersurfaces is not covariant – as the EPR case shows - , the probability distributions are Lorentz-covariant. (Aharonov/Albert 1980, 3323; Aharonov/Albert 1981, 361)
3. A further consequence, according to Aharonov and Albert, is the non-covariance of the state history in relativistic quantum field theories. Whilst in the non-relativistic case, a unique state history results from the equations of motion and the measurement act, this is not the case in relativistic quantum field theories. The reason for this situation is that 'no relativistically satisfactory version of the collapse postulate can be found.' (Aharonov/Albert 1980, 3316)

> (…) it will turn out that *no* covariant succession of states at a given time can consistently be associated with the system, although the notion of a state will continue to make sense within a given Lorentz frame. (Aharonov/Albert 1981, 361; italics in original)

That is, the history of a primed frame, which collapses at $t = t'$, will not be a Lorentz-transformed version of an unprimed frame. (Aharonov/Albert 1980, 3323) For instance, if a free particle is prepared in a momentum eigenstate at $t = -\infty$ in an unprimed frame, and if at t = 0 the location of the particle is measured by interaction with an appropriate device, the wave-function of the particle will change instantaneously from a momentum eigenfunction to a position eigenfunction. But this change of state will not occur instantaneously in any other primed frame moving relativistically with respect to the unprimed frame so that '*no* covariant succession of states at a given time can consistently be associated with the system.'

According to Aharonov and Albert, observers derive covariant probabilities for both local and non-local observables (like total charge in a system) because the latter are

> ‘ultimately’ local ones; that is, measurements are carried out on them by ‘*local* observations on the measuring apparatus.’ (Aharonov/Albert 1981, 369; 1980, 3322) Such claims are controversial[3] but they have no further implications for the argument in this paper.

In sum, relativistic field theories have the capacity to correctly predict probabilities but not to define covariantly the state history of relativistic systems, like the EPR case. A state history can be defined for the non-relativistic case but not for the relativistic case, although probabilities are covariant for both cases.

> If *A* monitors the succession of states at a given time in his own frame, this will with certainty confirm that the reduction process occurs along *t*=0, and will alter the state history as observed in *B*; and, conversely, if *B* monitors the state history in [frame] *k’*, then this will with certainty confirm that the reduction occurs along *t’*=0, and will alter the history as observed by *A*. Either of these two conflicting accounts, therefore, can be confirmed by experiment, and in this sense each of them is correct; and this involves no contradiction, since the two different measuring procedures, whereby these two accounts can, respectively, be confirmed cannot *both* be carried out on the same system. (Aharonov/Albert 1981, 365; Aharonov/Albert 1980, 3321; italics in original)

Clearly the covariance of the probability distributions, accompanied by a lack of covariance of a state history, does not warrant an inference to the ‘passage’ of time. Nevertheless, the authors observe, with respect to the radiation arrow, that ‘the nature of ensembles or beamsactually occurring in nature (…) is determined by the same cause as all macroscopic irreversibility, conceivably by the expansion of the universe’ (Aharonov *et al.*1964, B1416) or, they add, the ‘second law of thermodynamics’ (*ibidem* B1410). Thus, even though there is a covariance of the probability distribution but no ‘covariant collapse along equal time hypersurfaces’ (Aharonov/Albert 1980, §iv), there is at least a *de facto* ‘arrow’ of time if appropriate criteria are taken into consideration. But this very point is often neglected in the philosophical literature, where the view prevails that metaphysical positions follow deductively from the principles of scientific theories.[4]

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[3] Halvorson and Clifton argue that a relativistic quantum field theory (RQFT) does not permit an ontology of localizable particles. But RQFT ‘has no trouble explaining the appearance of macroscopically well-localized objects, and shows that our talk of particles, though a *façon de parler*, has a legitimate role to play in empirically testing the theory.’ (Halvorson and Clifton 2002, 23; italics in original) In a later paper they show that Algebraic Quantum Field Theory imposes practical and theoretical limits on an experimenter’s ability to ‘destroy entanglement between her field system [A] and [environment] *B*.’ (Clifton/Halvorson 2008, 5)

[4] John Earman, for instance, has offered a reformulation of McTaggart’s argument for the unreality of time in the General theory:

Penrose also appeals both to the invariance of the observational results (covariant probabilities) and the symmetry of the temporal relation, which is'a necessary feature of EPR measurements in order that they be consistent with the observational consequences of special relativity.' (Penrose 1994, 388) Penrose concludes from this situation that it requires a new understanding of 'reality' in the wake of the EPR correlations.

> The joint probabilities come out the same either way but O has a different picture of 'reality' from the one that I and my colleague had before. If we think of [the measurement] **R** as a real process then we seem to be in conflict with the principles of special relativity because there are two incompatible views as to which of us effected the reduction of the state and which of us observed the reduced state after reduction.' (Penrose 2005, 606-7; bold in original)

Although Penrose is in agreement with Aharonov *et al.* that the 'arrow' of time has to be accounted for by some other criterion, like the second law of thermodynamics, these discussions nevertheless reveal a certain conflation between, on the one hand, the question of the 'reality' of wave-function collapse, and, on the other hand, the puzzle of the anisotropy of time. Callender's criticism of Possibilism also assumes that an understanding of the behaviour of the wave-function has a significant impact on the question of the lapse of time.

IV. What Philosophy Says

Craig Callender regards this mismatch of the observers' temporal ordering of relativistic EPR events as a fatal blow to the 'tensed theory of time' (characterized as a transient Now, connecting the fixed past to the open future). Callender's assessment is only the latest position in a long-running debate about Parmenidean *stasis* versus Heraclitean *flux*, which goes back to Einstein and Minkowski. (Cf. Dieks 1988, Harrington 2008; Dorato 2006; Weinert 2004; 2013) It follows from the relativity of simultaneity in the Special theory of

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(P1') There must be physical change, if there is to be physical time.
(P2') Physical change occurs only if some genuine physical magnitude (a.k.a.''observable'') takes on different values at different times.
(P3') No genuine physical magnitude countenanced in the General theory changes over time.
From (P2') and (P3') Earman arrives at his first conclusion:
(C') If the set of physical magnitudes countenanced in the General theory is complete, then there is no physical change.
And from (P1') and (C') he arrives at his second conclusion:
(C'') Physical time as described by the General theory is unreal (Earman 2002, 5). According to Earman the frozen dynamic of the General theory implies the unreality of time; i.e. Earman 'derives' the unreality of time from the structure of the General theory but does not consider other criteria.

relativity that there exists no universal Now, since different observers judge the simultaneity of events according to their respective coordinate systems, which are in inertial motion with respect to each other. Although the clocks are invariant in each coordinate system (proper time), they are not invariant across different coordinate systems (co-ordinate time) and hence there are as many Nows as there are co-ordinate systems. But if there is no universal Now, there is no unique simultaneity plane and hence no unique time axis, as in classical mechanics. These discussions usually revolve around the compatibility or incompatibility of the relativity of simultaneity with a dynamic, tenseless, view of time.[5] Whatever version of a tenseless view is adopted, Callender's case is an attack on the belief that quantum mechanics 'makes the world hospitable to a tensed theory of time' since 'tensers' may still take refuge in some peculiar features of quantum mechanics: 1) Popper (1982, 30) argued that quantum non-locality required a preferred foliation of space-time to explain the Bell correlations; for it seems that the 'action-at-a-distance' between a space-like separated EPR-pair requires the simultaneity of the effect of a measurement on one component on its distant cousin; and 2) wave-function collapse seems to rescue temporal becoming. Callender claims that it is impossible to address the apparent conflict of non-locality and relative simultaneity in the absence of any interpretation of quantum mechanics. 'The mechanism responsible for enforcing the space-like correlations varies with interpretation.' (Callender 2007, 5) Although Callender refers to 'fundamental' physics, it is worth noting that the interpretation of what happens during 'collapse' is not at present part of an established agreed theory. The discussion in Section II has shown that this problem can be stated without any reference to interpretational issues of the quantum-mechanical measurement process. It arises because the space-like EPR-correlations are subject to the constraints of relativistic simultaneity. What matters is the detection of the measurement result, not the 'collapse' mechanism.

Against the first claim Callender develops a 'coordination problem' for tensers: The tensers must claim that one frame measures before the other frame but this may not be the

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[5] Callender seems to agree with Putnam (1967) and Rietdijk (1966) that the Special theory of relativity (STR) supports some sort of block universe: 'physics – and science itself – will always be against tenses because scientific methodology is always against superfluous pomp.' (Callender 2007, 18; see also Callender 2000) But in a later paper Callender (2008) characterizes the tenseless view as one whose fundamental properties are the relations of precedence and simultaneity between events. This characterization reveals a much more Leibnizian position, according to which time is the order of succession of events. Hence tenselessness does not imply timelessness.

preferred frame according to physics or interpretational frameworks. In other words, on various interpretations of the quantum measurement process (Bohm's view or the Ghirardi, Rimini and Weber model) the foliation does not correspond to the required metaphysics. The upshot is that no measurement will narrow down the preferred foliation. (Callender 2007, 15, 16; cf. Maudlin 1996) However, the question of foliation is independent of the question of quantum-mechanical interpretations, since it appears in all relativistic settings. It needs to be differentiated according to the relativistic and non-relativistic case. As Maudlin (1996) reminds us notions like absolute simultaneity and absolute time order are a consequence of the non-relativistic case, since the underlying space-time is a Galilean (or neo-Newtonian) structure. In the non-relativistic case one could 'foliate the space-time with space-like hyperplanes, which may be used, in essence, to define a preferred synchronization between widely separated systems.' (Maudlin 1996, 294-5) The real problem arises when the moment of detection becomes dependent on the hyperplane from which the event is observed; 'pairs, associated with *different* foliations, pose an entirely new, relativistic problem.' (Maudlin 1996, 301; italics in original)

With regard to the second claim, Callender also denies that 'real' collapse of the wave-function justifies a notion of quantum becoming. The open/fixed distinction does not map neatly onto the superposition/eigenstate distinction. One may add that if wave-function collapse happens, it happens in particular laboratory situations, which may present a poor criterion for the global distinction between the fixity of the past and the openness of the future. It may also be recalled that the computation of the probability outcomes in the above EPR case is time-symmetric.

One may have sympathy for Callender's view not to overload the scientific base structure with a metaphysical superstructure. Hence it is helpful to distinguish between the consequences, which follow deductively from the structure of scientific theories and mere philosophical consequences, which follow with more or less plausibility.

Nevertheless, tensers may not find Callender's arguments quite compelling:

a. Scientists and philosophers will no doubt agree that physics should explain our experience of the 'flow' of time, i.e. not only our psychological time sense but the intersubjective, objective lapse of time as revealed in many physical situations. Here it may be possible to refer to Stein's theorem, which defines a two-place relation, *yRx*, of y 'having become' with respect to space-time point, x, where R is both transitive (*yRx* and *yRz*) and reflexive (*xRx*). (Stein 1968, 15; cf. Savitt 2001, 16; Callender 2000) In the literature such considerations lead to notions like 'relational becoming' (Dorato 2006, §4) or chronological becoming along a world line (Clifton/Hogart 1996), but references to the invariance of proper time – the time shown by an appropriate clock along its world line - do not capture the point at issue here, which is the effect of relative simultaneity in the EPR case, which presumably prevents tensers from locating 'passage' in the area of quantum mechanics. The tensers' notion of 'passage' requires some preferred foliation (or simultaneity hyperplane) so that a tensed theory of time should seek some covariant state history, as discussed below, to save the notion of (global) 'passage'.

b. Although Callender seems to agree with Maudlin's warning against 'the dangers of launching into investigations of Relativity before having settled basic interpretational problems', (Maudlin 1996, 303-4), a different conclusion may be drawn. Given the apparent dependence of the mechanism of collapse on the divergent interpretations of the quantum-mechanical measurement process and the difficulties this poses for the tensers, any inferences regarding the nature of time from the wave-function collapse picture becomes unreliable and calls for different criteria to assess the question of the 'passage' of time, either – for instance - in terms of the foliation of space-time by appropriate hyperplanes or in terms of the thermodynamic features of appropriate clocks, as discussed below. (Recall that the physics literature cited above makes no reference to interpretational problems; i.e. the problem can be stated in terms of the relativity of simultaneity and detection events.)A physical mechanism may eventually be found, which explains the 'reality' of collapse but such an explanation would not single out a preferred foliation nor would it help to determine the measurement of the objective 'passage' of time. The claim that 'there is a unique hyperplane advancing throughout the whole of the universe of collapse into eigen-ness' (Lucas 1999, quoted in Callender 2007, 10) does not follow from EPR-like measurement situations, as will be discussed below.

c. Callender does not consider other aspects of scientific theories, which may shed further light on which plausible consequences could be drawn from the scientific problem situation, and which may be helpful to any theory, which wishes to save the notion of 'passage'. Although physics allows for the covariance of the probability distributions, which are time- symmetric, there may nevertheless be invariant processes, whose existence in nature and role in scientific theories may throw some light on the nature of time, as hinted at by Aharonov *et al.* (1964) and Penrose (2004).

d. In his analysis Callender does not sufficiently stress that the temporal ordering of the non-relativistic situation provokes no disagreement about the order of events. This point is, however, central in the analysis given by Aharonov *et al.* (1980; 1981) and Penrose (1989; 1994). The measurement of one member of the EPR pair immediately reduces the state of the other member (over large distances). A later measurement than encounters a reduced (unentangled) state. There is no disagreement about temporal ordering because at sufficiently low velocities a relativistic space-time world approximates a Galilean space-time structure and a universal Now. (Figure I) The disagreement arises from the introduction of an observer moving relativistically with respect to observers at rest, as discussed above. This discord, however, leads to a paradoxical consequence. When these observers move at speeds, relatively close to the speed of light (say 2/3 c), the disturbing effect arises. But when the same observers slow down to non-relativistic speeds and, to all appearances, to a classical world, the effect disappears! The same paradox affects the Aharonov/Albert view about the non-covariance of a pair's history of state. They claim that 'in contrast to the nonrelativistic case, it is not possible to define the quantum state of a system in relativistic quantum field theories, because in this latter case no consistent description of how the state changes as the result of a measurement can be developed.' (Aharonov/Albert 1980, 3316) But there is no precise boundary at which the non-covariance of the state histories arises. There is an even more dramatic illustration of this paradoxical situation. Penrose (1989, 260; cf. Savitt 2001, 10, 15) imagines two people, walking past each other in the street, who come to different conclusions regarding the temporal ordering of some events on the Andromeda galaxy. Although only slow velocities are involved their disagreement concerns the question whether some event *A* occurs earlier or later than some event *B*. But if, on a different day, the two walkers meet for a chat they

> will find themselves in agreement as to the temporal ordering of events on the Andromeda galaxy. The problem is that the theory of relativity specifies no 'phase' transitions at which relativistic space-time becomes Galilean space-time; just as there is not precise scale at which the quantum level goes over to the classical world. (Cf. Penrose 1994, 308) The tenser may well conclude that this paradox of reference frames blocks any inference to the unreality of the lapse of time.

It seems, so far, that questions of the temporal ordering of events, as well as the reality of collapse, depend on the velocity of the reference frames. Penrose, referring to the EPR-type experiments, concludes that 'there is a definite conflict with the spirit of relativity in our picture of 'physical reality'.' (Penrose 1989, 370) Do these scenarios suggest, then, that the effects are merely perspectival? It would certainly be unwise for the two observers to jump to the conclusion that 'time is unreal', since they have not yet explored other physical criteria, which may throw light on the 'passage' of time.

For these reasons it will be assumed (in what follows) that the observers involved in the relativistic EPR experiment operate behind a 'veil of ignorance', i.e. that they neither have any predetermined metaphysical views of the 'reality' or 'unreality' of time, nor any firm philosophical commitment to a particular interpretation of the measurement process, which is conventionally taken to be responsible for the reduction of the state vector. Clearly, the 'reality' of wave-function collapse or the objective 'passage' of time cannot be a function of interpretational issues in quantum mechanics. If they were, it would only reinforce the call for other criteria to be taken into account. How would the observers reason from behind such a veil of ignorance?

V. From an invariant point of view

When the observers come across the non-invariance of temporal ordering in the EPR measurements, their initial reaction may well be a Gödelian-like argument from the relativity of simultaneity to a denial of the objective 'passage' of time (or an inference to the block universe). Gödel (1949) makes the assumption that time is real only if space-time admits of a global time function, which implies that there is an unambiguous order of temporal events. As there is no such unambiguous time order in the relativistic EPR events on the observational level (Maudlin 1996), one possible inference may well be that there is no objective lapse of time in a relativistic universe. But it is not immediately obvious why a disagreement about simultaneity or temporal order should lead to such drastic steps as the endorsement of a block universe. Before such a radical step is taken the observers should investigate whether there exist other physical criteria, from which inferences about the ‘passage’ of time could be drawn.

As already mentioned the ‘joint probabilities come out the same either way’ (Penrose 2004, 606) but this covariance of probability outcomes cannot shed any light on the question of the anisotropy of time. Disagreement about the temporal order of space-like related events in either the relativistic or the non-relativistic case is a consequence of Minkowski space-time so that the ‘question of which of these measurements actually comes *first* is not really physically meaningful but depends on the observer’s state of motion.’ (Penrose 1989, 371; italics in original) A general agreement on this perspectival conclusion seems to prevail.

> In the case of space-like connected events simultaneity between such events can only be of a conventional, not of a fundamental kind. (Joos 1951, 241; Weingard 1972, 119)

Why does the problem arise in the first place? The EPR pair is space-like separated at the time of detection but has a common origin. (Figure I, II) What more, then, can be said about the disagreement about temporal order?

As Aharonov and Albert, as well as Penrose, indicate there are other important temporal indicators to which the observers may appeal. It is a well-known fact that a quantum measurement increases the entropy of the measured system. (Schlosshauer 2008, 41; Aharonov*et al.* 1964, B1410; Penrose 2004, 822, 845) Of particular importance is the fact that entropy is an invariant relation, hence one on which the two observers would agree, irrespective of their state of motion. (Einstein 1907; Planck 1907; Eddington 1932, 101)) Even though the observers will disagree about the temporal order of events, they will agree on the increase of the entropy gradient in the measurement process at the point of detection.[6]

Furthermore, their observational disagreement can be made to disappear if, by reducing their speeds, their description of temporal order can be reformulated in Galilean space-time; hence by transformation to a different reference frame.

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[6] Whist there are other conserved quantities like the total mass energy of a compound system or the angular momentum, entropy is particularly important because it is a criterion for the ‘passage’ of time.

As the disagreement about the temporal ordering of the EPR measurement events seems to be perspectival – in the sense of being a function of their state of motion - the observers could contemplate other criteria for the lapse of time as more reliable than the perspectival temporal ordering in the EPR measurement process: for instance, the expansion of the universe or thermodynamic processes. (Cf. Aharonov *et al.* 1964, B1410)
However, Callender dismisses the tensers' strategy to appeal to 'cosmic times' as a response to threats from the General theory of relativity:

> 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. (Callender 2007, 16)

Tensers will point out that the problem is not the coordination of the 'psychological lapse of time' with physical time. The problem is the objective measurement of the 'flow' of time or an objective distinction between past and future in time-orientable space-time. (Cf. Lehmkuhl 2012) Callender rightly stresses that physical and psychological time are separate issues. For instance, psychological time has neither enough regularity nor sufficient invariance to serve as a reliable clock. What is required of the observers in the case under consideration is the adoption of physical criteria, from which they can draw inferences about the anisotropy of time. The appeal to cosmic time seems to suggest that the observers could refer to one unique reference frame, as defined by a co-moving patch (a time slice) in the history of the universe, to settle their disagreement about the temporal ordering of events in the EPR experiment. The standard FLRW (Friedmann-Lemaître-Robertson-Walker) models of the universe are equipped with an upward-pointing time axis (starting from the Big Bang) and each model has a '1-parameter family of non-intersecting homogeneous space-like 3-surfaces Υ_t giving space at time t.' (Penrose 2004, 719) The co-moving patch, which follows the history of our observable universe, has an entropy today of approximately 10^{101}, which is much larger than at earlier times. (Cf. Penrose 2004, 718; Carroll 2010, 334) Such a comoving patch may help to define a universal Now – a cosmic time - but it would hardly be suitable to serve either as a criterion for the psychological lapse of time or as a clock in the present case, since the observers remain attached to their individual frames, which leads to the puzzle of the lack of agreement about the temporal ordering of events. The observers will be well advised to look for other criteria to establish the ordering of events.

Could our observers make any progress by using an entropic clock? Would it lead to a tensed theory of time? Entropy is frame-invariant by the principles of thermodynamics. As increases in entropy are invariant, they do not depend on the state of motion of a particular reference frame. Such entropic clocks would replace the reference to cosmic time scales but would they give the tenser a preferred foliation of hyperplanes?

VI. Thermodynamic Clocks

In a thermodynamic system, moving with a relative velocity, *v*, with respect to another system, considered at rest, several thermodynamic parameters remain invariant, i.e. the pressure *p*, the number of particles *N* and the entropy *S*. (Einstein 1907; Planck 1907)

$$p = p_0; N = N_0; S = S_0.$$

The question whether temperature, *T*, is also invariant is still controversial and at an experimental stage. (Weinert 2010) If this were the case, then, to adopt Einstein's famous train thought experiment, a cup of coffee drunk by a passenger on a fast-moving train would get neither colder nor hotter; it would have the same temperature as a cup of coffee drunk by a waiting passenger on a platform. If temperature were invariant, a specially constructed thermometer could be used by inertially moving observers at relativistic speeds to objectively measure the 'passage' of time. But relativistic thermodynamics offers other invariant parameters: we shall concentrate here on pressure, *p*, and in particular on the entropy, *S*, of thermodynamic systems. It is important to note that the lapse of time need not be measured by mechanical clocks, whose ticking rates are affected by relativistic speeds and gravitational fields, both resulting in a time dilation effect. It is equally important to note, for the arguments that follow, that physical time is based on physical processes. (Rugh/Zinknagel 2009) Such physical processes must display mathematically describable regularities, which are often of a periodic nature, since this periodicity helps to determine finite intervals of time. One problem, which arises in the Special theory of relativity is that clocks tick regularly in inertially moving systems, but their ticking is not invariant across such systems, as is revealed by the difference between proper and coordinate time. But if the regularities are to be invariant across different reference systems, two observers must clearly agree on the length of a temporal interval and the ticking rate of clocks. This is a prerequisite for the objective measurement of time. As several physicists have pointed out (Eddington 1932; Schlegel 1968, 1977) these features are satisfied by some of the thermodynamic parameters, mentioned above. Consider, for instance, two properties of a gas clock – its pressure and entropy – both of which are invariant according to relativistic thermodynamics. Such a clock could consist of a two-chamber system, connected by a valve, as used in thermodynamics, with gas molecules at $t = t_0$ being confined at first to, say, chamber A. When the valve is opened the gas molecules will, in accordance with thermodynamic laws, begin to fill chamber B until it reaches a final pressure, p_f. First, what does the invariance of p mean for the measurement of time in two inertial reference frames? As the relationship $p = p_o$ obtains, the pressure (force per unit area) is the same in these two systems, and independent of their respective velocities. In whichever way such clocks are built, the pressure measured will be the same for two observers. Hence the rate of change of pressure, $\Delta p = \Delta p_o$, is also the same (Schlegel 1968, 137), with the result that the pressure of gas clocks could be used as primitive clocks for two observers to coordinate activities in relativistically moving systems. When the two observers are at rest, carrying identical gas clocks in their respective systems, they can agree to perform a certain action, like an EPR-type experiment, when the pressure gauge reaches a certain value, p. What is important from the present point of view is that they will perform their action according to invariant clocks, since the proper times of the two gas clocks will agree. However, this agreement does not constitute a violation of the principle of relativity and does not give rise to a notion of 'absolute' simultaneity. Firstly, the gas clocks do not show the 'correct' time. They are not cosmic master clocks. They are simply two particular systems, amongst other clocks. Secondly, there are still as many clock times as there are reference frames. Thirdly, the theory of relativity forbids the choice of one particular clock as a preferred frame of reference, but it does not prohibit the choice of a particular type of clock as a criterion to draw inferences about the 'nature' of time. The proposal simply exploits an invariant feature of relativistic thermodynamics, in the same way that 'c' is an invariant feature of Minkowski space-time. Furthermore, the pressure gauge can serve as an invariant clock in the two systems, and hence 'time' in the two gas clocks ticks at the same rate, although they are in inertial motion with respect to each other, and at velocities which are relativistically significant. Whilst the two systems may move at high velocities, the motion of the gas molecules will not be affected by these relativistic speeds of the coordinate systems to which they are attached. And thus these observers will measure the 'passage' of time between their pre-arranged, coordinated actions, in an objective, frame-invariant manner. It may be called *thermal* time. (Cf. Rovelli 2009; Martinetti 2013)

A similar conclusion can be drawn from the consideration of entropy in relativistic systems. Boltzmann entropy is taken to be valid for all systems. (Carroll 2010, 284) The Lorentz-invariance of entropy in statistical mechanics follows from the equation $S = k \log N_o$. As $N = N_o$ – so that the number of microstates, N, does not depend on the velocity of the thermodynamic system - we also have $S = k \log N$, and hence $S = S_o$, where the spatial extension of the system in the x-direction must be kept small. It follows from this equation that, again, when the entropy reaches a certain state in one system, by the spreading of microstates into the available phase space, two observers can perform a prearranged action in their respective systems 'simultaneously' or in succession, according to their specific clocks. Note that the spreading of the microstates into the available phase space is a function of time, and this spreading of microstates into phase space occurs at the same rate. The spreading rate can therefore be used to define an entropy clock, Σ. Hence observers in two relativistically moving systems can use the rate of spreading of the microstates, which according to the equation, $S = S_o$, must be invariant, as a way of measuring the objective, frame-independent 'passage' of time, at least according to these clocks. Even the fact that one of the two systems, with an entropy clock Σ' attached to it, must be accelerated to reach its relativistic velocity does not change the invariant rate of entropy increment, δS, in the accelerated system. If we consider the velocity increase in the Σ'-clock as δv, then the invariance theorem can be written as $\frac{d}{dv}(\delta S) = 0$, and hence the change in velocity has no effect on δS.

> We must take it, then, that the Σ'-clock while being accelerated gains the same increments δS which comparable Σ clocks are gaining; if it were otherwise, entropy would not be independent of velocity. In the limiting case of zero velocity increments, we must also have the same entropy increments for the Σ and Σ' clocks, and hence also the same increases in clock readings. We conclude that similar entropy clocks, in relative uniform motion, will run at the same rate. (Schlegel 1968, 148; cf. Schlegel 1977)

Once again, then, two observers who use entropy clocks will know that the invariance of *S* ensures an objective measurement of the 'passage' of time in their respective systems. They are space-like separated at the time of detection but their entropic clocks were synchronized at the origin. These considerations do not, of course, question the validity of the Lorentz transformations for entropy clocks provide no 'preferred' temporal frame or universal Now. But they show that, if relativistic thermodynamics is taken into account, new invariant relationships come to light, which can be exploited for the objective measurement of the lapse of time in relativistic systems. Hence they should turn out to be useful in the relativistic EPR case.

VII. Consequences for a Theory of Time

What consequences do these considerations have for a tensed theory of time? Would the EPR observers opt for Possibilism? Not if this view requires a universal advancing knife-edge or even saddle-back of Now since to make 'one plane of simultaneity as uniquely metaphysically important' (Savitt 2001, 9) is incompatible with the relativity of simultaneity. But the EPR observers could argue that the entropic clocks nevertheless allow an inference to a 'passage' of time, in a (modified) Leibnizian sense of the order of succession of events. Let us assume that the usual Leibnizian notion of passage – as the order of succession of events -is adapted to the requirements of relative simultaneity, and the structure of Minkowski space-time. The EPR experimenters' conclusion is based on the ticking rate of various clocks:

- Their respective coordinate systems record proper time. The problem is, however, that one observer's proper time becomes another observer's co-ordinate time. And hence there are, in Pauli's words, as many Nows as there are reference frames.

- However the discovery of frame-invariant clocks shows that the relativistic observers do not need to conclude that 'the passage of time' is a human illusion, for entropic clocks constitute one physical system from which the 'passage' of time – the invariant succession of chosen events in Minkowski space-time – can be inferred. The frame-invariant clocks tick at the same rate in all coordinate systems, in which they are used, and may serve as a valuable criterion for a Leibnizian succession in these systems, as long as they have been synchronized. Their entropic time is measured along the trajectory of their respective observers.

Callender accepts that a minimalist conception of passage is compatible with Minkowski space-time but he does not find it philosophically interesting. (Callender 2000) However, it is the only reliable inference which can be made from the relativistic setting. But it is not as minimalist as Stein's relation *R*. It gives the tenser a partially covariant state history, at least according to the invariant entropic clocks. Yet, it still falls short of a universal or privileged present for all observers, since invariant entropic clocks cannot avoid the constraints of relative simultaneity.

Referring back to Figure II, assume that in frames I and II identical, synchronized entropic clocks are used to measure the respective proper times. In frame I *A* and *B* must have the same entropy value, whilst an earlier event, located at *B′*, has a lower value in frame I. Frame II must judge the event at *B′* to have a lower entropy value than *A* (or *A′*) even though *B* and *B′* are simultaneous for frame II. Thus the tenser can derive a frame-invariant succession of events for the space-like separated observers, but no frame-invariant Now. This result is already well established for time-like related events. (Weinert 2004, Ch. 4.4)

What the EPR observers can conclude, with some confidence, is that the usual identification of tenselessness with changelessness (cf. Callender 2000, S587) is mistaken, since there is a Leibnizian order of the succession of events, which, at least according to the entropic clocks is invariant across their reference frames. However, as has been argued, the existence of such invariant entropic clocks does not justify an inference to a universal Now, which seems to be required by a tensed theory of time. They are not master clocks but the invariant ticking of some appropriate clocks, may, in the footsteps of Leibnizian relationism about time, be enough to infer that even in a relativistic universe there is a 'passage' of time; past, present and future are not equally real, contrary to the assertions of the Block theorist.

The EPR observers are free to go further and view the four-dimensional world dynamically as a series of branching events, in which the future consists of a history of many branches, which are equally possible but not equally probable, with the present moving stochastically up the branching tree. If they endorse this view they enter some well-rehearsed debates: whether the Special theory of relativity is (or is not) compatible with probabilism (cf. Maxwell 1985; Dieks 1988) and what prospects there exists for Presentism in space-time theories. (Cf. *Philosophy of Science* 67, 2000, Supplement). For present purposes it must be concluded that the use of entropic clocks does not deliver the central item, which a tensed theory of time requires: a preferred foliation. It does, however, deliver one criterion to which the tenser may appeal to show that a frame-invariant succession of events is possible, at least as established by a pair of entropic clocks.

In the face of the difficulties which EPR seems to represent for the temporal ordering of events, R. Penrose calls for a new worldview. (Penrose 1994, §7.12; Penrose 1989, 480) Others seek refuge in the time-invariance of physical laws and seem to accept, as a consequence, the block universe. It seems to the present author that the EPR case does not justify such conclusions. The observers disagree about the simultaneity of the detection event to the extent that in one frame collapse appears to occur before measurement. But there is no disagreement about entropic gradients, due to the invariance of entropy, S. The use of entropic clocks can be compared to the idea of cosmic time – or an arrow of time – since the use of these clocks eschews the disagreement about the temporal order of events (at least between observers using entropic clocks). But in accordance with the principle of relativity it is to be expected that the employment of entropic clocks throws up a new puzzle about time: the observers now have to deal with different clocks whose clock times do not all agree. The observers' 'normal' clock would suffer the usual time dilation effects and lead to disagreement about the ordering of the EPR events. But the existence of entropic clocks will lead the observer to conclude that their disagreement, according to their mechanical clocks, may be due to perspectival effects, caused by their respective velocities just as the appearance of length-contracted objects in the Special theory of relativity has been interpreted as a perspectival effect. (Weisskopf 1960) Entropy clocks are not master clocks but they are frame-invariant and are not subject to the above-mentioned paradox of slow motion. They constitute a different criterion to make inferences about the dynamic 'nature' of time, rather than the block universe. The use of entropy clocks shows that observers do not need to conclude that the lapse of time is a human illusion. The 'passage' of time is a philosophical inference from given criteria. These criteria must be well-chosen but reliance on relativistic simultaneity may not be the best policy.

VIII. Conclusion

Callender is right that tensers cannot draw their conclusions about the 'flow' of time from quantum mechanics, not because it has been shown that there is no physical 'passage' of time but because EPR-type experiments in a relativistic context pose the difficulties of temporal order. But an inference to a Putnam-style block universe is as little justified as the tenser's conclusion about a universal Now. From the consideration of entropic clocks the detenser can infer that a tenseless view is characterized by precedence and simultaneity but no privileged Now. The tenser may conclude that there is a 'passage' of time and that some appropriately chosen clocks, indicating entropic gradients, may deliver a covariant history of specific events.

Callender's attack on tensed theories of time, in the context of appropriate scientific theories, indirectly confirms the thesis at the beginning of this paper that metaphysical positions, like Eternalism and Possibilism, are merely philosophical consequences, with differential claims to plausibility. As the only reliable inference from a consideration of the EPR correlations is a modified Leibnizian sense of 'passage' – as the invariant order of specific successive events in space-time, according to appropriate clocks – further inferences to the Parmenidean block universe or Heraclitean flux are necessarily empirically underdetermined. A consequence of the considerations in this paper is that such debates will remain unresolved because of their empirical underdetermination.

On the other hand, the establishment of temporal 'passage' at which this paper arrived through a reflection on entropic clocks, shows that whilst certain features of physical theories do not support inferences about the 'flow' of time others decidedly do. But this situation need not end in deadlock. If all the temporally relevant features are taken into account – the laws of statistical mechanics, Liouville's theorem and the topology of phase space, the expansion of the universe, the preponderance of outgoing radiation, the measurement process and decoherence – the inference to the anisotropy of time is more plausible than the inference to the block universe. The observers should trust their entropic rather than their mechanical clocks.

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