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The Ontology of Spacetime

Dennis Dieks

(Editor)

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Series Editors: Dennis Dieks and Miklos Redei

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Vol. 1: The Ontology of Spacetime
Edited by Dennis Dieks

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Edited by

Dennis Dieks

History and Foundations of Science, Utrecht University,
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Introduction

The nature of space and time is a traditional philosophical subject. Whether space is an independently existing "substance" or not, and whether time is a measure of change in material processes or rather something that exists and "flows" even if there are no material processes going on, are questions that go back to the very beginnings of natural philosophy. But in spite of this longevity no consensus has been reached, and these issues are still exercising the minds of both scientists and philosophers. The last few decades have even seen an upsurge of interest. This is due to a number of factors. Among these figures prominently the revival of the substantivalism versus relationalism debate as a consequence of recent foundational studies of general relativity, especially the renewed attention for Einstein's notorious "hole argument". Indeed, the diffeomorphism invariance of the equations of general relativity appears to indicate that *prima facie* different models of the theory that are related to each other by diffeomorphisms, actually represent the *same* physical situation. Indeed, the only difference between any two such models is in the manifold points where events take place: the contents of the events, their mutual relations, and the laws that apply are the same. If the verdict of physical sameness is accepted, the implication is that only physical objects and fields, and their coincidence relations, are relevant for the specification of the state of the universe. The identity of the spacetime points at which events take place plays no role. This suggests that it may be unnecessary at all to accept these points as independent parts of the ontological furniture of the world. Arguably, this would be a vindication of relationalism, since only structural properties of particles and fields, and their coincidence relations, remain as physically significant. It is possible not to go along with this conclusion, for example because one has qualms about accepting the metrical field as a physical object on the same footing as matter fields, or because of the suspicion that the spacetime points are still there, hiding in the structure of the fields in disguised form. But even so, it is clear that new light has been shed on the discussion about the ontology of spacetime.

Another reason for the interest in spacetime questions is the awareness that the global temporal structures exhibited by solutions of the general relativistic field equations are very relevant to debates about the nature of time. In particular, the notorious question of whether it makes sense to say that there is "becoming", or that "time is flowing", has received a new impetus from this direction. In the 1940s, Gödel published a number of seminal papers in which he demonstrated the existence of solutions of the Einstein equations in which closed time-like curves occur (Gödel, 1949). He concluded from this that the doctrine according to which time is "objectively lapsing" is incompatible with general relativity. In the 1960s, Rietdijk and Putnam rekindled the older theme that *special* relativity, even more clearly than general relativity, rules out that the history of the universe can be regarded as a unique continuous succession of three-dimensional worlds (Rietdijk, 1966). At least at first sight these observations seem to provide a justification for looking upon the universe as one four-dimensional, "static", whole; a "block universe" (actually a squarely pre-relativistic notion: the term seems to originate with William James (1979), in his essay "The Dilemma of Determinism"). These relativistic considerations inject new life into the famous McTaggart A versus B series discussion, with many arguing that only the B series is a viable option. Remarkably, in connection with recent work on quantum gravity the opposite opinion can also be heard. This is because in some approaches to the quantization of general relativity, it must be assumed that there exists a global time parameter, corresponding to a privileged foliation of spacetime — this would reinstate the notion that the universe's history consists in a succession of three-dimensional worlds. This may be interpreted as being congenial to the A-like doctrine of "presentism".

The surge of interest in questions of this kind has made the need felt for a permanent international platform on which philosophers and scientists can meet and engage in fundamental discussions. This provided the main motivation for the plan to find a new society: The International Society for the Advanced Study of Spacetime. Vesselin Petkov (Concordia University, Montreal) has been the driving force behind this plan and its successful execution. The Society was officially established during the First International Conference on the Ontology of Spacetime, held at Concordia University in Montreal from 11 to 14 May 2004. Follow-up conferences will be held every 2 years.

The present book contains selected papers from the first conference on the Ontology of Spacetime. As already mentioned, the ontological debate *par excellence* is between those who take space and time to be independent substances, and those who maintain that space and time are mere representational devices, introduced by us to order the spatial and temporal relations between physical systems. Think, in order to have a concrete example, of a system of classical point particles: the substantivalist will argue that these particles occupy points in absolute space, and that the distances between these spatial points induce distances between the particles. The particles therefore possess their distance relations by virtue of the geometrical relations antecedently present in the space in which they are contained. By contrast, the relationist will hold that the particles possess distances with respect to each other *directly*, i.e. without the intervention of an underlying space, and that Newtonian space only furnishes a mathematical representation of these physical distance relations. In the case of field theories, the relationist has to assume that elementary field-parts possess spatial relations with respect to each other, and that there are coincidence relations between the parts of different fields. It has to be noted that this characterization lacks bite if no restrictions are imposed on what counts as a *physical* field. For example, if the metrical field of special relativity were accepted as a *bona-fide* physical field, the above characterization would qualify special relativity as a fully relational theory; and a similar manoeuvre could be performed in the case of Newtonian theory. Newton's absolute space or Minkowski spacetime would become physical systems themselves, so that the state of the world would become fully describable in terms of relations between physical systems. But this is clearly not what the relationist intends: for him Newtonian absolute space or Minkowski absolute spacetime are very different from physical systems. Leibniz already provided a criterion here, by stipulating that physical "substances" *should not only act but should also be acted upon* — his relationism is meant to be about the relations between *such* substances. Newtonian space and Minkowski spacetime clearly are no substances in Leibniz's sense, since they constitute an inert background that cannot be changed. This obviates the just-mentioned strategy by means of which classical mechanics or special relativity could be construed as relational. However, in the *general* theory of relativity the metrical field does become dynamical, so that within this theory the state of the universe may be considered as completely specified by the coincidence relations between physical systems. The plausibility of this viewpoint obviously depends on whether one is prepared to go along with accepting the metrical field as a physical system that is on a par with the matter fields. If one does, general relativity appears as the vindication of relationalism. If one does not, general relativity appears as not amiable to relationalism after all: the theory allows possible universes in which there are no matter fields, so that in those universes there is only empty spacetime. It follows that in general relativity spacetime cannot be reduced to matter fields and their relations — at least not always. This may be taken as a vindication of substantivalism with respect to space and time. However, within the context of general relativity the difference between these two options might be considered slight and first of all semantical, depending as it does on whether we consider the metrical field as a physical field or not.

In Part I of this book the focus is on this ontology debate. The point about the importance of the lack of a fixed spacetime background in general relativity can be made in several ways. As Earman points out, there is a relation with the general covariance of the theory. This is true in spite of the fact that ever since Kretschmann's famous criticism of Einstein's reliance on general covariance, general covariance has had the reputation of being only a purely *formal* property of the equations, reflecting the way we write them down rather than saying something about their content (Norton, 1995). Indeed, with sufficient ingenuity we can give any system of equations a form that is the same whatever coordinate system we use to express them. But there is also a more substantive reading of general covariance, according to which the coordinate transformations are interpreted in an *active* way, as actual mappings from one point of the spacetime manifold to another, and are required to be *gauge transformations* of the theory. Gauge transformations connect situations that can be considered physically the same. Technically they are defined as transformations that leave the action invariant (up to a divergence term); they therefore also keep the equations of motion the same. "Observables", i.e. physically significant magnitudes that do not depend on a conventional choice of representation, have to be gauge invariant. This substantive version of general covariance is satisfied in general relativity: arbitrary diffeomorphisms — applied actively — are gauge transformations and therefore do not change the physical situation. This is because there is no fixed spatiotemporal background structure against which the action of the diffeomorphisms can be set out. It is only the coincidence relations between the dynamical fields (including the metric field) that count. Facts like the co-instantiation of field magnitudes are gauge invariant and therefore constitute objective observables — the individuality of the spacetime points at which these co-instantiations occur plays no role. Rovelli (in Chapter 2) arrives at this same conclusion via a direct investigation of the nature of diffeomorphism invariance. Rovelli infers that as a consequence space and time have disappeared from physics. What he means is that space and time no longer enter as independent entities, on top of what is already determined by all the coincidence relations between the dynamical fields. The spacetime structure is already present in the structure of the fields and their interrelations.

Following this line of thought, it appears natural to look for a formulation of physical theories that does without spacetime points altogether. If a successful formulation of this kind can be found, it follows that spacetime substantivalism is even unnecessary in the form that the independent existence of a manifold of spacetime points must be assumed (bare manifold realism). In such a "pointless" version of the theory, fields would no longer be definable as the assignment of field values to antecedently given spacetime points. It would have to be the other way around: the manifold structure should be derivable from the structure of the fields. Bain in his contribution investigates several concrete programmes that aim at this removal of spacetime points from the basic ontology. It turns out that this is feasible: several field theories can be formulated in ways that do not presuppose the existence of a manifold of spacetime points. In fact, there are more than one ways of accomplishing this that look mathematically very different. But as may be anticipated, these different formulations have *structural* characteristics in common — after all, these different formulations of a field theory still represent the *same* theory. Bain concludes that spacetime substantivalism is out: we can do without spacetime points in several ways, so that the substantivalist argument that spacetime points are an indispensable ingredient of any field theory that fails. However, Bain does not opt for relationalism. Instead, he argues for a structuralist conception of spacetime: spacetime does exist independently of physical objects, as a structure embodied in the world. I wonder, however, whether the relationalist should be daunted. It is true, of course, that all solutions of a particular theory share basic structural features that are typical of the theory, no matter what mathematical machinery is used to express these solutions. In field theories, fields always possess a manifold-like extensional structure. But does this imply that the shared structure exists independently of the physical objects (particles and fields) occurring in the solutions? This question reminds one of the debates about whether universale exists independently of their instantiations, and I suppose that analogous positions can be adopted here as have been proposed there. Part I is concluded by an attack on spacetime substantivalism that is independent of general relativity: it applies already to special relativity and classical Newtonian theory. Brown and Pooley argue that on close inspection it turns out that in these theories space and time do not possess an explanatory role in the way this concept is usually understood. The physical *laws* do the real explanatory work, not space and time. It is true that all these laws share certain characteristics, and that we usually interpret these common features as reflections of the properties of an underlying spacetime structure — e.g., in special relativity the laws are Lorentz invariant, which usually is seen as a consequence of the symmetry properties of Minkowski spacetime. But it is perhaps not really necessary to look for a deeper explanation of Lorentz invariance; one could accept it as a brute fact that all laws possess this characteristic. Moreover, and more importantly, one may well ask how a deeper explanation on the basis of the properties of spacetime is supposed to work in detail. There certainly is no causal mechanism involved: spacetime does not send signals to which particles respond. More generally, exactly *how* does spacetime inform the laws of nature? Failing a detailed account of what the purported explanation consists in, it can hardly be maintained that the existence of space and time is the plausible conclusion of an "inference to the best explanation".

If this line of argument is accepted, its concrete elaboration should probably go into the direction of a position according to which classical particles possess their positions directly (without embedding in space) and in which absolute accelerations also become direct particle properties. One may question the elegance or simplicity of such a scheme, but it seems certainly realizable in principle. Although the resulting position would not be relationalist in the sense that only relations between particles play a role, it would certainly be anti-substantivalist. The part ordinarily played by absolute space would be taken over by structural features of the laws, which could be interpreted as systematizations of regularities in the behaviour of particles and fields (Dieks, 2001). This would be in accordance with one of the original motivations of relationalism, namely to accept as little as possible that is not observable or solidly physical. However, it should be noted that in the context of Newtonian mechanics the prospects for relationalism are actually better than suggested by this proposal. It turns out that a completely relational theory is possible (the Barbour–Bertotti theory, in which only relative distances and orientations of particles occur; see Barbour & Bertotti, 1982) that yields the same solutions as ordinary Newtonian theory in all cases in which the total rotation of the universe vanishes. Given the fact that empirical data indicate that the actual value of the angular momentum of our universe has an exceedingly low upper bound, this is a truly remarkable result.

Parts II and III of this book concentrate on the nature of time. It is a common-sense notion that the universe develops itself in time via a process of *becoming:* What was future becomes present, and subsequently past. A comparison that forces itself upon us is that of a *flow* of time, like the flow of water in a river. This analogy is clearly defective; however, it is impossible, for example, to define the *rate* of the flow of time. Rate of flow in general can be defined as the change in the pertinent (flowing) quantity as a function of the independent time parameter. But this definition obviously cannot be applied to the flow of time itself. Furthermore, the very idea of one and the same event being subsequently past, present and future seems inconsistent, as famously argued by McTaggart. Already before the advent of relativity theory, considerations of this kind, together with arguments about the consequences of physical determinism, gave rise to the conception that the history of the universe is best represented in a four-dimensional picture, in which *all* events, be they past, present or future, are contained. Since all events are there in this diagram "at once", in one block as it were, the name "block universe" seems appropriate. The block universe presentation has gained additional popularity as a result of relativity theory, because Minkowski spacetime diagrams — standard in relativity texts — are of the block type. But there is also a more fundamental reason why relativity theory has favoured the block universe representation. In special relativity simultaneity is no longer an absolute concept: the so-called Einstein simultaneity is frame-dependent, so that observers who move with respect to each other disagree about which events are simultaneous with any given event. Worse still, the ontological status of this Einstein simultaneity itself is insecure. Einstein introduced his simultaneity relation as a *convention*, without ontological import. This has remained an important, albeit not uncontroversial, point of view. However, if there is no ontologically significant simultaneity, the history of the universe cannot be conceived as a succession of "nows", and this appears to shut the door on the doctrine of becoming, and the related doctrine of "presentism". According to the presentist only things being there at the present instant exist: the past has ceased to exist, and the future does not yet exist. But without a "now" the notion of "the present moment" does not seem to make sense, and ontological distinctions that correspond to the distinction between past, present and future have apparently to be abandoned as well. The only plausible alternative seems "eternalism", according to which all events in the history of the universe possess equal ontological statuses: everything exists in the same way, "at once".

On closer inspection things are not that clear, however. It is misleading to state that in Minkowski spacetime all events exist at once: they certainly do not take place at one spacetime point. Moreover, there are objective temporal ordering relations between events according to special relativity, so that at least some events are objectively later or earlier than any given event, in spite of the fact that they all belong to the same block universe. All these spatiotemporal relations between events are fully represented *within* the block diagram; what temporal or existential distinctions could be missing from it? The intuitive answer is that it is the absolute distinction between past, present and future, and the associated ontological differences, that are lacking. But as Dorato, Savitt and Dolev make clear in different ways, it is questionable whether it even makes sense to think that presentism and eternalism are committed to distinct ontologies. Arguing within the context of pre-relativistic physics, so that the complication of the non-absoluteness of simultaneity does not yet play a role, Dorato and Savitt point out that at any instant both presentists and eternalists will agree that past and future *do not* exist *now*, and that the future *will* exist whereas the past *existed.* Both parties also agree that past, present and future *all equally exist* in a tenseless way. So what differences in existence claims can there really be between the two camps? It seems that the presentism/eternalism debate can have no consequences at all for the ontology of spacetime. The block universe already contains all distinctions that can sensibly be made, and so is in no way ontologically incomplete. In particular, the block picture faithfully represents all differences there actually are between past, future and present.

Arthur and Dieks extend basically the same analysis so as to take relativity theory into account. The main new aspect introduced by relativity is the disappearance of an objective global "now". Still, this does not mean that it becomes impossible to speak about temporal relations and becoming. The block representation contains all events occurring in the history of the universe, exactly at the spacetime position where they actually happen. In other words, this *happening* of events has already been taken into account in the block universe representation. The same applies to the temporal relations between different happenings: these also are all part of the block universe. It is consequently false to maintain that the block universe offers no room for becoming. Becoming consists exactly in the *occurring*, or *happening*, of events after or before each other according to the temporal relations between them. The main difference with the pre-relativistic situation is that the process of becoming can no longer be taken to be something that takes place globally, over the whole universe. As Dieks argues, there indeed does not exist any global foliation that is relevant for becoming, neither in special nor in general relativity. In relativity theory, becoming must therefore turn into something *local.* This is completely in spirit with the action-by-contact character of relativistic processes. Arthur arrives at the same conclusion within the context of special relativity. But he objects to the idea that the locality of the "now" means restriction to a spacetime point, and wants to make room for the "specious moment". According to his proposal the "now" should be taken to be a small spacetime region, limited by the forward and backward lightcones of the beginning and end, respectively, of a brief section of a worldline.

According to these analyses, relativistic theories are just as congenial to becoming, or just as hostile to it, as classical theories. The only difference is in the structural properties of time. Unlike what is the case in classical theory, there is no fixed time difference between any two events according to relativity theory, because the amount of time that elapses depends on the spacetime path followed between the two events (as exemplified in the twin effect). Further, we have to face the disappearance of a global notion of simultaneity and the naturalness of the local point of view in relativity. But these differences in the temporal structure do not touch the possibility of becoming or the meaning of tense in an essential way.

McCall subscribes to the general outlines of this outlook. He proposes that the much discussed question of whether relativity favours "perdurance" (according to which objects are basically four-dimensional entities, of which the objects from everyday experience are three-dimensional parts) or "endurance" (according to which objects are basically three-dimensional, evolving and changing in time) is a pseudo-problem. Perdurantist statements can be translated into endurantist ones without remainder, and vice versa. The question of whether objects are really four- or three-dimensional does accordingly not have an objective answer. Both types of description can be given, and which one we choose is *a pragmatic* matter, having to do with our interests and preferences.

This deflation of the ontological importance of relativity theory is certainly not universally accepted, however. In Part III, the voices can be heard of authors who argue that relativity theory does have grave ontological consequences for the nature of time and the dimensionality of the world. These authors agree among each other that within the context of special relativity a four-dimensional block universe is unavoidable and that this means that there are no prospects for becoming or a tensed theory of time. But they disagree about the final conclusion to be drawn from this. Petkov acclaims the block universe picture as an important advance in our understanding of the universe. He argues, interestingly and controversially, that it is the only way of making sense of the empirical data that support relativity, and therefore concludes that becoming and presentism have been definitively disproved. The future and the past must be as real as the present. He thus places himself squarely within the Rietdijk–Putnam tradition, on whose papers he attempts to improve. Maxwell also accepts that relativity leads to a fixed four-dimensional world, but unlike Petkov he sees this as a reason for *discarding* relativity as a final theory. In fact, Maxwell is well known for having introduced a new argument against four-dimensionalism, which he explains in his contribution to this volume. In a nutshell, he reasons that there are good grounds for believing that the theories of a future, more final, physics will be probabilistic. That means, according to him, that such theories will treat the future as *open*, i.e. as harbouring genuinely different possibilities. But how could a block universe be compatible with such a variety of possible futures? And how could the notion of *the* future make sense at all if there is no universal "now"? There are therefore good reasons for believing that relativity will be rejected in a future physics, Maxwell maintains.

Peacock does not go that far, but he does believe that the usual relativistic picture has to be augmented in order to make room for becoming. He attempts to do so by supplying a definition for global "nows". Interestingly, his definition rests on relativistic notions: equal time hypersurfaces are identified as hypersurfaces of equal proper time (starting from a fiducial point). There is a clear motivation behind this, namely that physical evolution depends on proper time, not on coordinate time. It would be interesting to see whether this proposal can be worked out into a generally applicable consistent whole.

Finally, Monton considers the possibility that *general* relativity, and its quantization, can come to the rescue. One of the main approaches to the problem of quantum gravity is that of canonical quantization. In this programme, it is important to have global foliations of spacetime: the presence of such a foliation yields the possibility of regarding the history of the universe as the evolution in time of three-space. To this evolution the machinery of Hamiltonian mechanics can be applied, which can be quantized in the standard way. From the point of view of canonical quantum gravity it therefore is not unnatural to restrict the class of models of general relativity to those in which a global time parameter is available. The presentist may hope to use this parameter to fix global "nows" that play a role in becoming.

Monton's paper is one of the few in this volume that comment on the possible significance of quantum considerations for the ontology of spacetime. It seems to me that one of the challenges for future conferences on the Ontology of Spacetime will be to incorporate quantum aspects in a more extensive and systematic way. For example, the Hilbert space formalism of ordinary quantum mechanics does not have the form of a spacetime theory, in which all physical quantities are defined as "geometrical objects". Does this provide an argument against the fundamentality of space in quantum mechanics? By contrast, in quantum *field* theory space and time *are* assumed, albeit as a non-quantum background. How should his be interpreted? Is it possible to do without such an extraneous spacetime background, in analogy with the programmes described in Bain's article? And what about the claim sometimes heard that string theory would be able in principle to do without any spacetime background; that space and time will *emerge* in a future version of the theory? It seems clear that here we have a rich reservoir of questions for further research into the nature of space and time — a reservoir thus far hardly tapped by philosophers.

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PART I: THE ONTOLOGY OF SPACETIME

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Chapter 1

The Implications of General Covariance for the Ontology and Ideology of Spacetime

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Abstract

It generally agreed that the requirement of formal general covariance (i.e. the demand that laws be written in a form that is covariant under arbitrary coordinate transformation) is a condition of the well-formedness of a spacetime theory and not a restriction on its content. Physicists commonly take the substantive requirement of general covariance to mean that the laws exhibit diffeomorphism invariance *and* that this invariance is a gauge symmetry. This latter requirement does place restrictions on the content of a spacetime theory. The present paper explores the implications of these restrictions for interpreting the ideology and ontology of classical general relativity theory and loop quantum gravity.

1. Introduction

The story I have to tell here is not new. But it is worth retelling in various forms because it is not well known to philosophers. And some of the philosophers who know the story are in a state of denial. Perhaps the retelling will awaken them from their dogmatic slumber. If not, I have another message for them: physics is marching on despite your scruples. More generally, the story illustrates the trials and tribulations of scientific realism. Suppose that we resolve — as I think we should — to be realists in interpreting scientific theories. In carrying out our resolution we have to be aware of Roger Jones' (1991) question: what are we to be realists *about*? One of the morals that will emerge below is that for a generally covariant theory we cannot be naive realists and read the ontology/ideology of spacetime directly off the surface structure of the theory.

2. Two concepts of general covariance

I will distinguish two senses of general covariance, *formal* and *substantive*. A spacetime theory satisfies *formal general covariance* (FGC) just in case its laws are covariant under arbitrary spacetime coordinate transformations or, equivalently, its laws are true in every coordinate system if they are true in any. This is a condition on the well-formedness of a theory, not on its content[1]. There is nothing to celebrate about the fact that Einstein's general theory of relativity (GTR) satisfies FGC; or rather if there is, then celebration is also in order for many Newtonian and special relativistic theories since these theories can, without change of physical content, be formulated in a formally generally covariant manner. In hindsight, this should have been blindingly obvious: spacetime theories can be formulated in a completely coordinate-free manner, so coordinates cannot possibly matter in any substantive way[2].

To introduce some language I will be using throughout, FGC is an example (albeit a rather trivial example) of a gauge symmetry — that is, a symmetry that relates different descriptions of the same physical situation. To make this more concrete, assume that the models of a spacetime theory have the form (M, O_1, O_2, …, O_N), where M is a differentiable manifold (assumed for convenience to be C^∞) and the O_j are geometric object fields on M. In the case of GTR, the key geometric object fields are the spacetime metric g_{ab} and the stress-energy tensor T_{ab}. Each (local) coordinate system $\{x^i\}$ gives rise to a representation of these objects in terms of their coordinate components g_{ij} and T_{ij} in the given coordinate system. The result is a huge redundancy in description with many different coordinate representations, all corresponding to the same (M, g_{ab}, T_{ab}). The coordinate transformations that shuttle between the different representations are, thus, examples par excellence of gauge transformations (see the top portion of Fig. 1).

Now let d: $M \to M$ be a diffeomorphism (i.e. a one–one C^∞ map of M onto itself). Then a spacetime theory satisfies *substantive general covariance* (SGC) just in case (i) if (M, O_1, O_2, …, O_N) satisfies the laws of the theory, then so does

[1] At least on the assumption that the reality spacetime theories seek to capture can be completely described in terms of geometric object fields on a manifold; see below.

[2] For example, instead of characterizing, say, contravariant tensors as objects with coordinate components that transform in a specified way under coordinate transformations, they can be characterized in a coordinate-free manner as multilinear maps of tuples from tangent vectors to $\mathbb{R}$.

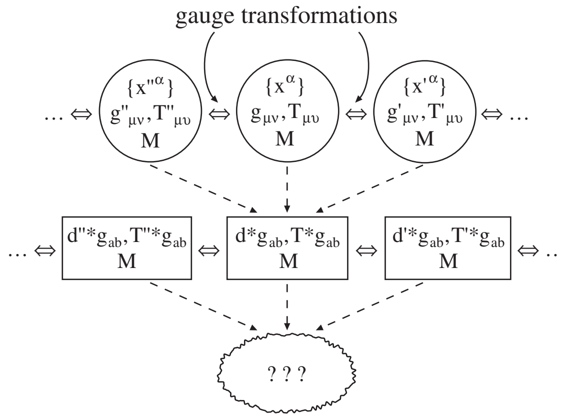

Fig. 1. Two levels of gauge redundancy in general relativity theory.

$(M, d^{*}O_1, d^{*}O_2, \ldots, d^{*}O_N)$ for any $d \in \mathit{diff}\,(M)$, where $d^{*}O_j$ stands for the drag along of O_j by d, and (ii) this diffeomorphism invariance is a gauge symmetry of the theory, i.e. $(M, O_1, O_2, \ldots, O_N)$ and $(M, d^{*}O_1, d^{*}O_2, \ldots, d^{*}O_N)$ are descriptions of the same physical situation. SGC thus implies that there is a second level of descriptive redundancy (see the bottom portion of Fig. 1)[3].

The distinction between the two concepts of general covariance lacks bite unless it is accompanied by an account of gauge symmetries. Here I have several claims. First, there is an extant account of gauge symmetries that is widely accepted in the physics community. My assumption is that this account should be taken as the default account of gauge. This assumption is, of course, defeasible; but philosophers who want to override it are obligated to provide an alternative account. Second, the application of the recommended account to GTR implies that diffeomorphism invariance is a gauge symmetry of this theory and, hence, that GTR satisfies SGC. Third, this account implies that diffeomorphism invariance is not a gauge symmetry of typical pre-general relativistic spacetime theories. Thus, while Einstein had no reason to celebrate because his GTR fulfilled FGC, the fact that the theory fulfills SGC is something to celebrate — or at least to underscore. The hesitancy here has to do with the question marks in Fig. 1; namely, what is the nature of the reality that underlies the second level of redundancy of description? Or to put it in the terminology physicists use, what are the gauge-invariant quantities (a.k.a. "observables") of

[3]The two concepts of general covariance are sometimes confused because a coordinate transformation $x^{\upsilon} \to x'^{\upsilon}(x^{\mu})$ can be taken to indicate a mere relabeling of points of M or as indicating a (local) diffeomorphism that sends a point $p \in M$ in the common domain of the coordinate systems to another point $p' \in M$ where $x'^{\upsilon}(p') = x^{\upsilon}(p)$.

GTR in particular and of substantively generally covariant spacetime theories in general? It is far from clear what the best positive answer is. But on the negative side, one thing is clear from the start: accepting the interpretation of SGC I am recommending implies that *none* of the quantities used in standard textbook presentations of GTR — not even "scalar invariants" — are observables. Evidently then, SGC implies a rejection of the naive realism that would have us read off the ideology and ontology of GTR from standard presentations of the theory. But first things first. In the next section, I will give a brief sketch of the account of gauge symmetries on which these claims are based.

3. Gauge symmetries

In this section, I will attempt to provide a bare-bones, non-technical sketch of what I will call the standard analysis of gauge symmetries. Those interested in the details are referred to Earman (2003b, 2006). The standard analysis has a broad scope since it applies to any theory whose equations of motion are derivable from an action principle $\delta\mathfrak{A} = 0$, $\mathfrak{A} = \int \mathscr{L}(x, u, u^{(n)})\,\mathrm{d}x$, where x stands for the independent variables, u for the dependent variables, and the $u^{(n)}$ are derivatives of the dependent variables up to some finite order n with respect to the independent variables. The equations of motion, thus, take the form of (generalized) Euler–Lagrange (EL) equations. This is a substantive restriction, but it is satisfied by the vast majority of theories studied in modern physics[4]. Associated with an action principle is the notion of a *variational symmetry group* — a Lie group $\mathscr{G} \ni g : (x, u) \to (x', u')$ whose generators leave the action invariant up to a divergence term. Variational symmetries are necessarily symmetries of the equations of motion, i.e. they carry solutions of the equations of motion to solutions; the converse is not necessarily the case. If the action is such that there is an associated variational symmetry group $\mathscr{G}$, which is a finite dimensional Lie group with N parameters, then *Noether's first theorem* shows that, as a consequence of the EL equations, there are N conserved currents. Under appropriate conditions, the Noether currents can be integrated to give N quantities whose values are constant over time. Thus, for theories whose equations of motion are derivable from an action principle, the first Noether theorem provides a connection between the symmetries of the equations of motion and conservation laws of the familiar form[5].

Gauge symmetries are concerned with the case where the variational symmetry group $\mathscr{G}$ is an infinite dimensional Lie group whose parameters are

[4]There are, however, some exceptions. For instance, some — but not all — of the various versions of Cartan-style formulations of Newtonian gravitational theory are such that not all of the equations of motion can be derived from a single action principle; see Bain (2004).

[5]For a good introduction to the Noether theorems, see Brading and Brown (2003).

arbitrary functions of all the independent variables in the action. In this case, *Noether's second theorem* shows that the EL equations are not independent — a case of underdetermination. Generally, this underdetermination expresses itself by the appearance of arbitrary functions of the independent variables in the solutions of the EL equations. If time is one of the independent variables, this result means that the initial-value problem will not have a unique solution — an *apparent* violation of determinism. The reason for the emphasis on "apparent" is that the applicability of Noether's second theorem is taken to signal the presence of gauge freedom. The doctrine of determinism was never meant to imply that all magnitudes evolve deterministically — otherwise the doctrine would be trivially false — but only that genuine physical magnitudes evolve deterministically. And whatever other conditions a genuine physical magnitude satisfies, it must be a gauge-invariant quantity. (*Example*: that the potentials for the Maxwell electromagnetic field do not evolve deterministically is no insult to determinism because these quantities are gauge dependent. Determinism holds in this case because the Maxwell equations for the electric and magnetic fields, which are related one–many to the potentials, do admit a well-posed initial-value problem.)

I will emphasize how the development of these ideas is carried out using the Hamiltonian formalism because I eventually want to discuss the loop quantum gravity (LQG), which aims to provide a quantum theory of gravity by applying canonical quantization techniques to GTR. From the Lagrangian state space $\mathscr{S}(Q, \dot{Q})$ (here Q stands for the configuration variables and $\dot{Q}$ for their time rate of change) one moves to the Hamiltonian-phase space $\Gamma(Q, P)$ where the canonical momenta P are defined by the Legendre transformation $P = \partial\mathscr{L}/\partial\dot{Q}$. In cases where Noether's second theorem applies, the Hamiltonian system is not of the familiar kind treated in introductory mechanics texts, but is a constrained system because from the definitions of the canonical momenta follow identities of the form $\phi(P,Q) = 0$, called the *primary* constraints. Demanding that the primary constraints be preserved by the equations of motion may produce *secondary* constraints, etc. The total set of constraints picks out a hypersurface $\mathscr{C} \subset \Gamma$, called the constraint *surface*. The *first-class* constraints, which are the constraints that commute weakly with all the constraints (i.e. commute on $\mathscr{C}$ with all the constraints), are taken to generate the gauge transformations. The gauge-invariant dynamical variables $F : \Gamma(P, Q) \to \mathbb{R}$ are the ones that are constant along the gauge orbits. These quantities evolve deterministically, confirming that, when viewed through the lens of the recommended account of gauge, the apparent failure of determinism was due to mistaking gauge-dependent variables for genuine physical magnitudes[6].

[6]For details of the constrained Hamiltonian formalism, the reader may consult Henneaux and Teitelboim (1992).

Most of the familiar theories of Newtonian physics fall within the ambit of the first Noether theorem. For typical actions, the (inhomogeneous) Galilean group is a variational symmetry group, and the resulting conserved quantities are the familiar ones (energy, momentum, and the constancy of velocity of the center of mass). There are no non-trivial constraints and, thus, no gauge freedom. Realists are free to be naive realists and read off the ontological commitments of these theories from their surface structure without fear of generating indeterminism. Analogous results hold for special relativistic theories. To take a concrete example that will be elaborated below, consider a scalar Klein–Gordon field Φ on Minkowski spacetime. The equation of motion can be written so as to fulfill FGC by using the covariant derivative operator ∇_a determined by the Minkowski metric η_{ab}:

$$\eta_{ab}\nabla_a\nabla_b\Phi - m^2\Phi = 0 \tag{1}$$

where $m \geq 0$ is the mass of the field. This equation can be derived from an action principle with

$$\mathfrak{A}(\Phi, \eta) = \int \frac{1}{2}\left(\eta_{ab}\nabla_a\Phi\nabla_b\Phi + m^2\Phi^2\right)\sqrt{-\eta}d^4x \tag{2}$$

in which Φ is varied but η_{ab} is not because it is an "absolute object"[7]. The action admits the Poincaré group as a variational symmetry group. The first Noether theorem applies and yields a proper conservation law in which the stress-energy tensor for Φ is conserved as a consequence of (1). In the Hamiltonian formulation, there are no non-trivial constraints so that, once again, the proffered account of gauge renders the verdict that there is no non-trivial gauge freedom in the offing.

The application to GTR of the proffered account of gauge leads to a radically different result. The diffeomorphism group is a variational symmetry group for the standard Hilbert action for Einstein's gravitational field equations (EFEs). Since arbitrary functions of the independent variables — here the spacetime position variables — are involved, Noether's second theorem applies and, thus, EFEs are subject to underdetermination. This explains why in the rigorous statements of the (local) existence and uniqueness theorems for the initial-value problems for EFEs, the uniqueness result is qualified with an "up to diffeomorphism" clause. And the justification for this clause is that the diffeomorphism invariance is a gauge symmetry. In 1913, Einstein discovered this underdetermination by a different route, using his infamous "hole argument."

[7]Indeed, for theories whose equations of motion are derivable from an action principle, the distinction between "dynamical" vs. "absolute" objects can be drawn in terms of the objects that are vs. those that are not varied in the action. This way of drawing the distinction has bite because trying to shift objects from the "absolute" to the "dynamical" category typically results in different equations of motion and different sets of observables.

Because at that juncture he was not willing to treat the metric and matter fields as gauge-dependent quantities and because he was not willing to abandon determinism, he concluded that general covariance had to be rejected. And because he did not distinguish formal and substantive general covariance, he forsook FGC and tried to work with gravitational field equations that were not covariant under general coordinate transformations. He was just able to rescue himself from this morass of confusions in time to beat David Hilbert to the generally covariant field equations that now bear his name[8].

It is important to realize that examples where non-trivial gauge freedom is in the offing are not confined to 20th-century physics. Indeed, the apparatus I have been touting can be used to illuminate the debate over absolute vs. relational theories of motion that raged in the 17th and 18th centuries. Start with theories of particle motion formulated against the backdrop of neo-Newtonian spacetime characterized by absolute simultaneity, a Euclidean metric structure for the instantaneous three spaces, a time metric that gives the temporal interval between non-simultaneous events, and a flat affine connection that defines the inertial structure. This background spacetime structure is rich enough to support absolute quantities of motion — in particular, it makes good sense to ask for the value of the acceleration of a point particle or for the magnitude of the rotation of an extended body even if the particle or extended body is alone in the universe. Those who are relationists about motion will want to modify this background structure to get rid of the absolute quantities of motion. But any such modification seems at first blush to lead to a failure of determinism. For example, consider the semi-relationist who only wants to weaken the inertial structure of neo-Newtonian spacetime to the extent that there is still absolute rotation but not absolute acceleration in general. The appropriate modification produces what I have dubbed Maxwellian spacetime (see Earman, 1989). The symmetries of this spacetime are rich enough that they contain mappings with the property that they are the identity on or below some chosen plane of absolute simultaneity but non-identity above. But since a symmetry of the spacetime should also be a symmetry of the laws of motion, the said mappings produce from any system of particle world lines satisfying the laws of motion, another system also satisfying the laws of motion such that the two systems coincide for all past times but diverge in the future — a violation of determinism. The Newtonians will conclude that in order to secure the possibility of determinism it is necessary to swallow absolute acceleration and return to the safe haven of neo-Newtonian spacetime[9]; here, the spacetime symmetries are

[8]For an account of how Einstein found his field equations, see Norton (1984).

[9]But, as is now well known, it is not necessary to retreat all the way to full Newtonian spacetime, which singles out a particular inertial frame — "Absolute Space" — that underwrites absolute velocity.

given by the (inhomogeneous) Galilean transformations, and any such transformation that reduces to the identity for any finite stretch of time is the identity.

Those who are familiar with the absolute-relational controversy know that the relationist will not be cowed by this argument. She will conclude that in order to be a relationist about motion it is necessary to be thorough-going relationists and to reject the "container" view of spacetime implicit in the above argument: it is the redundancy of description in the Newtonian theory that counts two systems of particle world lines related by a spacetime symmetry as corresponding to different physical situations and thereby produces faux violations of determinism.

In evaluating this response, it is illuminating to work through concrete examples and to subject them to the analysis of the touted account of gauge. Consider, for instance, the semi-relationist who wants to construct a theory of motion using the structure provided by Maxwellian spacetime. She would have to produce equations of motion derivable from an action principle that admits the Maxwell symmetry group as a variational symmetry group. Since this symmetry group[10] contains arbitrary functions of time t (which is the only independent variable in the action), she will find that the second Noether theorem applies and that arbitrary functions of t show up in the solutions to the EL equations, apparently wrecking determinism. But she knows not to be swayed by first appearances. When she switches to the Hamiltonian formulation, she finds that she is dealing with a constrained Hamiltonian system. And when she solves for the first-class constraints, she finds that the quantities that are constant along the gauge orbits are quantities like relative particle position and relative particle momenta and that these gauge-invariant quantities evolve deterministically[11]. Of course, it remains to be seen whether the relationist or semi-relationist can produce equations of motion that match Newton's in terms of empirical adequacy, simplicity, and explanatory power. But that is an issue that is beyond the brief of the current paper.

Einstein's GTR is undeniably a theory that is as impressive today as was Newton's theory in his day in terms of empirical adequacy, simplicity, and explanatory power. But one major difference is that the touted account of gauge entails that Einstein's theory, but not Newton's theory, contains gauge degrees of freedom. Does the gauge-invariant content of GTR characterize a reality that answers to the relationist's dreams, or do the terms of the absolute-relational controversy no longer suffice to adequately describe what Einstein wrought? Before turning to these questions, I need to respond to a challenge to the distinction between FGC and SGC on which the above discussion is premised.

[10]And the group of spacetime symmetries for any classical spacetime that eliminates or substantially weakens the inertial structure of neo-Newtonian spacetime.

[11]For the details of a specific example, see my (Earman, 2003b).

The challenge is that just as it is possible, with sufficient cleverness, to rewrite non-formally generally covariant theories so as to be formally generally covariant, so it is possible, again with sufficient cleverness, to turn a theory that does not fulfill SGC into one that does. For sake of concreteness, consider the above example of the Klein–Gordon field. The equation of motion is typically presented in textbooks in terms of inertial coordinates. But only a minimal amount of cleverness was needed to produce formulation (1), which is valid in arbitrary coordinates and which reduces to the familiar textbook form in inertial coordinates. A bit more cleverness is needed to conceive the following maneuver. Replace the Minkowski metric η_{ab} in (1) by a general Lorentzian metric g_{ab} to get

$$g_{ab}\nabla_a\nabla_b\Phi - m^2\Phi = 0 \tag{3}$$

and add the equation

$$R_{abcd} = 0 \tag{4}$$

where R_{abcd} is the Riemann tensor computed from g_{ab} and where ∇_a is now the covariant derivative operator determined by g_{ab}. The solution sets for (1) and for (3) and (4) are the same[12]. The new pair of equations strike one as fulfilling SGC, but the official doctrine of gauge cannot be applied until an action principle is found that has (3) and (4) as its EL equations. This step, which requires genuine cleverness, was supplied by Sorkin (2002). The diffeomorphism group is the variational symmetry group of the rewritten Klein–Gordon theory and in this sense diffeomorphism invariance is a gauge symmetry of the theory[13]. But arguably, the rewritten Klein–Gordon theory is not merely a notational variant of the original theory, but a theory with a different physical content. In the first place, the rewritten theory contains additional physical variables satisfying an additional field equation over and above (3) and (4). Sorkin (2002) has conjectured that there is a hidden gauge symmetry, which effectively cancels out this equation. Even if this conjecture proves correct, there is a second difference; namely, whereas in the original theory the scalar field Φ is counted as a genuine physical magnitude, in the rewritten theory it is a gauge-dependent variable. Since the two theories differ on what they count as genuine physical magnitudes, they should be counted as different theories rather than just different presentations of the same theory.

[12]It is assumed that the spacetime manifold is $\mathbb{R}^4$.

[13]The constraint formalism for the reworked Klein–Gordon theory has not been worked out. This leaves a gap in the analysis, but there is no doubt that the Hamiltonian formulation involves non-trivial constraints. What remains to be seen is how the first-class constraints reflect the diffeomorphism invariance.

It seems very plausible that other attempts to trivialize SGC will fail for similar reasons, confirming that SGC really is a substantive requirement on the content of theories. But the investigation will have to be carried out elsewhere.

4. Implications of substantive general covariance: classical spacetime[14] theories

I take it for granted that we want to be realists in interpreting spacetime theories. I will also take it for granted that a satisfactory answer to the question "What would the world have to be like for the theory to be true?" must be couched in terms of what the theory takes to be "observables" or gauge-invariant quantities. In this way, general covariance as a gauge symmetry imposes a constraint on a realistic interpretation of GTR in particular and of a theory satisfying SGC in general.

In more detail, there are two ways to get at the observables of a spacetime theory satisfying SGC. On the *spacetime approach*, the observables of a theory with models of the form $(M, O_1, O_2, \ldots, O_N)$ consist of diffeomorphically invariant, real-valued functions constructed from the object fields O_i. In the case of the source-free solutions to EFE for GTR, the observables are the diffeomorphically invariant, real-valued functions constructed from the metric g_{ab} and its derivatives. On the *canonical approach*, the observables are (as said above) phase space functions $F : \Gamma \to \mathbb{R}$ that weakly commute with all of the first-class constraints or, equivalently, that are constant along the gauge orbits. Alternatively, the gauge orbits can be quotiented out to produce the reduced phase space $\tilde{\Gamma}$, and then the observables are functions $\tilde{F} : \tilde{\Gamma} \to \mathbb{R}$. These latter observables are in one–one correspondence with the former if two gauge invariants Fs that are equal on the constraint surface $\mathscr{C} \subset \Gamma$ are identified. In the Hamiltonian formulation of source-free GTR the phase space consists of pairs (h_{ab}, π^{ab}), where the configuration variable h_{ab} is a Riemann metric on a three-dimensional manifold Σ and the canonical momentum π^{ab} is a symmetric tensor field on Σ. When Σ is embedded as a spacelike hypersurface of spacetime, h_{ab} and π^{ab} become respectively the spatial metric and the exterior curvature of Σ. There are two first-class constraints, the momentum (or vector) constraint and the Hamiltonian constraint[15]. When the momentum constraint is smeared with an arbitrary shift vector, which is tangent to the embedded hypersurface, it generates the gauge change in a dynamical variable $F(h_{ab}, \pi^{ab})$ that corresponds to the gauge change generated by performing an arbitrary diffeomorphism on the hypersurface. And when the Hamiltonian constraint is smeared with an arbitrary lapse function that measures distance along a normal to the

[14]Here the contrast for "classical" is "quantum." So I speak of classical GTR.

[15]More precisely, one should speak of two families of constraints since there is a family member for each point of space.

hypersurface, it generates the gauge change in a dynamical variable that corresponds to evolving the initial data via the equations of motion[16].

There are some obvious consequences of the proposed account of general covariance for the interpretation of classical (= non-quantized) spacetime theories. The first two are somewhat repetitive, but are stated for sake of emphasis. (C1) Since typical pre-general relativistic theories satisfy FGC, but not SGC, the general covariance of these theories does not rule out naive realism that takes the theory at face value as characterizing a world in terms of a manifold on which live various geometric object fields. (C2) For GTR and other spacetime theories that satisfy SGC, there are two immediate negative implications: (i) the so-called metrical essentialism is ruled out from the start since it is incompatible with diffeomorphism invariance as a gauge symmetry. (ii) Naive realism is also ruled out. In GTR, for example, the metric and matter fields, g_{ab} and T_{ab} are not observables, and the correspondence between the models (M, g_{ab}, T_{ab}) and the physical situations they describe is many–one. (C3) It also seems that in GTR no form of manifold substantivalism is salvageable because there are no local or even quasi-local observables. Consider first the spacetime approach to observables. In source-free solutions to EFE, a quantity like the Ricci curvature, scalar R is not an observable. More generally, there do not seem to be any diffeomorphically invariant quantities that are constructible from the metric and its derivatives and that attach to spacetime points, or to local spacetime neighborhoods, or to time slices. A completely non-local quantity like $\int_M R\sqrt{-g}d^4x$ is, if the integral converges, an observable. In the canonical approach, Torre (1993) has shown that in spatially closed solutions to the vacuum Einstein equations, no local or even quasi-local quantity constructed by integrating over a compact Σ local function of the canonical variables (h_{ab}, π^{ab}) and their derivatives is an observable[17]. In sum, it seems that spacetime points or proper subsets of spacetime points are not needed to support the observables of GTR.

So much for the easy and obvious consequences of SGC. To make more progress on what to fill in for the question marks in Fig. 1 would require, as a necessary first step, making explicit the various ontologies/ideologies for GTR that are compatible with SGC. In order to avoid false appearances, it would seem advisable to go about this task by concentrating on complete sets of observables. Call a set $\mathfrak{S}$ of quantities a complete set of observables for a set $\mathfrak{M}$ of models of a theory T iff every element of $\mathfrak{S}$ is an observable with respect to $\mathfrak{M}$, and also every observable for $\mathfrak{M}$ is a functional of the elements of $\mathfrak{S}$; and call

[16]The details of how the first-class constraints of the Hamiltonian formulation of GTR express the diffeomorphism invariance of the theory is a delicate matter; the interested reader is referred to Isham and Kuchař (1986a, 1986b).

[17]For spatially open asymptotically flat spacetimes, some quasi-local canonical observables are known to exist, e.g. the ADM energy.

$\mathfrak{S}$ complete simpliciter for T iff it is complete with respect to the full set of models of T. No explicit characterization of a complete set of observables for GTR is known. What follows are two partial examples, one from the spacetime approach and the other from the canonical approach.

Example 1. One idea for producing observables for GTR can be traced back to Kretchmann (1915, 1917) and was worked out in some detail four decades later by Komar (1958). Consider a solution M, g_{ab} to the vacuum EFE. Construct, if possible, four independent scalar fields φ^{μ}, $\mu = 1,2,3,4$, from algebraic combinations of the components of the Riemann curvature tensor, such that the four-tuples $(\varphi^1(p), \varphi^2(p), \varphi^3(p), \varphi^4(p))$ and $(\varphi^1(p'), \varphi^2(p'), \varphi^3(p'), \varphi^4(p'))$ are different whenever $p \neq p'$ for any $p, p' \in M$. Thus, the values of these fields can be used to coordinatize the spacetime manifold. Note that these scalar fields are *not* observables. But they can be used to support such observables in the following way. If $g^{\alpha\beta}$ are the contravariant components of the metric tensor in a coordinate system $\{x^{\upsilon}\}$, the new components in the $\{\varphi^{\mu}\}$ system are given by $g^{\mu\nu}(\phi^{\lambda}) := (\partial\phi^{\mu}/\partial x^{\alpha})\,(\partial\phi^{\upsilon}/\partial x^{\beta})g^{\alpha\beta}$. These quantities do count as observables because they are diffeomorphic invariants. And when they are available, they form a complete set of observables. Unfortunately, they are not available across the board since in spacetimes with sufficiently high symmetries the four independent scalar fields required by the construction may not exist. One could try to dismiss such cases by proving that they form a set of "measure zero" in the full set of solutions to EFE. But such a dismissal would be shortsighted in view of the fact that historically the debate about the ideology and ontology of spacetime theories has often revolved around cases of spacetime symmetries. Of course, one might try to turn this round and argue that we have been misled by constructions that use spacetime symmetries. In the end, this attitude may turn out to be correct. But at the outset it would seem a better strategy not to beg the question and to strive for an account of observables that does not pre-suppose that spacetime symmetries are absent[18].

[18]For another example of how to construct observables in the spacetime approach, see Rovelli (2001). Suppose that there are four particles of small enough masses that their effect on the spacetime metric can be neglected. Assume that the world lines of these particles are timelike geodesics; that these geodesics intersect at a point o; and that at o their four velocities form the vertex of a tetrahedron. Let p be a spacetime point to the future of o. The past lightcone of p will intersect the particle geodesics in four points p_{α}, $\alpha = 1,2,3,4$. Assign to p the four numbers s^{α}, which are the spacetime distances, as measured along the geodesics, from o to the p_{α}. The s^{α} take the place of the Komar coordinates. Thus, the components of the metric $g^{\mu\nu}(s^{\alpha})$ in these coordinates are observables. These "GPS observables" obviously have a practical and operational significance lacking in the Komar observables — they can be implemented with current satellite technology! On the other hand, their applicability is limited to a small subset of the models of GTR.

Example 2. The line element for a cylindrically symmetric spacetime has the form

$$\mathrm{d}s^2 = \exp(\gamma - \psi)\left[\left(-N^2 + (N^1)^2\right)\mathrm{d}t^2 + 2N^1\,\mathrm{d}t\mathrm{d}r + \mathrm{d}r^2\right] + R^2\exp(-\psi)\,\mathrm{d}\phi^2 + \exp(\psi)\,\mathrm{d}z^2 \tag{5}$$

where N, N^1, $R \geq 0$, γ, and ψ are functions of the radial coordinate r and time t only. An explicit characterization of a complete set of observables in the canonical approach for cylindrically symmetric vacuum solutions to EFE has been given by Torre (1991). Elements of this set take the form ($Q(r)$, $P(r)$), $r \in [0, +\infty)$, with

$$Q(r) = \int_0^\infty \mathrm{d}\omega \frac{1}{2} J_0(\omega r)\left\{\int_0^\infty \mathrm{d}x \exp\left(-i\omega \int_\infty^x \mathrm{d}y\, \Pi_\gamma(y)\right)(\omega R(x)\psi(x)\right.$$
$$x\left[-i\Pi_\gamma(x)J_1(\omega R(x)) + R'(x)J_0(\omega R(x))\right] + iJ_0(\omega R(x))\,\Pi_\psi(x))$$
$$\left. + \text{complex conjugate}\right\} \tag{6}$$

where Π_γ and Π_ψ are the momenta conjugate to γ and ψ, respectively and j_n is the n^{th}-order Bessel function. The expression for $P(r)$ is similar. Together $Q(r)$ and $P(r)$ form a complete set since they are invariant under reparametrization of r. And they are observables because they commute weakly with the momentum and Hamiltonian constraints.

The physical meaning of such observables can be seen from the fact that $Q(r)$ and $P(r)$ are respectively the values that ψ and Π_ψ take when $\Pi_\gamma = 0$ and $R(r) = r$, respectively. This idea can in principle be generalized to cover all solutions of EFE. In the canonical approach, a complete set of observables is obtained by expressing in terms of observables, the values of the true degrees of freedom at a given time. But obtaining explicit expressions for such a complete set is tantamount to solving the EFE, something that is beyond the capabilities of mere mortals except in very special cases. While this route to obtaining observables is useless for practical applications, it is revealing for purposes of getting a grip on the deep-level ontology and ideology of GTR.

What conclusions can be drawn from such examples? In both examples, the observables that aspire to completeness have a coincidence character: in Example 2, the observables are the values that ψ and Π_ϕ take when $\Pi_\gamma(r) = 0$ and $R(r) = r$, respectively; in Example 1, the observables are the values metric components $g^{\mu\nu}$ take when the fields ϕ^μ take on values such-and-so. Historically it is interesting to note that Einstein (1916) hit on a limited version of the notion of coincidence observables in extricating himself from the hole he had dug himself with his "hole argument." His "point coincidences" were quite literally that — the intersection of two light rays or the like. This coincidence character of observables should not come as a surprise. What is going on in the canonical approach can be described as follows. Some subset of dynamical variables — which in themselves are not observables — are being used to fix a gauge. Geometrically, a hypersurface $S\subset\Gamma$ in phase space transverse to the gauge orbits is picked out, and the values of the chosen variables are used to coordinatize S. Then writing other dynamical variables — which again are not in themselves observables — as functions of these coordinates does serve to define observables. But once you see the trick, you see that it can be done in many different ways, yielding many different sets of observables. Completeness does not serve to single out a preferred set. Nor apparently does any other non-pragmatic requirement.

While the lens of SGC does not focus on a specific ontology/ideology for GTR, it does reveal an ontology/ideology that does not fit comfortably with either of the traditional absolute/substantivalist vs. relational alternatives. It is tempting to say that the gauge-invariant content of GTR is closer to the relational side because the coincidence nature of observables has a relational flavor. But this misses the really radical change that general covariance as a gauge symmetry has wrought. Both sides in the absolute/substantivalist vs. relational debate accept the traditional subject–predicate parsing of spacetime ontology and ideology. For the relationist, the subjects are material bodies and/or events in their histories, and the spatiotemporal predicates are relational properties of these subjects. For the absolute/substantivalist, the subjects are points or regions of space or spacetime, and the spatiotemporal predicates are relational and non-relational properties of these subjects. Twentieth-century physics has been unkind to both sides. First, classical field theory elevated fields to coequal status with particles, and subsequently quantum field theory (QFT) (arguably) demoted particles to a second class if not epiphenomenal status. This ascendancy of fields seems at first to be a god-send for the substantivalist since it seems to lend itself to the view that spacetime is the only basic substance *qua* object of predication. But diffeomorphism invariance as a gauge symmetry seems to wipe away spacetime points as objects of predication.

Coming to grips with the ramifications of SGC indicates that we need to rethink the traditional subject–predicate ontology/ideology. I want to tentatively suggest that the gauge-invariant content of GTR is best thought of in terms of a new ontological category that I will call a *coincidence occurrence*. I use "occurrence" rather than "event" since the latter is traditionally conceived in subject–predicate terms, whereas coincidence occurrences lack subjects and, thus, also predicates insofar as predicates inhere in subjects; rather, a coincidence occurrence consists in the corealization of values of pairs of (non-gauge invariant) dynamical quantities. The textbook models of GTR are to be thought of as providing many–one representations of coincidence occurrences in terms of the co-occurrence of the relevant values of the pairs of quantities at a spacetime point. If further pressed to give a representation-free characterization of coincidence occurrence, I have nothing to offer. But I doubt that the defender of the traditional subject–predicate ontology can do much better in explaining what it is for a subject to take on or lose a predicate. If pressed far enough, any ontological view eventually reaches the stage where the basic concepts cannot be further explained except through gestures and analogies. Ultimately, the competing ontological views have to be judged on how well they facilitate an understanding of the best theories science has to offer, not the folk theories on which philosophy is largely based. And my feeling is that spacetime theories satisfying SGC are telling us that traditional subject–predicate ontologies, whether relational or absolute, have ceased to facilitate understanding.

Of course, it is one thing to keep an open mind, it is quite another thing to be so open-minded that your brains fall out. And it might be urged that the sort of open-mindedness I am encouraging is of the latter sort. One indication of this (it might be urged) is that the sort of disappearance-of-subjects view I have been running would seem to undercut B-series change since such change consists, for instance, of a subject s being P-at-t_1 and being $\neg P$-at-t_2 for $t_1 \neq t_2$ (endurance version) or a subject stage s-at-t_1 being P and subject stage s-at-t_2 being $\neg P$ (perdurance version). But rather than serving as an indication of the brains-falling-out open-mindedness, this consequence can be seen as a quick and dirty way of arriving at the "problem of time" in GTR. The "problem" takes its most dramatic form in the canonical approach where all the observables are "constants of the motion": because of the Hamiltonian constraint, the dynamics in the canonical approach is pure gauge, and so any observable, which, by definition, is constant along the gauge orbits, does not change its value as the system evolves[19].

Several comments are called for. First, I think that this "problem" is not a problem to be avoided, but a result that has to be accommodated in any thorough-going understanding of the foundations of GTR (see Earman, 2002). Second, this result is not a consequence of SGC *per se*. A counterexample is provided by unimodular gravity, which satisfies SGC but does not yield the result in question (see Earman, 2003a, 2006). Formally unimodular gravity resembles Einstein's GTR when a cosmological constant term is added to EFE. The difference is that in standard GTR the cosmological constant Λ is not only a spacetime constant — having the same value at each point of spacetime in any solution to EFE — but is also a universal constant having the same value in every solution, while in unimodular gravity the value of Λ can vary from solution to solution. This might seem to be a small difference, but unimodular gravity introduces additional spacetime structure over and above the metric g_{ab}. When unimodular gravity is run through the constraint algorithm of the canonical approach, it is found that some of the observables are not constants of the motion. I conjecture that in the absence of additional spacetime structure over and above the metric,

[19]As noted above, if one restricts GTR to models that are asymptotically flat, then there are some non-trivial quasi-local canonical observables, such as ADM mass, which can be used to define a non-zero Hamiltonian and to give conventional change.

SGC does entail that all canonical observables are constants of the motion. Third, the "no change" result for GTR is not an artifact of the canonical approach to observables, for a similar result holds on the spacetime approach to observables. But those who take the "no change" result to be an absurdity may say: so much the worse for general covariance interpreted as a gauge symmetry!

This leads me back to my first comment, which calls for elaboration. There is no need for hysteria in the face of the "no change" result at issue. Consider the following dilemma designed to saddle the advocate of taking seriously the "frozen" dynamics of GTR with an absurdity. Ask him: is the universe expanding? If he answers no, dismiss him as a kook who goes against the best available evidence, which indicates that our universe is expanding and at an increasing rate at that. If he answers yes, then dismiss him as holding contradictory views since he has denied that there is change. This is a little too quick. Consider solutions to EFE with compact spacelike slices. For such solutions, spatial volume-at-a-time is not a canonical observable. Nevertheless, the expansion of the universe is "observable" in a broader sense: there are enough genuine canonical observables to distinguish between (gauge equivalence classes of) those familiar spacetime models — manifold plus metric — where the volume of space is expanding and those where the volume of space is unchanging (*pace* Smolin, 2000; see also Earman, 2002). What is going on here mirrors some familiar moves in the classical phase of the absolute vs. relational debate. The relationist says that, at base, there is no space *per se* but only material bodies and their spatial relations. The absolutist may be upset: "You are taking away my space! I want space as a container in which bodies reside!" The relationist can reply: "If you want a container space you can have it — as a representation of relational reality. And as such, a container space is not a chimera because it can be part of an accurate mapping of relational reality. But you go astray if you take the representation literally, which is to say that you take the container space representations to correspond one–one rather than many–one to physical reality." And so it is with B-series change in the sense described above. If you want it, you can find it in the familiar (non-stationary) spacetime models that represent the gauge-invariant content of GTR. And this change is not a chimera because it can be part of an accurate mapping of the gauge-invariant reality. But again you go astray if you take these models literally.

It remains to explain how conscious observers experience the world as a B-series of subject–predicate events. But I view this task as being on a par with explaining how conscious observers experience "temporal passage." In the latter case, enlightened opinion has it that the task is to be carried out without forcing physics to recognize an A-series or a shifting "now." Equally enlightened opinion will, I think, come to see that the former task is to be carried out without backsliding from SGC by forcing physics to recognize a B-series of subject–predicate events. Nor need the former task be more difficult than the latter; indeed, if one starts with a temporally ordered series of coincidence occurrences and one assumes that conscious observers accurately perceive this order, then the former task reduces to that of explaining how conscious observers perceive the coincidence occurrences as subject–predicate events.

5. The implications of substantive general covariance: quantum spacetime theories

Even if it is conceded that a goal of 21st-century physics should be to develop a quantum theory of gravity, there is no knock-down argument to the effect that such a theory must proceed by way of quantizing the gravitational field (cf. Callender & Huggett, 2001 and Wüthrich, 2006). But since a sizable number of theoretical physicists are devoting their careers to developing such a theory, it seems a worthwhile enterprise for philosophers of science to try to discern the implications of quantum gravity for the ontology and ideology of spacetime. Of course, the philosophical work of providing an interpretation — realistic or otherwise — of a quantum theory of gravity can only begin in earnest after such a theory has been constructed. And while the candidate quantum theories of gravity are still very much works-in-progress, LQG has reached a stage of maturity that makes worthwhile some initial philosophical spadework. This is fortunate for present purposes since SGC plays a key rule in LQG.

LQG aims at a quantum theory of gravity by following the canonical quantization program for GTR. Thus, in this program the classical quantities that get transmuted into quantum observables — in the sense of self-adjoint operators on the Hilbert space of quantum gravity — are the observables of the canonical formulation of GTR, i.e. the phase space quantities that are gauge invariant in the sense that they commute weakly with the first-class constraints. LQG follows Dirac's constraint-quantization scheme. The idea is to turn the classical constraints into operators on a Hilbert space $\mathscr{H}$ and then to enforce gauge invariance by requiring that the physical sector $\mathscr{H}_{\text{phy}} \subset \mathscr{H}$ of the Hilbert space is the subspace corresponding to the kernel of the constraint operators. LQG is able to make progress on this program by replacing the canonical variables discussed in the previous section by a different set of variables invented by Amitaba Sen and deployed by Abay Ashtekar. At first, this replacement seems to make the problem worse since instead of the two families of constraints discussed above, there are now three — called the Gauss constraint, the vector (or diffeomorphism) constraint, and the scalar (or Hamiltonian) constraint. But in fact, the new variables facilitate the handling of the constraints. The first two constraints have been solved using the so-called spin network states $|s\rangle$, which describe discretized three geometries. Work on the scalar or Hamiltonian constraint is too technical to report here, but the implications for some of the issues discussed above can be summarized in a relatively non-technical manner.

Formally what one wants is a projection operator $\hat{P} : \mathscr{H}_{\text{Gauss, vector}} \to \mathscr{H}_{\text{phy}}$ that projects the subspace $\mathscr{H}_{\text{Gauss, vector}}$ lying in the kernel of the Gauss and vector constraints onto the kernel of the Hamiltonian constraint. Using this projector one defines the transition amplitudes $W(s, s') := \langle s|\hat{P}|s'\rangle$ between spin network states[20]. These quantities are gauge invariants and, thus, genuine observables of LQG; and they also form a complete set of observables (see Perez & Rovelli, 2001). In theories for which general covariance is not a gauge symmetry, analogous transition amplitudes can be thought of as matrix elements of the time evolution operator. But in LQG, which is a quantum implementation of the idea that the diffeomorphism invariance of GTR is a gauge symmetry, these transition amplitudes do not give time evolution in any conventional sense. Rather, they solve the Hamiltonian constraint and define the inner product on $\mathscr{H}_{\text{phy}}$. This is the quantum expression of the disappearance of time in the canonical formulation of classical GTR.

Assuming that the states $\hat{P}|s\rangle$ form a basis for $\mathscr{H}_{\text{phy}}$, one can ask whether this basis is unitarily equivalent to a natural basis that lies in the common kernel of the constraint operators that derive from the more familiar canonical formulation of GTR (a.k.a. geometrodynamics) discussed above in Section 4. Callender and Huggett (2001) have opined that if the answer is no, then "spacetime is not fundamental, but a result of a more basic reality" (p. 21). The first issue here is whether or not the physical Hilbert spaces of the two formulations of canonical quantum gravity are separable. Some versions of $\mathscr{H}_{\text{Gauss, vector}}$ for LQG are non-separable, raising the worry that $\mathscr{H}_{\text{phy}}$ might not be separable. But it has been shown that some technical tweaking can restore separability (see Fairburn & Rovelli, 2004). The basis elements that have typically been contemplated for the kinematic Hilbert space of geometrodynamics are neither normalizable nor countable, but this does not settle the issue of whether the physical Hilbert space of geometrodynamics has a countable orthonormal basis. A negative answer would indicate that this route to quantum gravity is defective since non-separability is generally regarded as a pathology in QFT. A positive answer would entail a positive answer to the Callender–Huggett question since all infinite dimensional Hilbert spaces are the same (isomorphic) and all orthonormal bases of any such space are unitarily equivalent. But, I would maintain, the answer to their question has little to do with whether spacetime is retained as a fundamental entity. (i) If LQG leads to what comes to be regarded as the correct quantum theory of gravity, then *classical* general relativistic spacetime can no longer be taken as a fundamental entity because none of the states of the physical Hilbert space of LQG describes a classical general relativistic spacetime at the subPlanck scale, and some of the states fail to describe a classical general relativistic spacetime at the macroscopic scale. Of course, a condition of adequacy on a quantum theory of gravity requires a demonstration that there are appropriate conditions under which classical general relativistic spacetime

[20]How to add flesh to the bare formalism by providing a means of calculating values for these transition amplitudes is another matter. The so-called spin-foam models can be seen as means for accomplishing this task.

emerges in some classical limit. Giving such a demonstration for LQG is one of the most important challenges that the proponents of this theory now face. The lack of progress to date could be taken as an indication that LQG strikes a Devil's bargain: by making it easier to handle the constraints, it makes it more difficult to see how classical general relativistic spacetime emerges[21]. Here again philosophers might take a wait-and-see attitude. But I think that it is a useful exercise to try to provide a nomenclature of the various senses in which classical general relativistic spacetime can be an emergent entity (see Wüthrich, 2006). One thing is clear from the outset, however: if LQG is the correct theory of quantum gravity, then classical general relativistic spacetime is not emergent in a sense that is congenial to relationism; in particular, classical spacetime does not emerge from the matter fields and their interactions since LQG is quite happy to quantize curved empty general relativistic spacetimes. (ii) On the other hand, although *classical* general relativistic spacetime has been demoted from a fundamental to an emergent entity, spacetime *per se* has not been banished as a fundamental entity. After all, what LQG offers is a quantization of classical general relativistic spacetime, and it seems not unfair to say that what it describes is *quantum* spacetime. This entity retains a fundamental status in LQG since there is no attempt to reduce it to something more fundamental.

6. Conclusion

Some of the issues that philosophers debate about the ontology/ideology of spacetime are not merely philosophical — they make a difference to ongoing scientific research programs. The nature and status of the requirement of general covariance is an example par excellence of such an issue. Indeed, I want to suggest that there is a kind of empirical test of the hypothesis that one of the lessons classical GTR teaches is that general covariance should be a gauge symmetry of spacetime theories. This hypothesis receives confirmation if LQG, which incorporates this hypothesis as a central tenet, prospers in the way that good scientific theories do. And it receives disconfirmation if LQG degenerates as a research program for reasons can be traced to the hypothesis. SGC also plays an important role in differentiating LQG from the string theory approach to quantum gravity. SGC strongly suggests that a quantum theory of gravity ought to be "background independent," i.e. should not rely on a split of the spacetime metric into a part that provides a fixed background metric and a part that encodes the dynamical degrees of freedom of the gravitational field[22]. But

[21] For a treatment of the semi-classical limit in loop quantum cosmology, see Bojowald (2001).

[22] I say "strongly suggests" rather than "implies" because I have not seen a tight argument to the effect that SGC entails background independence. But it seems plausible that on the analysis of SGC I propose here, a spacetime theory cannot satisfy SGC if it uses a fixed or absolute background metric.

so far, the string theory approach to quantum gravity has not been formulated in a background-independent fashion.

A decade ago John Norton (1993) published a masterly review article entitled "General covariance and the foundations of general relativity: Eight decades of dispute." The dispute is now over nine decades old, and it will undoubtedly continue for many more decades to come. The main reason for the longevity of the dispute is that pursuing the nature and status of general covariance leads directly to some of the most fundamental issues in the foundations of spacetime theories, issues that do not easily yield to neat solutions. I also want to suggest that some of the implications of SGC are counterintuitive, so much so that those who have glimpsed them have turned away in search of an avoidance strategy. Philosophers are nothing if not clever, and sufficient cleverness will undoubtedly produce a variety of avoidance strategies. But it seems to me that the road to wisdom goes not by way of avoidance, but by way of facing the implications and in trying to understand how they change the terms of the debate about the ontology and ideology of spacetime.

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Chapter 2

The Disappearance of Space and Time

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Abstract

I argue that lesson of general relativity is that at our present state of knowledge the best way for making sense of the world is to discard the notions of space and time. Newtonian space and time can be reinterpreted as aspects of the gravitational field, which is only one among the various dynamical physical fields making up the world. Physical fields do not need to inhabit spacetime in order to exist. The resulting understanding of space is to some extent a return to the Aristotelian-Cartesian relational tradition; while the resulting interpretation of temporality, appears to have strong elements of novelty. I consider the viability of a foundation of our understanding of the world in which space and time play no role.

1. The ontology of spacetime after relativity

Our understanding of the natural world evolves. We have developed a conceptual structure that allows us to apprehend and frame the world that we perceive and think; but this conceptual structure evolves, driven by experience and rational investigation. Science is a continuous exploration of novel and more effective ways for thinking the world. We cannot exit our own way of thinking; but we can modify it from within, exploring modifications of our basic assumptions, and testing them for consistence and against experience. This process of exploration of the space of the ideas is at the core of theoretical physics.

The notions of space and time of classical physics are a characteristic product of this process. We own them to a large extent to the work of Newton, in the 17th century. Newton defended a novel way of thinking space and time against the dominant views of his time. This way proved then extraordinarily effective. The Newtonian notions of space and time have been extensively utilized and discussed in depth. With time, they have been ‘‘absorbed’’ by our culture at large, and have become the dominant view.

The relativistic revolution of early 20th century, once more due to a remarkable extent to a single man, has taught us that there is a more effective way of understanding space and time than the Newtonian one. The novel *relativistic* understanding of space and time, however, has not yet been integrated into the common, and not even into the learned, way of thinking the world. Yes, mental habits take time to change; but I am often surprised by the excessive attachment that many thinkers maintain to ideas for understanding the world that have been clearly proven ineffective. These ideas were useful for a while, roughly in the three centuries between Newton and Einstein. But we must not mistake a tool that has proven useful for an eternal truth. There are commonly used concepts, such as the idea of an ‘‘objective present state of the world’’, that make no sense, in the light of what we have learned about the universe. Relativity is not ‘‘contemporary science’’: it is close to a century old. It is certainly time to take it seriously, discuss it in depth, and get used to it.

A reason for the slow adaptation to the relativistic understanding of space and time is that the relativistic revolution has happened in more than one step. The first step is special relativity (SR); shortly after came general relativity (GR)[1]. For a few decades, while SR was blessed by continuous confirmations, especially from particle physics, GR had spectacular but scarce empirical support. In this situation, the attention was mostly on the relatively simpler conceptual novelty of SR, leaving GR in a limbo at the borders of our map of reality. But in the last decades the number and the success of experiments and observation confirming the physical validity of GR have exploded, and the theoretical interest in GR has boomed. Today, we cannot leave GR out of the picture. SR is little more than a minor variation of the Newtonian conceptualization of spacetime. The *special* relativistic universe is a theoretical model whose true interest as a fundamental way to understand reality was significant for less than 10 years, between 1905 and 1915. Therefore we must focus on GR if we want to hold a view of space and time compatible with what we have understood so far about the natural world.

[1]To further complicate matters, the relativistic revolution has not yet ended, because we have not yet fully unraveled its relation with quantum physics. Knowledge of quantum theory induces us to certain conceptual choices in understanding relativity, but care should be taken in reading these hints because we still lack a definitive synthesis.

The new understanding of spacetime that has emerged from the relativistic revolution differs from the Newtonian picture especially with regard to the ontological status of spacetime — the subject of this book. Newton made the successful hypothesis that space and time are fixed structured background entities underlying material reality, which participate in governing the motion of physical objects. What Einstein has discovered is that Newton had mistaken a physical field for a background entity. The two entities hypostatized by Newton, space and time, are just a particular local configuration of a physical entity — the gravitational field — very similar to the electric and the magnetic field.

Einstein's discovery is that Newtonian space and time and the gravitational field are the same entity. There is a tradition of expressing this discovery saying that "there is no gravitational field: space and time become dynamical". I think that this is a convoluted and misleading way of thinking, which does not do justice to Einstein's discovery, and has the additional flaw of becoming meaningless as soon as we take into account the fact that the gravitational field has quantum properties.

The clean way of expressing Einstein's discovery is to say that there are no space and time: there are only dynamical objects. The world is made by dynamical fields. These do not live in, or on, spacetime: they form and exhaust reality.

One of these fields is the gravitational field. In the regimes in which we can disregard its dynamics, this field interacts with the rest of the physical objects as if it were a fixed background. This background is what Newton discovered and called space and time. We can keep using the evocative terminology "spacetime" to indicate the gravitational field. But it has practically none of the features that characterized space and time. Relativistic spacetime is an entity far more akin to Maxwell's electric and magnetic fields than to Newtonian space.

In classical GR, a given solution of the field equations might still have some vague resemblance to the Newtonian's notions, since it defines a "continuum" which things can be imagined "to inhabit". But the only compelling reason for thinking that "spacetime" is the gravitational field, and not — say — the electromagnetic field, is the contingent fact that we live in a portion of the universe where the gravitational field is sufficiently constant for us to use it as a convenient reference.

Quantum mechanics reinforces this point of view. A solution of the classical field equations is like a particle trajectory: a notion that only makes physical sense in the classical limit. The gravitational field has quantum properties, and therefore it cannot define a spacetime continuum in the small.

Properly speaking, relativity has taught us that the effective way of thinking about the world in the light of what we have learned so far is to give up the notions of "space and time entities" entirely. This is not a dramatically radical view, since it is not far from the way space was commonly conceptualized before Newton. On the other hand, it has a novel twist of great interest, especially as far as time, and the relation between time and space, are concerned.

In Newtonian physics, if we take away the dynamical entities, what remains is space and time. In relativistic physics, if we take away the dynamical entities, nothing remains. As Whitehead put it, we cannot say that we can have spacetime without dynamical entities, anymore than saying that we can have the cat's grin without the cat (Whitehead, 1983).

In the rest of this text, I discuss relativistic spacetime in some more detail. I start by recalling a few facts about pre-Newtonian western ideas about space and time. This is important because the Newtonian scheme is often mistaken for a sort of "natural" understanding of space and time. Nothing is more wrong: the Newtonian space and time "entities" form a strongly counter-intuitive theoretical construction, which met fierce resistance at first. Next, I illustrate the modification of the notions of spacetime introduced by SR and GR. I focus on the Newtonian notions that are to be abandoned. I close by mentioning the possibility of a proper relativistic foundation of the physical description of the world where the notions of space and time play no role.

2. Space

There are two traditional ways of understanding space in the western culture: as an *entity* or as a relation. "Space is an entity" means that space exists also when there is nothing else than space. It exists by itself, and objects may move in it. "Space is a relation" means that the world consists entirely of physical objects (particles, bodies, fluids, fields …). These objects have the property that they can be in touch with one another, or not. Space is this "touch", or "contiguity", or "adjacency" relation between objects. Connected to these two manners of understanding space, are two manners of understanding motion. If space is an entity, motion can be defined as going from one part of space to another part of space. This is denoted by "absolute motion". If space is a relation, motion can only be defined as going from the contiguity of one object to the contiguity of another object. This is called "relative motion". For a physicist, the issue is which of these two ways of thinking about space and motion allows a more effective description of the world.

The dominant view in the European tradition, from Aristotle to Descartes, was to understand space and motion as relational. Aristotle, for instance, defines the spatial location of an object as "the inner surface of the innermost object that surrounds the body" (Aristotle, Physics, Book IV, Chapter 4[20], Aristotle, 1952). This is relational space. Descartes defines motion as "the transference of one part of matter or of one body, from the vicinity of those bodies immediately contiguous to it, and considered at rest, into the vicinity of some others'' (Descartes, *Principia Philosophiae*, Section II-25, p. 51, Descartes, 1983). Aristotle as well insists that motion is relative. He illustrates the point with the example of a man walking over a boat. The man moves with respect to the boat, which moves with respect to the water of the river, which moves with respect to the ground … .

The alternative view of space, as an independent entity, existed since ancient times (mostly in the Democritean tradition), but became dominant only with Newton. It is also the way spacetime (rather than space) is understood in SR. For Newton, space is absolute and motion is absolute: ''So, it is necessary that the definition of places, and hence local motion, be referred to some motionless thing such as extension alone or *space*, in so far as space is seen truly distinct from moving bodies'' (Newton, *De gravitatione et Aequipondio Fluidorum*, pp. 89–156, Newton, 1962). This is in patent contrast with Descartes definition, given above.

It should be noted that the difference between the two points of view is not so strong as it seems at first sight. Starting from a relational point of view, we can always *choose* a physical entity, refer all motion to this preferred entity and *call* this entity ''space''. Newton does not miss this point, and in fact he specifies that what is to be called space has to be ''truly distinct from moving bodies''. Newton thought he had discovered this entity ''truly distinct from moving bodies'', the way to detect it and its effects. GR is the realization that the entity discovered by Newton is not at all ''truly distinct from moving bodies''. In fact, it is barely distinguishable from the other fields.

In introducing the idea of absolute space, Newton did not challenge a long tradition with light heart: he devotes a long initial section of the *Principia* to explain the reasons for his choice. Today we can say that the strongest argument in Newton's favor is a posteriori: his theoretical construction works extraordinary well. Relational Cartesian and Leibnizian proposals were never as effective. But this was not Newton's argument. Newton invokes empirical evidence, discussing the famous bucket experiment. This experiment proves that there are physical effects (the bending of the surface of the water in the bucket) that do not depend on the relative motion of the water with respect to the surrounding objects (the bucket).

The surface of the water curves when the water rotates: but rotates with respect to *what*?

Newton argues that the only reasonable answer is absolute space. The concavity of the water's surface is an effect of the absolute circular motion of the water: the motion with respect to absolute space. This, claims Newton, proves the existence of absolute space. Newton's argument is subtle; it has been often challenged, but it has withstood all attacks for three centuries[2]. It has then collapsed under Einstein's alternative and more effective answer.

Newton needed (accelerated) motion, exemplified by the rotation of the water in the bucket, to be absolute for the foundation of his dynamics. Without this, Newton's main law $\vec{F} = m\vec{a}$ would not even make sense: what would be the meaning of the acceleration $\vec{a}$?

Opposition to Newton's absolute space was very strong. Leibniz and his school argued fiercely against absolute motion and absolute acceleration. Doubts never really disappeared all along the centuries and a feeling kept lingering that something was wrong with Newton's argument. Ernst Mach returned to the issue suggesting that Newton's bucket argument could be wrong because the water does not rotate with respect to absolute space: it rotates with respect to the full matter content of the universe. But the immense empirical triumph of Newtonianism could not be overcome. For three centuries.

After three centuries, Einstein found a new and simpler answer. The bending of the surface of the water is due to the relative motion of the water with respect to a physical entity: the local gravitational field. It is the gravitational field, not Newton's inert absolute space that tells objects if they are accelerating or not, if they are rotating or not. There is no inert background entity such as Newtonian space: there are only dynamical physical entities. Among these are the fields, introduced in our physical picture of the world by Faraday and Maxwell. Among the fields is the gravitational field.

Whether the water surface in Newton's bucket is concave or flat is not determined by the motion of the water with respect to absolute space. It is determined by the physical interaction between the water and the gravitational field. Einstein's discovery is that Newton had mistaken the gravitational field for absolute space.

In Newtonian physics, the spacetime coordinates $\vec{x}$ and t refer to absolute space. They can be identified with the reading of measuring devices carefully selected as the ones that capture the structure of space and time. This selection is obtained by monitoring and correcting the "inertial" effects such as the bending of the water of the water, which signal motion with respect to absolute space.

[2]Or course relationalism, i.e., the idea that motion can be defined only in relation to other objects, should not be confused with Galilean relativity. Galilean relativity is the statement that "rectilinear uniform motion" is a priori indistinguishable from stasis. This is equivalent to saying that velocity (just velocity!), is only relative to other bodies. Relationalism, on the other hand, holds that any motion (however zigzagging) is a priori indistinguishable from stasis. The very formulation of Galilean relativity assumes a nonrelational definition of motion: "rectilinear and uniform" with respect to what? When Newton claimed that motion with respect to absolute space is real and physical, he, in a sense, overdid it, by insisting that even rectilinear uniform motion is absolute. This caused a painful debate, because there are no physical effects of inertial motion (therefore the bucket argument fails for this particular class of motions). Newton is well aware of this point, which is clearly stated in the Corollary V5 of the Principia, but he chooses to ignore it in the introduction of the Principia. I think he did this just to simplify his argument, which was already hard enough for his contemporaries.

Einstein realized that finding out the pre-GR "inertial" $\vec{x}$ and t is nothing else than detecting local features of the gravitational field. In the theoretical apparatus of GR, on the other hand, the spacetime coordinates $\vec{x}$ and t have a completely different status, and it is only an unfortunate historical accident that they are denoted in the same manner as the pre-general-relativistic inertial coordinates. The relativistic $\vec{x}$ and t coordinates have no direct physical meaning (unless we gauge fix them to represent something else). The reading of measuring devices is identified with quantities in the theory that are independent of $\vec{x}$ and t.

More formally, in the mathematics of classical GR we employ a background "spacetime" manifold and describe the fields as living on this manifold. However, the diffeomorphism invariance of the theory demands that the localization on this manifold is pure gauge. That is, it is physically irrelevant. The manifold is just an artifice for describing a set of fields and other physical objects whose only "localization" is with respect to one another.

A state of the universe does not correspond to one field configuration over the spacetime manifold M. It corresponds to an equivalence class under active diffeomorphisms of field configurations. Therefore localization over M is physically irrelevant. In fact, M has no physical interpretation. It is a mathematical device without physical counterpart. It is a gauge artifact. M cannot be interpreted as a set of physical "events", or physical spacetime points "where" the fields take value. The only possibility of locating points is with respect to the dynamical fields and particles of the theory itself. It is meaningless to ask whether or not the gravitational field is flat around the spacetime point A, because there is no physical entity "spacetime point A". Contrary to Newton, spacetime points are not entities where particle and fields live[3].

The gravitational field $g_{\mu\nu}(x)$ determines a four-dimensional continuum with a metric structure. Excessive significance is often attributed to this structure, as if distance was an essential property of space, or even an essential property of reality. This is like an Eskimo thinking that snow is an essential property of the ground.

We could have developed physics without ever thinking about distances, while nevertheless retaining the complete predictive and descriptive power of our theories. We live in physical conditions where atoms form and interact with the gravitational field in such a way that they maintain structures characterized by the fact that the integral of the gravitational field $d = \int \sqrt{g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu}$ along these structures is very stable. We call this integral d "distance", and we have developed useful mathematics — geometry — to describe the structure of these distances.

[3]Physical field are not attributes of space, anymore than a mosaic is an attribute of the wall. The wall can be taken away from the mosaic, without necessarily destroying the mosaic. The clearest intuition of the nature of a field (in particular, a gauge field) is the original Faraday's intuition of a field as a collection of lines.

Geometry has repeatedly been mistaken for an a priori feature of reality. Euclidean geometry was erroneously thought of as necessary. Later, Riemannian geometry as well has been erroneously considered necessary. However, there is no a priori reason for which reality has to be understood as a continuum with metric properties. Nor, for that matter, as a continuum at all. Indeed, contemporary research in quantum gravity points in a very different direction.

Conceptually, what disappears with GR is the idea of space as the "container" of the physical world. As mentioned, this disappearance is not so revolutionary after all: to some extent it amounts to return to the pre-Newtonian view of space as a relation between equal-status physical entities.

Allow me to close this section with a playful observation on the relation between the shift in our views about space and our overall world conception. In the pre-Copernican world the cosmic organization of the "things" was hierarchically structured. The Heavens above, the Earth below, spheres in order of decreasing perfection. Objects were located with respect to one another — this served to grant each object a precise "status" in the grand scheme of things, analogous to the social position of humans. With the Copernican revolution, this hierarchical structure was lost. Position lost any ranking value. Newton offered reality a global frame. He offered every object the equal dignity of a position in a uniform space. For Newton this frame was grounded in God. He called space the "sensorium" of God: the world as perceived by God. Thus, the position in space for Newton is, literally, the position of the objects in the eyes of God. Against the multiplicity of the individual points of view determined by the observation of the relative motions, absolute space grants a single-organizing principle. According to Newton, our rationality allows us to unveil the absolute point of view of God (by detecting inertial effects such as the bending of the surface of the water). With or without such an explicit reference to God, for three centuries space has been regarded as the preferred Entity with respect to which all other entities are located. In the 20th and 21st centuries and with GR we have been learning that we do not need this frame to keep reality in place. Reality keeps itself in place. Objects interact with other objects, and this is reality. Reality is the net of these interactions. We do not need an external entity to hold this net. We do not need Space, to hold the universe. Maybe the Copernican revolution is finally being completed.

3. Time

The disappearance of physical time is the second characteristic feature of the relativistic revolution. The notion of time is harder to deal with than the notion of space, and represents a more radical step than the disappearance of space.

Once again, much of the common understanding of time derives from the 17th century. Galileo was the first to use a mathematical time variable t to formulate equations describing the motion of terrestrial objects. These are equations for functions $X(t)$ of time. Newton was well aware that we never measure the variable t appearing in these equations directly. We use clocks whose reading T should be taken as a good approximation of the hypothetical "true" time t. As in the case of spatial measurements, we select better and better clocks by eliminating effects that *the theory* denounces as produced by the difference between T and t. The relation $T(t)$, between clock reading and true time, can itself be calculated from the theory, using a mechanical model of the clock. From $X(t)$ and $T(t)$ we can compute $X(T)$, which is the only relation we effectively observe. Newtonian theory is formulated in terms of the not directly observable quantity t. The scheme is delicate and involved, but it has worked wonderfully well for three centuries.

SR takes the first step out of the Newtonian understanding of time. SR does not change the Newtonian hypostatization of absolute space and time, but destroys the clean distinction between the two.

SR is the discovery that it makes no physical sense to say that two distant physical events happen "at the same time". It is true that Einstein provides a definition of simultaneity, two events A and B, relative to an object O in a given state of motion[4]. But although this is a useful working definition, it is a mistake to give it ontological significance. There is nothing in SR that would lead us to think that A and B have an ontic property of being "existant at the same time with respect to O", besides satisfying a useful conventional definition.

To illustrate this point, consider a standard expanding cosmological model. Its space like surfaces of homogeneity are formed by the events at equal proper time after the big bang, or equal Friedmann time t_{Fr}; these are the surfaces naturally considered "simultaneous" in cosmology. These surfaces are *not* equal time surfaces according to Einstein's simultaneity definition[5]. Therefore, in a cosmological context we have the alternative to call either "simultaneous" events at the same Friedmann time, or events that satisfy Einstein's definition of simultaneity. Both definitions are useful. The choice between them is a matter of taste or computational convenience, not a matter of ontology.

The simple physical fact, revealed by SR, is that there are physical events on, say, Andromeda that have no temporal relation with events on Earth. A small gravitational wave passing in between could change Einstein's simultaneity between us and them by years, without affecting the physics here or there anymore

[4]The event A along the trajectory of an observer O is said to be simultaneous to a distant event B if a light signal emitted by O a time interval T before A and reflected by B, returns to O at a time T after A.

[5]I thank Marc Lachieze-Rey for pointing this out to me.

than works on the highway change relations between two cities. The lesson is that the idea that there exists a "now" all over the universe does not square with what we know about the universe. At best, we can talk of time lapsed along individual world lines, or time experienced by individual observers.

The picture of a Universe changing from one global instant to the next is incompatible with what we know about the world.

What is then "time" in the light of GR? This is a deep and important question that in my opinion has not yet been sufficiently investigated. I offer here what I think is the most useful answer to this question.

GR inherits from SR the melting of space and time into spacetime. Therefore the relational nature of space revealed by GR extends to time as well. It follows that in GR there is no background spacetime and therefore in particular no time along which things happen. GR teaches us that we must abandon the idea that the flow of time is an ultimate aspect of reality. The best description we can give of the world is not in terms of time evolution. The dynamics of GR itself cannot be cleanly described in terms of evolution in time.

There are many distinct notions of time employed in GR: coordinate time t, proper time S, clock times T, cosmological time t_{Fr}, asymptotic Poincaré time … . The last two refer to the description of special solutions of the Einstein field equations only. They are irrelevant in a discussion of the ontology of time, because a different ontology for different solutions of the same theory is certainly unsatisfactory. Clock times are simply the readings of certain physical variables, which can be locally employed as the independent variable for convenience. Once again, they have nothing to tell us about the ontology of time. Coordinate time is unobservable (unless the gauge is fixed, in which case it designates something else) because of general coordinate invariance. The only residual time notion that keeps a resemblance of temporality is proper time. Proper time does not flow uniformly in the universe. It is defined along a world line and, generically, if two world lines meet twice, the two proper times lapsed between the two encounters differ. Proper time S depends on the gravitational field, which is influenced by the interaction with many systems. Typically, harmonic oscillations are isochronous in S. Therefore, S like the distance d described in the previous section, is just an observable feature of the gravitational field, which is particularly convenient to use as a stable reference in our environment, when describing the motion of objects assuming the gravitational field fixed. The dynamics of the gravitational field itself, on the other hand, cannot be naturally described in terms of evolution in any well-defined preferred time variable.

Instead, we must describe reality in terms of correlations between observables. We can measure physical quantities around us. The physical theory restricts the combinations of quantities that we can measure. It predicts relations between these quantities. Only in particular situations we can choose one quantity as the independent variable, call it time, and express the others as functions of it. In general, this may not be possible, and the physical theory gives us constraints on the values of measurable quantities that we can obtain from physical measurements, not evolution laws in a preferred time variable. Quantum theory assigns probabilities to such outcomes.

Basic physics without time is viable, it is forced upon us by relativity, and it is conceptually coherent and consistent with our experience of the world. A complete discussion of the foundations of mechanics in the absence of a notion of time is given for instance in Rovelli (2002). Remarkably if we give up the idea that there is a special "time" observable, mechanics takes a far more compact and elegant form. This shift of point of view is forced upon us by classical GR. If, in addition, we take quantum theory into account, the spacetime continuum, with its last vague resemblance to temporality disappears completely, and we confront the absence of time at the fundamental level in full.

So, where does temporality, with all its peculiar features ("flow" of time, whatever this means, irreversibility, memory, awareness ...) come from? I think that all this has nothing to do with mechanics. It has to do with statistical mechanics, thermodynamics, perhaps psychology or biology. In Rovelli (1993) I have developed, in collaboration with Alain Connes, the idea that it may be possible to recover temporality from statistical mechanics, within an atemporal mechanical universe (statistical time hypothesis). If this point of view is correct, temporality is an artifact of our largely incomplete knowledge of the state of the world, not an ultimate property of reality.

Some people find the absence of time difficult to accept. I think that this is just a sort of nostalgia for the old Newtonian notion of an absolute "Time" along which everything flows, a notion already shown by SR to be inappropriate for understanding the real world. I think that the motivation for holding on to Poincaré invariance, to unitary time evolution, to the idea that there is a "Present" extending all over the universe, is only to provide an anchorage for our familiar notions, which are appropriate to describe the garden of our daily life. But a bit more at large, these are notions that are inappropriate to describe this beautiful and surprising world we inhabit.

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Chapter 3

Spacetime Structuralism

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Abstract

In this essay, I consider the ontological status of spacetime from the points of view of the standard tensor formalism and three alternatives: twistor theory, Einstein algebras, and geometric algebra. I briefly review how classical field theories can be formulated in each of these formalisms, and indicate how this suggests a structural realist interpretation of spacetime.

1. Introduction

This essay is concerned with the following question: If it is possible to do classical field theory without a 4-dimensional differentiable manifold, what does this suggest about the ontological status of spacetime from the point of view of a semantic realist? In Section 2, I indicate *why* a semantic realist would want to do classical field theory without a manifold. In Sections 3–5, I indicate the extent to which such a feat is possible. Finally, in Section 6, I indicate the type of spacetime realism this feat suggests.

2. Manifolds and manifold substantivalism

In classical field theories presented in the standard tensor formalism, spacetime is represented by a differentiable manifold M and physical fields are represented by tensor fields that quantify over the points of M. To some authors, this has suggested an ontological commitment to spacetime points (e.g., Field, 1989; Earman, 1989). This inclination might be seen as being motivated by a general semantic realist desire to take successful theories at their face value, a desire for a *literal interpretation* of the claims such theories make (Earman, 1993; Horwich, 1982). Arguably, the most literal interpretation of classical field theories motivated in this way is manifold substantivalism. Manifold substantivalism consists of two claims.

(i) *Substantivalism*: Manifold points represent real spacetime points.
(ii) *Denial of Leibniz Equivalence*: Diffeomorphically related models of classical field theories in the tensor formalism represent distinct physically possible worlds.

Both claims can be motivated by a literal interpretation of the manifold M that appears in such theories. Claim (i) follows, as suggested above, from a literal construal of tensor fields defined on M, and claim (ii) follows from a literal construal of M as a set of *distinct* mathematical points. Unfortunately for the semantic realist, however, manifold substantivalism succumbs to the hole argument, and while spacetime realists have been prolific in constructing versions of spacetime realism that maneuver around the hole argument, all such versions subvert in one form or another the semantic realist's basic desire for a literal interpretation[1]. But what about interpretations of classical field theories formulated in formalisms in which the manifold does not appear? Perhaps spacetime realism can be better motivated in such formalisms while at the same time remaining true to its semantic component.

As a concrete example, consider classical electrodynamics (*CED*) in Minkowski spacetime. Tensor models of *CED* in Minkowski spacetime are given by $(M, \eta_{ab}, \partial_a, F_{ab}, J_a)$, where M is a differentiable manifold, η_{ab} is the Minkowski metric, ∂_a is the derivative operator associated with η_{ab}, and F_{ab} and J_a are tensor fields that represent the Maxwell field and the current density and that satisfy the Maxwell equations.

$$\eta_{ab}\partial_a F_{bc} = 4\pi J_c, \qquad \partial_{[a}F_{bc]} = 0 \tag{1}$$

This suggests that M plays two roles in tensor formulations of classical field theories.

(a) A *kinematical* role as the support structure on which tensor fields are defined. In this role, M provides the mathematical wherewithal for representations of physical fields to be defined.

[1] For a quick review of the hole argument and positions staked out in the literature, see Bain (2003). Spacetime realists who adopt (i) but deny (ii) (“sophisticated substantivalists”) give up the semantic realist's desire for a literal interpretation of manifold points and subsequently have to engage in metaphysical excursions into the notions of identity and/or possibility.

(b) A *dynamical* role as the support structure on which derivative operators are defined. In this role, M provides the mathematical wherewithal for a dynamical description of the evolution of physical fields in the form of field equations.

To do away with M and still be able to do classical field theory, an alternative formalism must address both of these roles. In particular, it must provide the means of representing classical fields, and it must provide the means of representing the dynamics of classical fields.

3. Manifolds vs. twistors

In this section, I indicate that for certain conformally invariant classical field theories, the twistor formalism is expressively equivalent to the tensor formalism. Standard examples of such theories include

(a) fields that describe geodesic, shear-free, null congruences;
(b) zero rest mass fields;
(c) anti-self-dual Yang-Mills fields; and
(d) vacuum solutions to the Einstein equations with anti-self-dual Weyl curvature.

I indicate how these results follow from a general procedure known as the Penrose Transformation, and discuss their extensions and limitations[2]. I suggest that the concept of spacetime that arises for such field theories is very different, under a literal interpretation, from the one that arises in the tensor formalism.

The twistor formalism rests on a correspondence between complex, compactified Minkowski spacetime $\mathbb{CM}^c$ and a complex projective 3-space referred to as projective twistor space $\mathbb{PT}$. One way to initially understand this correspondence is to first note that compactified Minkowski spacetime $\mathbb{M}^c$ is the carrying space for matrix representations of the 4-dimensional conformal group

[2]The limitation to conformally-invariant field theories will be discussed below at the end of Section 3.1. For some initial motivation, the conceptual significance of example (a), for instance, is that spacetimes that admit geodesic, shear-free, null congruences are *algebraically special* (technically, one or more of the four principle null directions of the Weyl curvature tensor of such spacetimes coincide). Whether or not there is physical significance associated with this mathematical constraint, it does allow solutions to the Einstein equations to be more readily constructed. For instance, the Kerr solution that describes a charged, rotating black hole is algebraically special.

$C(1, 3)$, comprised of conformal transformations on Minkowski spacetime[3]. Next note that (non-projective) twistor space $\mathbb{T}$ is the carrying space for matrix representations of $SU(2, 2)$, which is the double-covering group of $SO(2, 4)$, which itself is the double-covering group of $C(1, 3)$. Hence twistor space encodes the *conformal structure* of Minkowski spacetime, and the twistor correspondence will allow us to rewrite *conformally invariant* field theories in terms of twistors. The precise correspondence requires the complexification of $\mathbb{M}^c$ and the extension of $\mathbb{T}$ to projective twistor space $\mathbb{PT}$. To get a feel for the latter, note that $\mathbb{T}$ can be defined as the space of solutions $(\omega^A, \pi_{A'}) \equiv Z^\alpha (\alpha = 0, 1, 2, 3)$ of the *twistor* equation $\nabla_{B'}{}^B \omega_C(x) = -i\varepsilon_B{}^C \pi_{A'}$, a general solution having the form $\omega^A(x) = \omega_0^A - ix^{AA'}\pi_{A'}$, where ω_0^A and $\pi_{A'}$ are constant 2-spinors[4]. So-defined, $\mathbb{T}$ is a 4-dimensional complex vector space with a Hermitian 2-form $\sum_{\alpha\beta}$ (a "metric") of signature $(+ + - -)$, and one can then show that it carries a matrix representation of $SU(2, 2)$. $\mathbb{PT}$ is then the 3-complex-dimensional space of 2-spinor pairs $(\omega^A, \pi_{A'})$, up to a complex constant, that satisfy the twistor equation. Under this initial understanding, a twistor Z^α is nothing but a particular "spacetime-indexed" pair of 2-spinors. However, as will be noted below, there are a number of other ways to interpret twistors.

To reiterate, the twistor correspondence allows solutions to certain conformally invariant hyperbolic differential equations in Minkowski spacetime to be encoded in complex-analytic, purely geometrical structures in an appropriate twistor space. Hence, the dynamical information represented by the differential equations in the tensor formalism gets encoded in geometric structures in the twistor formalism. Advocates of the twistor formalism emphasize this result — they observe that, in the twistor formalism, there are no dynamical equations; there is just geometry. This suggests that a naive semantic realist may be faced with a non-trivial task in providing a literal interpretation of classical field theories in the twistor formalism. Before discussing this task, I will briefly

[3]Conformal transformations preserve angles but not necessarily lengths. In Minkowski spacetime (M, η_{ab}) they preserve the Minkowski metric η_{ab} up to scale (i.e., they map $\eta_{ab} \mapsto \Omega^2 \eta_{ab}$, where $\Omega = \Omega(x)$ is a smooth, positive scalar function on M) and consist of Poincaré transformations $x^a \mapsto \Lambda_b^a x^b + r^a$, dilations $x^a \mapsto kx^a$, and inversions $x^a \mapsto (y^a - x^a)/(y_b - x_b)(y^b - x^b)$, where $\Lambda_b{}^a$, r^a, and k are constant. Inversions are singular at points on the light cone centered at y^a. To construct a carrying space that includes inversions, M is compactified by attaching a boundary $\mathscr{I} = \partial M$ consisting of a light cone at infinity. Inversions then interchange $\mathscr{I}$ with the light cone at y^a. We thus have $\mathbb{M}^c = (\mathscr{I} \cup M, \eta_{ab})$.

[4]Recall that the 2-spinor ω^A is an element of a complex 2-dimensional vector space $\mathbb{S}$ endowed with a bilinear anti-symmetric 2-form (the spinor "metric") ε_{AB}. $\mathbb{S}$ is the carrying space for representations of the group, $SL(2, \mathbb{C})$, which is the double-covering group of the Lorentz group $SO(1, 3)$. The 2-spinor $\pi_{A'}$ is an element of the Hermitian conjugate vector space $\mathbb{S}'$. (Here and below the abstract index notation for 2-spinors and for tensors is used. In particular, 2-spinor indices are raised and lowered via the metrics ε_{AB}, $\varepsilon_{A'B'}$, and tensor indices b can be exchanged for pairs of spinor indices BB'.)

describe the mathematics underlying the twistor correspondence and its application to classical field theories[5].

3.1. The twistor correspondence and the Penrose transformation

The twistor correspondence can be encoded most succinctly in a double fibration of a correspondence space $\mathbb{F}$ into $\mathbb{CM}^c$ and $\mathbb{PT}$ (see, e.g., Ward & Wells, 1990, p. 20). In fiber bundle lingo, such a construction consists of two base spaces that share a common bundle space[6]. This common bundle space then allows structures in one base space to be mapped onto structures in the other. In the case in question, the common bundle space $\mathbb{F}$ is given by the primed spinor bundle over $\mathbb{CM}^c$ consisting of pairs $(x^a, \pi_{A'})$ where x^a is a point in $\mathbb{CM}^c$ and $\pi_{A'}$ is a primed 2-spinor. The double fibration takes the explicit form,

$$\begin{tikzcd} & \mathbb{F} \arrow[dl, "\mu"'] \arrow[dr, "\upsilon"] & \\ \mathbb{PT} & & \mathbb{CM}^c \end{tikzcd} \qquad \begin{tikzcd} & \textit{correspondence space} \arrow[dl] \arrow[dr] & \\ \textit{twistor space} & & \textit{spacetime} \end{tikzcd}$$

where the projection maps μ, v are given by

$$v : (x^a, \pi_{A'}) \rightarrow x^a$$

$$\mu : (x^a, \pi_{A'}) \rightarrow (\mathrm{i}x^{AA'}\pi_{A'}, \pi_{A'})$$

These maps are constructed so that they give the correspondence between elements of $\mathbb{CM}^c$ (complex spacetime points) and elements of $\mathbb{PT}$ (projective twistors) by the following relation

$$\omega^A = \mathrm{i}x^{AA'}\pi_{A'} \tag{KC}$$

known as the Klein correspondence[7]. It expresses the condition for the twistor $(\omega^A, \pi_{A'}) \in \mathbb{T}$ to be incident with the point $x^a \in \mathbb{CM}^c$[8]. Based on this correspondence,

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[5]What follows is an exposition of what has been informally called "Stone-Age" twistor theory (twistor theory during the period 1967–1980). "21st Century" twistor theory has advanced quite a way from $\mathbb{CM}^c$ with current applications in such far-flung areas as string theory (Witten, 2004) and condensed matter physics (Sparling, 2002).

[6]In fiber bundle theory, a bundle space consists of algebraic objects (the "fibers") that are parameterized by the points of a base space. Intuitively, the bundle space lives over the base space and consists of fibers, one for each point of the base space, that are woven together in a smooth way.

[7]So-named for a construction in algebraic geometry that was first given by F. Klein in 1870 ("Zur Theorie der Liniercomplexe des ersten und zweiten Grades', *Math. Ann.* **2**, 198). Klein demonstrated that the points of a 4-dimensional quadric surface embedded in a 6-dimensional space can be put in 1–1 correspondence with the lines of a projective 3-space. Penrose (1967) introduced the twistor formalism based on the related observation that compactified Minkowski spacetime $\mathbb{M}^c$ can be viewed as a 4-quadric surface embedded in the projective 5-space associated with the 6-dimensional carrying space of representations of $SO(2, 4)$.

[8](KC) gives the locus of points in $\mathbb{CM}^c$ where solutions to the twistor equation vanish.

Table 1
Geometrical correspondences between projective twistor space and complex compactified Minkowski spacetime

$\mathbb{PT}$	$\mathbb{CM}^c$
Point	α-plane
Line	Point
Point in $\mathbb{PN}$	Real null geodesic
Point in $\mathbb{PT}^+ \cup \mathbb{PT}^-$	Real Robinson congruence
Line in $\mathbb{PN}$	Real point
Intersection of lines	Null separation of points

the maps allow structures in $\mathbb{PT}$ to be pulled up to $\mathbb{F}$ and then pushed down to $\mathbb{CM}^c$, and vice versa. In particular, the copy in $\mathbb{PT}$ of the fiber $v^{-1}(x^a)$ is obtained directly from (*KC*) by holding $x^{AA'}$ fixed and varying $(\omega^A, \pi_{A'})$. One obtains a complex linear 2-dimensional space in $\mathbb{T}$, which defines a line in $\mathbb{PT}$. The copy in $\mathbb{CM}^c$ of the fiber $\mu^{-1}(\omega^A, \pi_{A'})$ is obtained in a similar manner by holding the twistor $(\omega^A, \pi_{A'})$ fixed and varying the spacetime point $x^{AA'}$. This defines a complex null 2-dimensional plane in $\mathbb{CM}^c$ referred to as an α-plane. Hence under (*KC*), points in $\mathbb{CM}^c$ (complex spacetime points) correspond to "twistor lines", and points in $\mathbb{PT}$ (projective twistors) correspond to α-planes. A summary of similar geometrical correspondences is given in Table 1[9].

We have thus obtained the points of $\mathbb{CM}^c$ from twistors. But to do field theory, we need more than just manifold points: we need fields and derivative operators. More precisely, we need to identify those field-theoretic structures in $\mathbb{CM}^c$ that can be pulled up to $\mathbb{F}$ and then pushed down to $\mathbb{PT}$. A number of results in the twistor literature indicate the extent to which such an identification is possible. These results collectively are referred to as the *Penrose Transformation*. Each establishes a correspondence between purely geometrical/topological structures in an appropriate twistor space and the solutions to particular field equations in spacetime. These results can be divided overall into two categories.

(A) Those that are based on the double fibration between $\mathbb{PT}$ and $\mathbb{CM}^c$. ("Flat" twistor theory.)
(B) Those that are based on a structurally similar double fibration in which $\mathbb{CM}^c$ is replaced by a curved manifold. ("Curved" twistor theory.)

[9]For details see, e.g., Huggett and Todd (1994, pp. 55–58). In Table 1, $\mathbb{PT}^+$, $\mathbb{PT}^-$, and $\mathbb{PN}$ are regions of $\mathbb{PT}$ defined by $Z^\alpha \bar{Z}_\alpha > 0$, $Z^\alpha \bar{Z}_\alpha < 0$, and $Z^\alpha \bar{Z}_\alpha = 0$, respectively, where $\bar{Z}_\alpha$ is the dual twistor defined by the Hermitian 2-form on $\mathbb{T} : \bar{Z}_\alpha = \sum_{\alpha\beta} Z^\alpha = (\bar{\pi}_A, \bar{\omega}^{A'})$, where the bar is complex conjugation. A *Robinson congruence* is a family of null geodesics that twist about each other (the origin of the term "twistor").

There are three important results under (A): Kerr's Theorem, The Zero Rest Mass Penrose Transformation (*ZRMPT*), and Ward's Theorem; and one primary result under (B): The Non-linear Graviton Penrose Transformation (*NGPT*). In the remainder of this section, I will state each without proof and briefly describe its content.

(A1) Kerr's Theorem. Let Q be a holomorphic surface in $\mathbb{PT}$; i.e., defined by $f(Z^\alpha) = 0$, for some homogeneous holomorphic function $f(Z^\alpha)$. Then the intersection of Q with $\mathbb{PN}$ defines an analytic shear-free congruence of null geodesics in $\mathbb{M}^c$. Conversely, an analytic shear-free null congruence in $\mathbb{M}^c$ defines the intersection of $\mathbb{PN}$ with a holomorphic surface Q given by the zero locus of an arbitrary homogeneous holomorphic function $f(Z^\alpha)$[10].

Comments. For a proof, see Huggett and Todd (1994, p. 60). An analytic shear-free null congruence in $\mathbb{M}^c$ is given by a spinor field o^A satisfying $o^A o^B \partial_{BB'} o_A = 0$. Kerr's Theorem thus states that such spinor fields in $\mathbb{M}^c$ correspond to the intersections of surfaces in $\mathbb{PT}$.

(A2) Zero Rest Mass Penrose Transformation (ZRMPT).

$$H^1(\mathbb{PT}^+; \mathcal{O}(-n-2)) \cong \{ZRM \text{ fields } \varphi_{A'\ldots B'}(x) \text{ of helicity } n \text{ holomorphic on } \mathbb{CM}^+\}.$$

$$H^1(\mathbb{PT}^-; \mathcal{O}(n-2)) \cong \{ZRM \text{ fields } \phi_{A\ldots B}(x) \text{ of helicity } -n \text{ holomorphic on } \mathbb{CM}^-\}.$$

Comments. For a proof, see Huggett and Todd (1994, pp. 91–98). *ZRMPT* states two isomorphisms. First the objects on the left: Here, for instance, $H^1(\mathbb{PT}^+; \mathcal{O}(-n-2))$ is the first cohomology group of $\mathbb{PT}^+$ with coefficients in $\mathcal{O}(-n-2)$, the sheaf of germs of holomorphic functions of homogeneity $-n-2$ over $\mathbb{PT}^+$[11]. The elements of $H^1(\mathbb{PT}^+; \mathcal{O}(-n-2))$ consist of equivalence classes $[f]$ of homogeneous functions of degree $-n-2$ defined on the intersections $U_i \cap U_j$ of a given open cover $\{U_i\}$ of $\mathbb{PT}^+$. Two elements f_{ij}, g_{ij}, of $[f]$ are equivalent *iff* they differ by a coboundary: $f_{ij} - g_{ij} = h_{ij}$, where $\delta h_{ij} = 0$ for the coboundary map δ. Next, the objects on the right: zero rest mass (*ZRM*) fields are fields (here represented by spinor fields) that satisfy the zero rest mass field equations: $\partial^{AA'} \phi_{A'_{\ldots B'}}(x) = 0$, and $\partial^{AA'} \varphi_{A_{\ldots B}}(x) = 0$, where the number of indices corresponds to twice the spin/helicity. Hence, *ZRMPT* again establishes a correspondence between geometric (topological) objects in $\mathbb{PT}$ and fields satisfying a dynamical field equation in $\mathbb{CM}^c$.

[10] $f(Z^\alpha)$ is holomorphic if it satisfies the Cauchy–Riemann equations: $\partial f \big/ \partial \bar{Z}^\alpha = 0$. $f(Z^\alpha)$ is homogeneous of degree k if $Z^\alpha(\partial f \big/ \partial \bar{Z}^\alpha) = kf$.

[11] A *sheaf* over a topological space X assigns a type of algebraic object to every open set U of X. (Compare with a fiber bundle over X, which assigns an object to every point of X.) The cohomology "group" $H^1(\mathbb{PT}^+; \mathcal{O}(-n-2))$ is really a module over the ring defined by $\mathcal{O}(-n-2)$, i.e., it is a "slightly relaxed" vector space with vectors in $\mathbb{PT}^+$ and scalars in $\mathcal{O}(-n-2)$.

(A3) Ward's Theorem. Let U be an open region in $\mathbb{CM}^c$ and U' the corresponding region in $\mathbb{PT}$ under (KC), which maps points $x \in \mathbb{CM}^c$ into lines $L_x \subset \mathbb{PT}$. There is a 1–1 correspondence between

(a) anti-self-dual $GL(n, \mathbb{C})$ Yang-Mills gauge fields F_{ab} on U; and
(b) rank n holomorphic vector bundles B over U', such that the restriction $B|_{Lx}$ of B to the line $L_x \subset U'$ is trivial for all $x \in U$.

Comments. For a proof, see Ward and Wells (1990, pp. 374–381). Ward's Theorem states that an anti-self-dual[12] Yang-Mills gauge field on $\mathbb{CM}^c$ is equivalent to a holomorphic vector bundle over $\mathbb{PT}$ which is trivial (i.e., constant) on twistor lines. For $n = 1$, one obtains an anti-self-dual Maxwell field as a complex line bundle on $\mathbb{PT}^+$. This is a non-linear version of the *ZRMPT* $n = 1$ case.

The twistor correspondences (A1–A3) are for flat spacetimes (in particular, for $\mathbb{CM}^c$). The extension to curved spacetimes is non-trivial. It turns out that solutions to the twistor equation are constrained by the condition $\Psi_{ABCD}\omega^D = 0$, where Ψ_{ABCD} is the Weyl conformal curvature spinor. Hence, twistors are primarily only well defined in *conformally flat* ($\Psi_{ABCD} = 0 = \bar{\Psi}_{A'B'C'D'}$) spacetimes[13]. One way to circumnavigate this "obstruction" is to complexify the spacetime and impose the conditions $\bar{\Psi}_{A'B'C'D'} = 0$ and $\Psi_{ABCD} \neq 0$[14]. This entails that the Weyl tensor is anti-self-dual, hence such a spacetime $\mathscr{M}$ is referred to as anti-self-dual (or right-conformally flat). Such an $\mathscr{M}$ has a globally well-defined

[12] A Yang-Mills field F_{ab} is anti-self-dual just when it satisfies $^*F_{ab} = -\mathrm{i}F_{\mathrm{ab}}$, where * is the Hodge-dual operator. The theorem rests primarily on the fact that F_{ab} is anti-self-dual *if and only if*, for every α-plane Z' that intersects U, the restriction of the covariant derivative ∇_a to $U \cap Z'$ satisfies $n_a \nabla_a \psi = 0$, for any vector field n_a tangent to Z' and any section ψ of the vector bundle associated with F_{ab}. Put simply, F_{ab} is anti-self-dual *if and only if* its associated covariant derivative $\nabla_a = \partial_a$ — $\mathrm{i}eA_a$ is flat on α-planes.

[13] The Weyl conformal curvature tensor C_{abcd} is the trace-free, conformally invariant part of the Riemann curvature tensor. Its 2-spinor equivalent is $C_{AA'BB'CC'DD'} = \Psi_{ABCD}\varepsilon_{A'B'}\varepsilon_{C'D'} + \bar{\Psi}_{A'B'C'D'}\varepsilon_{AB}\varepsilon_{CD}$. Solutions to the twistor equation also exist in (algebraically special type IV) spacetimes in which the Weyl spinor is null; i.e., can be given by $\Psi_{ABCD} = \alpha_A\alpha_B\alpha_C\alpha_D$, for some non-vanishing α_A.

[14] This cannot be done in real spacetimes in which the primed and unprimed Weyl spinors are complex conjugates of each other. The move to complex spacetimes removes the operation of complex conjugation allowing both quantities to be treated independently. For details, see Penrose and Ward (1980). They also review two alternative ways to address the obstruction by considering twistors at a point on each null geodesic ("local twistors"), or twistors defined relative to hypersurfaces ("hypersurface twistors"). For the latter, when the null cone at infinity is chosen as the hypersurface, the resultant structures are known as asymptotic twistors. These approaches seem problematic in the context of the present essay insofar as they define twistors relative to structures defined on a pre-existing spacetime manifold. Recently, Sparling (1998) has introduced negative rank differential forms as another means of addressing the obstruction.

family of α-planes, hence a corresponding (projective) twistor space $\mathbb{P}\mathcal{T}$ can be constructed. Schematically, we then have the following double fibration.

$$\begin{tikzcd} & \mathbb{F} \arrow[dl] \arrow[dr] & \\ \mathbb{P}\mathcal{T} & & \mathcal{M} \end{tikzcd}$$

The primary result based on this double fibration is the following:

(B1) Non-Linear Graviton Penrose Transform (NGPT). There is a 1–1 correspondence between anti-self-dual models $\mathscr{M} = (M, g_{ab})$ of general relativity that satisfy the vacuum Einstein equations and 4-dimensional complex manifolds $\mathcal{T}$ equipped with the following structures

(i) a four-parameter family of holomorphic curves which in $\mathbb{P}\mathcal{T}$ are compact and have normal bundle $\mathcal{O}(1) \oplus \mathcal{O}(1)$,
(ii) a projection π to primed spin space $\mathbb{S}'$,
(iii) a homogeneity operator Υ, and
(iv) a 2-form $\tau = \varepsilon^{A'B'} d\pi_{A'} \wedge d\pi_{B'}$ and a 2-form $\mu = \varepsilon_{AB} X^{AA'} Y^{BB'} \pi_{A'} \pi_{B'}$ on each fiber over $\mathbb{S}'$.

Comments. For a proof, see Huggett and Tod (1994, pp. 108–109). Structure (i) corresponds to the conformal structure of (M, g_{ab}) while (ii), (iii), and (iv) correspond to the metric g_{ab}[15].

Extensions and Limitations. In addition to the above results, there are twistor constructions for stationary axi-symmetric vacuum solutions to the Einstein equations, extensions of *ZRMPT* for fields with sources, and extensions of Ward's Theorem for other non-linear integrable field equations (in particular, the Korteweg–de Vries equation and the non-linear Schrödinger equation). See Penrose (1999) for a review and references. Moreover, the work of Sparling (1998) demonstrates that, in principle, the twistor space corresponding to any real analytic vacuum Einstein spacetime can be constructed.

Despite these extensions, however, it should be noted that no consistent twistor descriptions have been given for massive fields or for field theories in

[15] $\mathbb{P}\mathcal{T}$ is the space of α-planes in M. In (i) the curves in $\mathbb{P}\mathcal{T}$ correspond to points in M and the normal bundle requirement encodes the correspondence in Table 1 between null separation of points in M (on which conformal structure can be based) and intersection of lines in $\mathbb{P}\mathcal{T}$. (A normal bundle N to a curve γ in $\mathbb{P}\mathcal{T}$ has fibers N_p consisting of all vectors at p modulo tangent vectors at p. One can show that N is a rank 2 vector bundle of the form , where $\mathcal{O}(1)$ is the sheaf of germs of homogeneous functions on $\mathbb{CP}^1$ of degree 1.) Properties (ii) and (iii) follow from the fact that $\mathbb{P}\mathcal{T}$, as the space of α-planes in M, becomes naturally fibered over projective spin space if $\mathscr{M}$ satisfies the vacuum Einstein equations. The 2-forms in (iv) together encode the metric $g_{ab} = \varepsilon_{AB}\varepsilon_{A'B'}$.

generally curved spacetimes with matter content. Essentially, as noted above, the twistor formalism is built on conformal invariance, and problems arise when it comes to rendering non-conformally invariant classical field theories. This indicates that the twistor formalism is not completely expressively equivalent to the tensor formalism, in so far as there are classical field theories that can be expressed in the latter and that cannot be expressed in the former. This may raise concerns about whether the twistor formalism should be read literally by a semantic realist. Toward assuaging these concerns, the following observations can be made.

First, to be clear, for those classical field theories outlined above, complete expressive equivalence holds between the twistor and tensor formalisms. For these examples, the twistor constructions indicate that the differentiable manifold is not essential. Second, and more importantly, while this essay is primarily concerned with classical field theories, the real (potential) benefit of the twistor formalism comes when the move is made to quantum theory. In this context, it should be noted that the verdict is still out on whether 4-dimensional interacting quantum field theories can be reformulated in a conformally invariant way. The motive for doing so stems from the fact that 2-dimensional interacting conformal field theories are exactly solvable (whereas standard formulations of 4-dimensional interacting quantum field theories are far from consistent), and from the fact that particles in any 2-dimensional quantum field theory are approximately massless in the high-energy limit (see, e.g., Gaberdiel, 2000, p. 609). Moreover, 2-dimensional conformal field theories are at the basis of string theory. (In string theory, particle masses are replaced by string tensions, and the basic Lagrangian for a propagating (bosonic) string is that of a 2-dimensional conformal field theory.) The point then is that if string theory turns out to be the correct approach to quantum gravity, for instance, or if interacting quantum field theory can be consistently reformulated in a conformally invariant way, then what tensor formulations of classical field theories have right is conformal structure, as opposed, for instance, to metrical structure predicated on points. Moreover, extensions of the twistor formalism have been proposed for formulations of 4-dimensional conformal field theory[16], and more recently, Witten (2004) has reformulated perturbative quantum Yang-Mills gauge theory as a

[16]See, e.g., Hodges, Penrose, and Singer (1989). In brief, the basic construction is referred to as a "pretzel" twistor space P with boundary ∂P consisting of copies of $\mathbb{PN}$. Such a space replaces the compact Riemann surface X with boundary ∂X that is used in 2-dimensional conformal field theory to model interacting quantum fields. ∂X consists of copies of the circle S^1 on which complex-valued functions representing in- and out-scattering states can be defined. These functions split into negative and positive frequencies, according to whether they extend into the north or south hemispheres of the Riemann sphere with equator S^1. This is similar to the splitting of twistor functions defined on $\mathbb{PN}$ into negative and positive frequencies according to whether they extend into $\mathbb{PT}^+$ or $\mathbb{PT}^-$.

string theory in twistor space. The general point then is that the semantic realist should not discount twistor theory solely based on its limited applicability to classical field theories. To do so would be to ignore potential inter-theoretical relations that are key to understanding how new theories evolve from old ones[17].

3.2. Interpretation

How might a semantic realist take the twistor formulation of the above classical field theories at its face value? In particular, in what sense does the twistor formalism do away with the manifold of the tensor formalism? Two observations seem relevant here. First, the Penrose Transformation in all its above guises encodes the solution space of a local dynamical field equation formulated in terms of a derivative operator on a spacetime manifold, in a global geometric structure in the corresponding twistor space. In a literal sense, the local dynamics in the spacetime formulation gets encoded in a global "static" geometric structure in the twistor description, as twistor advocates like to point out.

> Note that in the Ward construction the local 'field' information in the space time description is coded in the global structure of the twistor description, whereas there is no local (differential) information in the twistor description … . This way in which local space-time field equations tend to 'evaporate' into global holomorphic structure is a characteristic (and somewhat remarkable) feature of twistor descriptions (Penrose & Rindler, 1986, p. 168).

The *dynamical* role that the manifold plays in tensor formulations of field theories is thus side-stepped in the twistor formalism; namely, the role of providing a local back-drop on which differential equations can be defined that govern the dynamical behavior of fields.

As a concrete example, tensor models of anti-self-dual CED are given by (M, η_{ab}, ∂_a, F_{ab}) such that

$$\eta_{ab}\partial_a F_{bc} = 0, \qquad \partial_{[a}F_{bc]} = 0, \qquad {}^*F_{ab} = -\mathrm{i}F_{ab} \tag{2}$$

By Ward's Theorem, twistor models of anti-self-dual *CED* may be given by ($\mathbb{PT}$, B), where $\mathbb{PT}$ is projective twistor space and B is a line bundle over $\mathbb{PT}$ satisfying the geometrical property (A3b). Explicitly, no derivative operators occur in such twistor models.

The second observation concerns the *kinematical* role that M plays in classical field theories. In the tensor formalism, traditional semantic realists have tended to read literally the mathematical fields that quantify over the points of the

[17]The twistor formalism is, in fact, generally viewed by its proponents as one route to quantum gravity. One could argue that the limitations it faces with respect to classical fields are just a particular manifestation of the obstructions to uniting quantum theory with general relativity.

manifold. The resulting literal interpretation describes physical fields that quantify over spacetime points, and that are evolved in time by means of the derivative operator associated with a connection on M. One might quibble over the details of such a literal interpretation: Do the manifold points really represent real substantival spacetime points? Which tensor fields defined on M in the context of a given classical field theory should be awarded ontological status (potential fields vs. Yang-Mills fields, for instance)? What manifold objects should we take such fields to be quantifying over (points or loops, for instance)? But, arguably, the *nature* of the mathematical objects under debate is not in question. (Everyone agrees on what a manifold point is, for instance.) The twistor formalism is not as clear-cut.

In the twistor formalism, the mathematical tensor field has vanished, as has the derivative operator, and both have been replaced by an appropriate geometric structure defined on a twistor space. Literally, such structures quantify over the twistor space (in the same sense that tensor fields quantify over M). Ward's Theorem, for instance, replaces an anti-self-dual Yang-Mills field defined on $\mathbb{CM}^c$ with a vector bundle over projective twistor space $\mathbb{PT}$. Literally, this bundle is a collection of vector spaces labeled by the points of $\mathbb{PT}$, these points being projective twistors. Recall from Table 1 that, under the Klein Correspondence (*KC*), projective twistors correspond to complex null surfaces (α-planes) in $\mathbb{CM}^c$, and when (*KC*) is restricted to real compactified Minkowski spacetime $\mathbb{M}^c$, projective twistors correspond to twisted congruences of null geodesics referred to as Robinson congruences[18]. One option, then, for a traditional semantic realist is to view such null geodesics as the individuals in the ontology of field theories formulated in the twistor formalism. Under this interpretation, twisted null geodesics are the fundamental objects, with spacetime points derivative of them (identified essentially as their intersections). This alone should give a traditional semantic realist pause for concern. But there is an additional twist: Just what the twistor individuals are is not as clear-cut as the geometric interpretation provided by the Klein correspondence might at first appear. Non-projective twistor space $\mathbb{T}$ can also be constructed *ab initio* as the phase space for a single zero rest mass particle, or as the space of charges for spin 3/2 fields (see, e.g., Penrose, 1999), or, most recently, as the space of "edge-states" for a 4-dimensional fermionic quantum Hall-effect liquid (Sparling, 2002).

To get a feel for the first of these alternative interpretations, one can show that a non-null twistor Z^α uniquely determines a triple (p_a, M^{ab}, s), where p_a, M^{ab} are

[18]Roughly, the real correlates of projective twistors correspond to the intersections of α-planes and their duals, referred to as β-planes and defined with respect to the Hermitian twistor "metric" $\sum_{\alpha\beta}$. For a null twistor Z^α that satisfies $\sum_{\alpha\beta} Z^\alpha Z^\beta = 0$, this intersection is given by a null geodesic. For non-null twistors, the intersection is given by a Robinson congruence — a collection of null geodesics that twist about the axis defined by the null case.

tensor fields on $\mathbb{M}^c$, and $s \in \mathbb{R}$, that defines the linear momentum, angular momentum, and helicity, respectively, of a zero rest mass particle[19]. Conversely, a zero rest mass triple uniquely determines a projective twistor.

To get a feel for the second alternative interpretation, note that in Minkowski spacetime, spin-3/2 zero rest mass fields can be represented by totally symmetric spinor fields $\psi_{A'B'C'}$ (with the number of indices equal to twice the spin) that satisfy the spin-3/2 zero rest mass field equations, $\partial^{AA'}\psi_{A'B'C'} = 0$. The procedure then is to transform $\psi_{A'B'C'}$ into a spin-1 (self-dual) Maxwell field $\varphi_{A'B'}$, and then define its charge via Gauss's Law. This transformation is accomplished simply by contracting $\psi_{A'B'C'}$ on the right with a dual twistor $W_\alpha = (\lambda_A, \mu^{C'})$ to obtain $\varphi_{A'B'} = \psi_{A'B'C'}\mu^{C'}$[20]. The charge Q, a complex number, associated with $\psi_{A'B'C'}$ is then defined by integrating $\varphi_{A'B'}$ over a volume containing the spin-3/2 sources: $Q = \oint_S \varphi_{A'B'}\mathrm{d}S^{A'B'}$, where S is the surface enclosing the sources. Since Q depends linearly on W_α, we can let $Q = Z^\alpha W_\alpha$, for some "charge" twistor Z^α. Hence for each spin-3/2 field $\psi_{A'B'C'}$, we have a map from twistor space $\mathbb{T}$ to the space $\mathbb{C}$ of spin-3/2 charges Q[21].

Finally, to get a feel for the last alternative interpretation, and not get too far afield of the present essay, note that Hu and Zhang (2002) have demonstrated that the edge states of a 4-dimensional quantum Hall-effect liquid can be described by $(3+1)$-dimensional effective field theories of relativistic zero rest mass fields[22]. Sparling (2002) observes that their 2-spinor formalism extends naturally onto the twistor formalism and attempts to construct twistor spaces directly from Hu and Zhang's edge states.

[19]The correspondence is given by $p_a = \bar{\pi}_A \pi_{A'}$, $M^{ab} = \mathrm{i}\omega^{(A}\bar{\pi}^{B)}\varepsilon^{A'B'} - \mathrm{i}\bar{\omega}^{(A'}\pi^{B')}\varepsilon^{AB}$, and $\sum_{\alpha\beta} Z^\alpha \bar{Z}^\beta = 2s$. This ensures that the following relations that define a zero rest mass particle hold: $p_a p^a = 0$, $M^{ab} = 2r^{[a}p^{b]}$, $sp^a = 1/2\varepsilon_{abcd}\,p^b M^{cd} \equiv S^a$, where r^a defines a point relative to an origin of $\mathbb{M}^c$, and S^a is the Pauli–Lubanski vector.

[20]The dual twistor W_α is actually fully specified by $\mu^{C'}$. One can show that the (dual) twistor equation in full generality is given simply by $\partial_A{}^{(A'}\mu^{B')} = 0$. One can also show that the so-defined field $\varphi_{A'B'}$ satisfies the spin-1 zero rest mass equations $\partial^{AA'}\varphi_{A'B'} = 0$, which describe a self-dual Maxwell field.

[21]This result motivates a program in twistor theory that seeks to construct twistor spaces for full vacuum Einstein spacetimes, based on the fact that, in general, the spin-3/2 zero rest mass field equation is consistent in a spacetime $\mathscr{M}$ *if and only if* the Ricci tensor on $\mathscr{M}$ vanishes. The idea then is to look for the space of conserved charges for spin-3/2 fields on a general Ricci-flat spacetime, and this will be the corresponding twistor space.

[22]The 2-dimensional quantum Hall effect occurs when a current flowing in a 2-dimensional conductor in the presence of an external magnetic field sets up a transverse resistivity. For strong fields, this Hall resistivity is observed to be quantized in either integral or fractional units of the ratio of fundamental constants h/e^2. Various effective field theories have been constructed that describe this effect in terms of the properties of a highly correlated 2-dimensional quantum liquid. In particular, the low-energy excitations of the edge states of such a liquid have been described by a $(1+1)$-dimensional effective field theory of relativistic 2-spinor (Weyl) fields. The extension of the 2-dimensional quantum Hall effect to 4 dimensions was first given a consistent theoretical description by Zhang and Hu (2001). Their work and the similar work of others in condensed matter physics has yet to be fully considered by philosophers of spacetime.

Hence, the semantic realist committed to an individuals-based ontology has to decide between two seemingly incompatible literal construals of classical field theories: The tensor formalism suggests a commitment to local fields and spacetime points, whereas the twistor formalism suggests a commitment to twistors, which themselves admit diverse interpretations. The traditional realist might respond by claiming that the Penrose Transformation just shows that solutions to certain field equations behave in spacetime as if they were geometric/algebraic structures that quantify over twistors. In other words, we should not read the twistor formalism literally — it merely amounts to a way of encoding the behavior of the real objects, which are fields in spacetime, and which are represented more directly in the tensor formalism. In other words, we should only be semantic realists with respect to the tensor formalism. This strategy smacks a bit of *ad hocness*. All things being equal (keeping in mind the discussion at the end of Section 3.1), what, we may ask, privileges the tensor formalism over the twistor formalism? From a conventionalist's point of view, tensor fields on a manifold are just as much devices that encode the data provided by measuring devices as are vector bundles over $\mathbb{PT}$. If the semantic realist is to be genuine about her semantic realism, it appears that she must be willing to give up commitment to individuals-based ontologies and seek the basis for her literal construal at a deeper level.

4. Manifolds vs. Einstein algebras

In this section, I indicate how the points of a differentiable manifold can be non-trivially reconstructed from an Einstein algebra. In particular, I indicate how any classical field theory presented in the tensor formalism can be recast in the Einstein algebra formalism, and consider what this suggests about the nature of spacetime.

4.1. Einstein algebras and their generalizations

The Einstein algebra (*EA* hereafter) formalism takes advantage of an alternative to the standard definition of a differentiable manifold as a set of points imbued locally with topological and differentiable properties. The manifold substantivalist's gloss of this definition awards ontological status to the point set. The alternate definition emphasizes the differentiable structure, as opposed to the points of M on which such structure is predicated. It is motivated by the following considerations: The set of all real-valued C^∞ functions on a differentiable manifold M forms a commutative ring $C^\infty(M)$ under pointwise addition and multiplication. Let $C^c(M) \subset C^\infty(M)$ be the subring of constant functions on M. A derivation on the pair $(C^\infty(M), C^c(M))$ is a map $\mathrm{X} : C^\infty(M) \to C^\infty(M)$ such that $X(af+bg) = aXf + bXg$ and $X(fg) = fX(g) + X(f)g$, and $X(a) = 0$, for any f,

$g \in C^{\infty}(M)$, $a, b \in C^{c}(M)$. The set $\mathscr{D}(M)$ of all such derivations on $(C^{\infty}(M), C^{c}(\mathrm{M}))$ forms a module over $C^{\infty}(M)$ and can be identified with the set of smooth contravariant vector fields on M. A metric g can now be defined as an isomorphism between the module $\mathscr{D}(M)$ and its dual $\mathscr{D}^{*}(M)$. Tensor fields may be defined as multi-linear maps on copies of $\mathscr{D}(M)$ and $\mathscr{D}^{*}(M)$, and a covariant derivative can be defined with its associated Riemann tensor. Thus all the essential objects of the tensor formalism necessary to construct a model of general relativity (*GR*) may be constructed from a series of purely algebraic definitions based ultimately on the ring $C^{\infty}(M)$. At this point Geroch's (1972) observation is that the manifold only appears initially in the definition of $C^{\infty}(M)$. This suggests viewing C^{∞} and C^{c} as algebraic structures in their own right, with M as simply a point set that induces a representation of them[23]. Formally, Geroch (1972) defined an Einstein algebra $\mathscr{A}$ as a tuple $(\mathscr{R}^{\infty}, \mathscr{R}, g)$, where $\mathscr{R}^{\infty}$ is a commutative ring, $\mathscr{R}$ is a subring of $\mathscr{R}^{\infty}$ isomorphic with the real numbers, and g is an isomorphism from the space of derivations on $(\mathscr{R}^{\infty}, \mathscr{R})$ to its algebraic dual such that the associated Ricci tensor vanishes (and a contraction property is satisfied)[24].

Two observations are relevant at this point. First, Geroch's algebraic treatment of *GR* can be trivially generalized to include all classical field theories presented in the tensor formalism. In general, the latter are given by tuples (M, O_i), where M is a differentiable manifold and the O_i are tensor fields defined on M and satisfying the appropriate field equations (via a derivative operator on M). After Earman (1989), let a Leibniz algebra $\mathscr{L}$ be a tuple $(\mathscr{R}^{\infty}, \mathscr{R}, A_i)$, where $\mathscr{R}^{\infty}$ is a commutative ring, $\mathscr{R}$ is a subring isomorphic with the real numbers, and the A_i are algebraic objects defined as multi-linear maps on copies of $\mathscr{D}$ (the set of all derivations on $(\mathscr{R}^{\infty}, \mathscr{R})$) and its dual $\mathscr{D}^{*}$, and satisfying a set of field equations (via the algebraic correlate of a derivative operator). For an appropriate choice of A_i, such an $\mathscr{L}$ is the correlate in the *EA* formalism of a model of a classical field theory in the tensor formalism.

The second observation concerns the extent to which an Einstein (or Leibniz) algebra is expressively equivalent to a tensor model of a classical field theory. In particular, in what sense is the manifold M done away with in the *EA* formalism? There seems to be both a trivial and a non-trivial sense in which M is done away with. The trivial sense is based on the following considerations. The maximal ideals of an abstract algebra $\mathscr{A}$ (if they exist) are in 1–1 correspondence with the

[23]Such a representation is given by the Gelfand representation. Any abstract linear algebra $\mathscr{A}$ (over a field) admits a Gelfand representation defined by $\rho : \mathscr{A} \rightarrow \mathbb{K}^{\mathscr{A}^{*}}, \rho(x)(\phi) = \phi(x)$, where $x \in \mathscr{A}$, $\phi \in \mathscr{A}^{*}$, and $\mathscr{A}^{*}$ is the algebraic dual of $\mathscr{A}$ (i.e., the set of homomorphisms $\phi : \mathscr{A} \rightarrow \mathbb{K}$) and $\mathbb{K}^{\mathscr{A}^{*}}$ is the algebra of $\mathbb{K}$-valued functions on $\mathscr{A}^{*}$. Intuitively, the Gelfand representation turns the abstract object $\mathscr{A}$ into a "concrete" algebra of functionals on a space $\mathscr{A}^{*}$.

[24]The above deviates slightly from Geroch's notation. The condition on the algebraic Ricci tensor can be relaxed and algebraic correlates of the Einstein tensor and cosmological constant can be introduced to model general solutions to the Einstein equations (see, e.g., Heller, 1992).

elements of its algebraic dual $\mathscr{A}^*$[25]. Hence, if $\mathscr{A}$ has maximal ideals, the points of the space $\mathscr{A}^*$ can be reconstructed by means of the Gelfand representation of $\mathscr{A}$ (see footnote 23). In particular, the points of a topological space X can be reconstructed from the maximal ideals of the ring $C(X)$. (Concretely, one shows that any maximal ideal of $C(X)$ consists of all functions that vanish at a given point of X.) A differentiable manifold M can then be reconstructed by imposing a differentiable structure (i.e., a maximal atlas) on X[26]. Hence, there is a 1–1 correspondence between Einstein (Leibniz) algebras and models of classical field theories in the tensor formalism, *and this correspondence extends all the way down to the point set of M*. This suggests that, from the point of view of literal interpretations of spacetime, nothing is gained in moving to the *EA* formalism: any interpretive options under consideration in the tensor formalism will be translatable in 1–1 fashion into the *EA* formalism[27].

The non-trivial sense will have to wait until the next section, after some extensions of the *EA* formalism have been reviewed.

Extensions. Heller and Sasin have extended Geroch's original treatment of *GR* to spacetimes with singularities. A non-singular general relativistic spacetime can be represented by a differentiable manifold M, or an Einstein algebra generated by the ring $C^\infty(M)$. To represent certain types of curvature singularities in the tensor formalism requires additional structures on M. In particular, the b-boundary construction collects singularities in a space $\partial_b M$ and attaches it as a boundary to M to create a differentiable manifold with boundary $M' = M \cup \partial_b M$. In the *EA* formalism, one can now consider an algebraic object of the schematic form $C^\infty(M')$, consisting of real-valued C^∞ functions on M'. Originally, this object was identified as a sheaf of (commutative) Einstein algebras over M' (Heller & Sasin, 1995). Heller and Sasin (1996) demonstrated that such an object can also be analyzed as a non-commutative Einstein algebra of complex-valued C^∞ functions over a more general structure (in particular, the semi-direct product $OM \rtimes O(1, 3)$, of the Cauchy completed frame bundle OM over M' and the structure group $O(1, 3)$). This analysis was then extended to a schema for quantum gravity in Heller and Sasin (1999). The theory presented there takes as the fundamental object an "Einstein C^*-algebra" $\mathscr{E}$, constructed

[25]Elements of $\mathscr{A}^*$ are sometimes called the "characters" of $\mathscr{A}$. A maximal ideal of $\mathscr{A}$ is the largest proper subset of $\mathscr{A}$ closed under (left or right) multiplication by any element of $\mathscr{A}$.

[26]Note that there are (at least) two ways to view the reconstruction of points of a differentiable manifold. One can reconstruct the points of a topological space X from the maximal ideals of $C(X)$, and then impose a differentiable structure on X to obtain a differentiable manifold. Alternatively, one can directly reconstruct the points of M from the maximal ideals of $C^\infty(M)$. See, e.g., Demaret, Heller, and Lambert (1997, p. 163).

[27]In particular, some authors have claimed interpretive issues surrounding the hole argument cannot be addressed simply by moving to the *EA* formalism. For a discussion, see Bain (2003).

from the non-commutative algebra of complex-valued C^∞ functions with compact support on a transformation groupoid (see Bain, 2003 for a brief review).

4.2. Interpretation

As indicated above, there is a trivial sense in which the original *EA* formalism does away with manifolds; namely, simply by renaming them: instead of manifold points, the original *EA* talk is about maximal ideals. One might argue that renaming an object does not make it go away. In particular, Einstein algebras for non-singular spacetimes reproduce the diffeomorphism "redundancy" of *M*. An argument could be made, however, that the extended *EA* formalism does do away with *M* in a non-trivial manner. First, as Heller and Sasin (1995) note, the (commutative) extensions of *EA* to singular spacetimes in effect place non-singular and singular spacetimes under a single category (namely, the category of "structured spaces": spaces structured by a sheaf of Einstein algebras); whereas in the tensor formalism, technically, non-singular and singular spacetimes belong to different categories (the categories of smooth manifolds and manifolds with boundaries, respectively)[28]. In not talking about manifold points to begin with, the extended *EA* formalism can handle field theories characterized by missing manifold points in a conceptually cleaner manner than the tensor formalism.

Heller and Sasin (1995) further suggest that certain conceptual problems associated with the *b*-boundary construction in the tensor formalism do not arise in the extended *EA* formalism. Briefly, in the closed Friedman universe (of Big Bang fame), the *b*-boundary consists of a single point corresponding to both the initial and final singularities, and in both the closed Friedman and Schwarzschild solutions, the *b*-boundary is not Hausdorff-separated from *M*. These results are hard to reconcile with any notion of localization. (Intuitively, some amount of separation between the initial and final singularities in the Friedman solution should obtain.) Moreover, that the points of the *b*-boundary are not Hausdorff-separated from the points of the interior implies counter intuitively that every event in spacetime is in the neighborhood of a singularity. The suggestion of Heller and Sasin (1995) is that these decidedly non-local aspects of *b*-boundary constructions are pathologies only when viewed from within the differentiable manifold category and its emphasis on local properties. In the extended *EA* formalism (in particular, in the category of structured spaces), in contrast, the emphasis throughout is on sheaf-theoretic global features, and these features allow a natural distinction between the decidedly non-local behavior of fields on the *b*-boundary and the local behavior of fields on the interior *M*.

[28]Unlike a manifold with boundary, a smooth (C^∞) differentiable manifold is differentiable at all points; intuitively, it has no "edge points" at which differentiation may break down. For the theory of structured spaces, see Heller and Sasin (1995) and references therein.

A second point is that in the non-commutative extensions of *EA* given in Heller and Sasin (1996, 1999), the manifold *M* truly disappears. In these extensions, a commutative algebra is replaced with a non-commutative algebra, and, simply put, these latter, in general, have no maximal ideals. Thus well-behaved point sets cannot, in general, be reconstructed from them. Intuitively, one might claim that Einstein algebras, both commutative and non-commutative, encode the *differentiable structure* of a differentiable manifold first and foremost, and only secondarily encode *M*'s point set.

How might a semantic realist take the *EA* formulation of classical field theories at its face value? In particular, what might a literal interpretation of a (commutative) Einstein algebra amount to? In the original *EA* formalism, the correlates of manifold points are the maximal ideals of the algebra $\mathscr{A}$. Under the Gelfand representation, these are certain subsets of functionals defined on $\mathscr{A}^*$, which, under the intended manifold interpretation, become real-valued C^∞ functions defined on *M*. Some authors have suggested that these functions can be interpreted as a system of scalar fields, which the literal-minded semantic realist can include in her ontology *in lieu* of manifold points (see, e.g., Penrose & Rindler, 1984, p. 180; Demaret et al., 1997, p. 146). This interpretation suggests a notion of spacetime as arising out of the relations between these fundamental fields[29].

In the extended *EA* formalism, we have replaced commutative algebras with non-commutative algebras, and these latter, in general, do not possess maximal ideals. Hence, there are, in general, no correlates of manifold points to help the literal-minded semantic realist. One option for the semantic realist is a literal interpretation not of the objects of any particular representation of an Einstein algebra (commutative or not), but rather of the algebraic structure intrinsic to the algebra itself. An Einstein algebra $\mathscr{A}$ can be realized in many ways on many different types of spaces. Some of these spaces can be interpreted as smooth differentiable manifolds, others as manifolds with boundaries, and still others do not admit a manifold interpretation at all. An "algebraic structuralist" might claim that the concrete representations of $\mathscr{A}$ should not be read literally; rather, the structure defined by the algebraic properties of $\mathscr{A}$ is what should be taken at face value.

5. Manifolds vs. geometric algebra

In this section, I indicate how classical field theories can be recast using geometric algebra and the extent to which the geometric algebra formalism is

[29]Relationalists like Rovelli (1997) hold a similar view with respect to the metric field in tensor formulations of general relativity. Note, however, that such metric field relationalists differ from algebraic relationalists in so far as the former posit a single "manifold-generating" field that has physical significance (being a solution to the Einstein equations), whereas the latter require an uncountable infinity of fields, most of which will not have physical significance. (Thanks to an anonymous referee for making this point explicit.)

non-trivially expressively equivalent to the tensor formalism. Whereas an Einstein algebra may be said to encode the differentiable structure of a manifold in an abstract algebraic object, a geometric algebra on first glance may be said to encode the *metrical structure* of a manifold in a *concrete* algebra of "multivectors". As it turns out, there is also an abstract algebraic object lurking behind the scenes here, too; namely, an abstract Clifford algebra.

In slightly more detail, a geometric algebra $\mathcal{G}$ can be initially viewed as a generalization of a vector space. The elements of $\mathcal{G}$ are referred to as multivectors and come in "grades". The intended geometrical interpretation identifies 0-grade multivectors as scalars, 1st-grade multivectors ("1-vectors") as vectors, 2nd-grade multivectors ("bivectors") as directed surfaces, 3rd-grade multivectors ("trivectors") as directed volumes, etc. For any r, the collection of all r-grade multivectors forms a subalgebra $\mathcal{G}^r$ of $\mathcal{G}$, with $\mathcal{G}$ then being the direct sum of all the $\mathcal{G}^r$, $r = 0 \ldots \infty$. This allows any n-dimensional vector space V^n to be identified with a geometric algebra $\mathcal{G}(V^n)$ for which $\mathcal{G}^1(V^n) = V^n$. The real significance of $\mathcal{G}$ lies in the geometric product which encodes both an inner product (bilinear form) and an outer (wedge) product. These properties of $\mathcal{G}$ allow classical field theories to be presented in the geometric algebra (*GA* hereafter) formalism in an intrinsically coordinate free manner in a way that does away with the differentiable manifold of the tensor formalism.

5.1. *Geometric algebra*

From a mathematical point of view, a geometric algebra $\mathcal{G}$ is first and foremost a real Clifford algebra. There are numerous ways of defining the latter. For instance, let V be a real vector space equipped with a bilinear form $g : V \times V \rightarrow \mathbb{R}$ with signature (p, q). The real Clifford algebra $\mathcal{C}_{(p,q)}$ is the linear algebra over $\mathbb{R}$ generated by the elements of V via "Clifford multiplication" defined by $xy + yx = g(x, y)\mathbf{1}$, $x, y \in V$, where $\mathbf{1}$ is the unit element. In this, and other standard definitions, a Clifford algebra is defined in terms of a bilinear form (or its associated quadratic form) defined on a vector space[30]. Given such definitions, Clifford algebras might seem limited to applications in metrical geometry, or might seem less fundamental than tensor algebra. The axiomatic treatment of Hestenes and Sobczyk (1984) is meant to address these apparent limitations.

[30]An alternative definition is the following (Ward & Wells, 1990, p. 209): Let V be a vector space over a commutative field $\mathbb{K}$ with unit element $\mathbf{1}$ and equipped with a quadratic form $q : V \rightarrow \mathbb{K}$. (Such a q is defined by $q(xr) = r^2 q(x), r \in \mathbb{K}, x \in V$ such that the map $h : V \times V \rightarrow \mathbb{K}$ defined by $h(x, y) = q(x+y) - q(x) - q(y)$ is a bilinear form on V. A simple consequence of this definition is that $h(x, x) = 2q(x)$.) The tensor algebra of V is given by $\mathcal{T}(V) = \Sigma_{r=0}^{\infty} \otimes^r V$. Let $\mathcal{J}$ be the two-sided ideal in $\mathcal{T}(V)$ generated by elements of the form $x \otimes x + q(x)\mathbf{1}$, for $x \in V$. The Clifford algebra associated with V is then defined as the quotient $\mathcal{C}(V, q) \equiv \mathcal{T}(V)/\mathcal{J}$. The Clifford product in $\mathcal{C}(V, q)$ is then the product induced by the tensor product in $\mathcal{T}(V)$.

Their goal is to construct a real Clifford algebra (now referred to as a geometric algebra) as a primitive object in its own right, with the notions of vector space and bilinear form as derivative concepts. In what follows, I will briefly review their axiomatic construction before reviewing its application to classical field theories in Minkowski spacetime and in generally curved spacetimes.

In Hestenes and Sobczyk's (1984) treatment, a geometric algebra $\mathcal{G}$ is a *graded real associative* algebra with a few additional properties. Elements of $\mathcal{G}$ are referred to as multivectors. As a *real associative* algebra, a geometric algebra is a septuple $\mathcal{G} = (\mathcal{G}, +_g, \times_g; \mathbb{R}, +, \times; *)$, where $(\mathcal{G}, +_g, \times_g)$ is a ring with unity closed under geometric addition $+_g$ and non-commutative geometric multiplication $\times_g$; $(\mathbb{R}, +, \times)$ is the real field, and $*$ denotes the external binary operation of scalar multiplication (in the following, the subscript on $+_g$ has been dropped and $\times_g$ and $*$ are represented by juxtaposition). As a *graded* algebra, $\mathcal{G}$ admits a linear idempotent grade operator $\langle\ \rangle_r$: $\mathcal{G} \to \mathcal{G}$ by means of which any multi-vector $A \in \mathcal{G}$ can be written as the sum $A = \langle A\rangle_0 + \langle A\rangle_1 + \langle A\rangle_2 + \cdots = \sum_r \langle A\rangle_r$. If $A = \langle A \rangle_r$, then A is referred to as homogeneous of grade r and called an *r-vector*. The space of all r-vectors is denoted $\mathcal{G}^r$ and is an r-dimensional linear subspace of $\mathcal{G}$. The space $\mathcal{G}^0$ is identified with $\mathbb{R}$. The role of the bilinear form in standard treatments is accomplished by including an axiom relating scalar and vector multiplication: for $a \in \mathcal{G}'$, $aa = a^2 = \langle a^2 \rangle_0$. In words: the square (under geometric multiplication) of a "1-vector" is a scalar[31]. This relation is then extended to arbitrary r-vectors by the axiom: For any $r > 0$, an r-vector can be expressed as a sum of *r-blades*, where A_r is an r-blade *iff* $A_r = a_1a_{2\ldots}a_r$, where $a_ja_k = -a_ka_j$, for $j, k = 1 \ldots r$ and $j \neq k$. Finally, Hestenes and Sobczyk posit the existence of non-trivial blades of every finite grade: For every non zero r-blade A_r, there exists a non-zero vector a in $\mathcal{G}$ such that A_ra is an $(r+1)$-blade. (Hence, $\mathcal{G}$ is infinite dimensional.)

The geometric product can be decomposed into an inner product and an outer product. For homogeneous multivectors, the inner product $\cdot$ and the outer product $\wedge$ are defined by $A_r \cdot B_s \equiv \langle A_rB_s\rangle_{|r-s|}$, if r and $s > 0$, otherwise $A_r \cdot B_s \equiv 0$, and $A_r \wedge B_s \equiv \langle A_rB_s \rangle_{r+0}$[32]. Intuitively, the inner product decreases the grade of multivectors, whereas the outer product increases grade. These definitions entail that the geometric product of a 1-vector a and an arbitrary multivector A can be decomposed as $aA = a \cdot A + a \wedge A$. In particular, the geometric product of 1-vectors has the simple decomposition $ab = a \cdot b + a \wedge b$, where $a \cdot b = 1/2(ab + ba)$

[31] In standard treatments, $\mathcal{G}$ would be identified as the Clifford algebra of the quadratic form $q(a) = a^2$ with associated bilinear form $h(a, b) = (a+b)^2 - a^2 - b^2$ (see previous footnote).

[32] For arbitrary multivectors, they are defined as $A \cdot B \equiv \sum_r \sum_s \langle A\rangle_r \cdot \langle B\rangle_s$ and $A \wedge B \equiv \sum_r \sum_s \langle A\rangle_r \wedge \langle B\rangle_s$.

is the totally symmetric part of ab, and $a \wedge b = 1/2(ab - ba)$ is the totally anti-symmetric part of ab[33].

Every n-dimensional vector space V^n determines a subalgebra $\mathcal{G}(V^n)$ of $\mathcal{G}$ by geometric multiplication and addition of elements in V^n such that $\mathcal{G}^1(V^n) = V^n$ and $\mathcal{G}^r(V^n)$ is the linear subspace of $\mathcal{G}(V^n)$ consisting of all r-vectors formed by taking products of elements of V^n. In particular, let $\{e_1, \ldots, e_n\}$ be a basis for V^n. Then a basis for $\mathcal{G}^r(V^n)$ is given by $\{1, e_i, e_{i_1} e_{i_2}, \ldots, e_{i_1} \ldots e_{i_n}\}$, $i = 1 \ldots n$, and a multivector element $B \in \mathcal{G}^r(V^n)$ may be expanded as, $B = c + c^i e_i + c^{i_1 i_2} e_{i_1} e_{i_2} + \cdots + c^{i_1 \cdots i_n} e_{i_1} \ldots e_{i_n}$, where the c^i are scalar coefficients. $\mathcal{G}(V^n)$ can thus be decomposed into a direct sum of linear subspaces $\mathcal{G}^r(V^n)$. Note that the dimension of $\mathcal{G}(V^n)$ is 2^n.

Two subalgebras of $\mathcal{G}$ play essential roles in the formulation of classical field theories in the *GA* formalism: the Pauli algebra associated with Euclidean 3-space and the Dirac algebra associated with Minkowski spacetime.

Pauli algebra and Dirac algebra. The Pauli algebra $\mathcal{P}$ is the geometric algebra $\mathcal{G}(E^3)$ (alternatively, the real Clifford algebra $\mathcal{C}_{(0,3)}$) of the vector space E^3 tangent to a point in Euclidean 3-space. A basis for E^3 is given by $\{\sigma_1, \sigma_2, \sigma_3\}$, where the basis 1-vectors satisfy $\sigma_I \cdot \sigma_j = \delta_{ij}$, $\sigma_i \wedge \sigma_j = 0$[34]. The corresponding 8-dimensional basis for $\mathcal{P}$ is then,

$$\{1, \ \{\sigma_1, \sigma_2, \sigma_3\}, \quad \{\sigma_1\sigma_2, \sigma_1\sigma_3, \sigma_2\sigma_3\}, \quad \{\sigma_1\sigma_2\sigma_3\}\} \tag{3}$$

where, e.g., $\sigma_1\sigma_2 = \sigma_1 \cdot \sigma_2 + \sigma_1 \wedge \sigma_2 = -\sigma_2\sigma_1$. Note that the highest-grade basis element (or "pseudoscalar") $\sigma_1\sigma_2\sigma_3$ of $\mathcal{P}$ has the properties $(\sigma_1\sigma_2\sigma_3)^2 = -1$ and $(\sigma_1\sigma_2\sigma_3)\sigma_\mathrm{k} = \sigma_\mathrm{k}(\sigma_1\sigma_2\sigma_3)$, i.e., $\sigma_1\sigma_2\sigma_3$ commutes with all basis elements. This motivates the denotation $\sigma_1\sigma_2\sigma_3 \equiv i$. Hereafter, "$i$" will denote the pseudoscalar of $\mathcal{P}$ (and, as will be seen, that of the Dirac algebra $\mathcal{D}$ as well). Any $A \in \mathcal{P}$ can be expanded in the basis (3) as $A = \alpha + \mathbf{a} + i\mathbf{b} + i\beta$, where $\mathbf{a} = a_k\sigma_k$, $\mathbf{b} = b_k\sigma_k$ are 1-vector elements of $\mathcal{P}^1 \equiv \mathcal{G}^1(E^3)$ and a_k, b_k, α, β are scalars.

The Dirac, or spacetime, algebra $\mathcal{D}$ is the geometric algebra $\mathcal{G}(M^4)$ of Minkowski vector space M^4 (alternatively, the real Clifford algebra $\mathcal{C}_{(1,3)}$). It can be generated by the set of 1-vectors $\{\gamma_\mu\}$, $\mu = 0 \ldots 3$, satisfying $\gamma_0\gamma_0 = 1$, $\gamma_k\gamma_k = -1$, and $\gamma_\mu \cdot \gamma_\nu = 0$ for $\mu \neq \nu$[35]. The Minkowski metric $\eta_{\mu\nu}$ is then recovered as

[33] In standard treatments, the inner product is defined by the bilinear form $h(x, y) = x \cdot y$ associated with the quadratic form $q(x) = x^2$. The outer product is the wedge product of tensor algebra.

[34] The Pauli operator algebra of non-relativistic quantum mechanics can be realized in $\mathcal{P}$ (hence the name). Under this realization, the 1-vectors σ_1, σ_2, σ_3 correspond to the Pauli spin matrix operators, and 2-component $SU(2)$ "non-relativistic" spinors correspond to even elements of $\mathcal{P}$ (see, e.g., Lasenby, Doran, & Gull, 1993). Thus, insofar as $\mathcal{P}$ is a real Clifford algebra in which the object i has a definite geometric interpretation (see below), one can reconstruct the kinematics of non-relativistic quantum mechanics in $\mathcal{P}$ without introducing the complex field $\mathbb{C}$.

[35] The Dirac operator algebra of relativistic quantum mechanics can be realized in $\mathcal{D}$ (hence the name). Under this realization, the 1-vectors γ_μ correspond to the Dirac matrix operators, and 4-component Dirac spinors correspond to even elements of $\mathcal{D}$ (see, e.g., Lasenby et al., 1993).

$\gamma_\mu \cdot \gamma_\nu = 1/2(\gamma_\mu\gamma_\nu + \gamma_\nu\gamma_\mu) = \eta_{\mu\nu}$ The corresponding 16-dimensional basis for $\mathscr{D}$ is given by

$$\{1,\ \{\gamma_\mu\},\ \{\sigma_k, \mathrm{i}\sigma_k\},\ \{\mathrm{i}\gamma_\mu\},\ i\} \tag{4}$$

where the pseudoscalar of $\mathscr{D}$ is given by $\gamma_0\gamma_1\gamma_2\gamma_3 = \sigma_1\sigma_2\sigma_3 = i$, and $\sigma_k \equiv \gamma_k\gamma_0$, $k = 1 \dots 3$, are bivectors (in $\mathscr{D}$) that form an orthonormal frame in the Euclidean 3-space orthogonal to the γ_0 direction. In terms of this basis, the Pauli algebra generated by the σ_k is the even subalgebra of $\mathscr{D}$. Vectors in $\mathscr{D}$ are embedded into $\mathscr{P}$ by geometric right-multiplication by γ_0, bivectors in $\mathscr{D}$ are embedded into $\mathscr{P}$ by expansion in the basis $\{\sigma_k, i\sigma_k\}$, and scalars and pseudoscalars in $\mathscr{D}$ remain scalars and pseudoscalars in $\mathscr{P}$.

Any $A \in \mathscr{D}$ can be expanded in the basis (4) as $A = A_S + A_V + A_B + A_T + A_P$, where the labels S, V, B, T, P refer to the scalar, vector, bivector, trivector, and pseudoscalar part of A, respectively. Geometric interpretations of these objects are as follows: Scalars are elements of the subalgebra $\mathscr{G}^0(M^4)$, identified with $\mathbb{R}$; elements of the subalgebra $\mathscr{G}^1(M^4) = M^4$ are Minkowski 4-vectors; elements of the subalgebra $\mathscr{G}^2(M^4)$ are bivectors: directed surface elements in M^4; elements of the subalgebra $\mathscr{G}^3(M^4)$ are trivectors: directed volume elements in M^4; and elements of $\mathscr{G}^4(M^4)$ are pseudoscalars: directed hypervolumes in M^4.

Fields and derivative operators. Physical fields are represented in the *GA* formalism by geometric functions. A *geometric* function $F(A)$ is a function whose domain and range are subsets of $\mathscr{G}$. The standard definitions of limit and continuity for scalar-valued functions on $\mathbb{R}^n$ can now be employed for geometric functions using the scalar magnitude, which defines a unique distance $|A - B|$ between any two multivectors A, B[36]. A geometric function of r variables $T = T(A_1, A_2, \dots, A_r)$ is called an *extensor of degree r on* $\mathscr{G}^n$ if it is linear in each of its arguments and each variable is defined on a geometric algebra $\mathscr{G}^n$. In particular, if $n = 1$, then T is a *tensor of degree r*. A tensor $T = T(a_1, \dots, a_r)$ of degree r that takes values in a geometric algebra $\mathscr{G}^s$ is said to have grade s and rank $s + r$.

A geometric calculus for the Dirac algebra $\mathscr{D}$ can be constructed by extending the well-defined notion of derivative in $\mathscr{G}^0(M^4)$ to all of $\mathscr{D}$. Naively, this is possible since both addition and multiplication are well defined for all elements of $\mathscr{D}$ (hence, specifically, limits of quotients can be defined). In general, the vector derivative ∂ for $\mathscr{G}$ is defined by $\partial \equiv e^\mu(e_\mu \cdot \partial_x)$ where $\{e_\mu\}$ is a basis for $\mathscr{G}^1$ and $(e_\mu \cdot \partial_x)$ is a scalar derivative operator[37]. The vector derivative ∂ so-defined

[36]For arbitrary $A, B \in \mathscr{G}$, the *scalar product* $*$ is defined as $A*B \equiv \langle AB \rangle_0$ (note that this is distinct from the inner product). The *scalar magnitude* of A is then defined by $|A|^2 \equiv A^\dagger * A$, where the *reversion map* $\dagger$: $\mathscr{G} \to \mathscr{G}$ is defined on r-vectors by $A_r^\dagger = (-1)^{r(r-1)/2} A_r$ (reversion reverses the order of all products of 1-vectors in A_r).

[37]In general, let $F(x)$ be a multivector-valued geometric function of $x \in \mathscr{G}^1$ on $\mathscr{G}$ and let $a \in \mathscr{G}^1$. The *directional derivative* of $F(x)$ in the direction of a is defined by $(a \cdot \partial_x)F(x) \equiv \lim_{\tau \to 0}(F(x + \tau a) - F(x))/\tau$ One can show that the operator $(a \cdot \partial_x)$ has all the properties of a scalar derivative operator (Hestenes & Sobczyk, 1984, pp. 44–53).

is the geometric product of a 1-vector e^{μ} and a scalar differential operator $(e_{\mu} \cdot \partial_x)$, acquiring the algebraic properties of a 1-vector from the former and differential properties from the latter. Since it is a vector quantity its action on geometric functions can be decomposed into inner and outer products: For any differentiable geometric function $A(x)$ of a vector argument with values in $\mathscr{G}$, $\partial A(x) = \partial \cdot A(x) + \partial \wedge A(x)$. To specialize to $\mathscr{D}$, let $\{\gamma_{\mu}\}$ be a basis for $\mathscr{D}^1$. Then the vector derivative for $\mathscr{D}$ is given by $\partial \equiv \gamma^{\mu}(\gamma_{\mu} \cdot \partial_{\mu})$, where $\{\gamma^{\mu}\}$ is the reciprocal basis defined by $\gamma^{\mu} \cdot \gamma_{v} = \eta^{\mu}{}_{v}$.

We are now in the position of being able to transcribe classical field theories in Minkowski spacetime into the *GA* formalism. In all such transcriptions, the differentiable manifold *M* that appears in the tensor formalism is replaced with the Dirac algebra $\mathscr{D}$. As an example, the Maxwell equations can be written in the *GA* formalism as

$$\partial F = 4\pi J \tag{5a}$$

where the electromagnetic field $F = F(x)$ is a bivector-valued tensor on $\mathscr{D}^1$ (i.e., a tensor of degree 1, grade 2, and rank 3) and the current density $J = J(x)$ is a tensor on $\mathscr{D}^1$ of degree 1, grade 1 and rank 2. To show that (5a) reproduces the Maxwell equations, it can be decomposed into

$$\partial \cdot F = 4\pi J, \qquad \partial \wedge F = 0 \tag{5b}$$

These equations then reproduce the standard tensor formulation (1) in a given basis $\{\gamma_{\mu}\}$.

To formulate general relativity in the *GA* formalism, two options are available. First, Lasenby, Doran, and Gull (1998) have constructed a gauge theory of gravity in flat Minkowski vector space that reproduces the Einstein equations and that is similar to Poincaré gauge theory formulations of *GR*. In these latter theories, one typically imposes local Poincaré gauge invariance on a matter Lagrangian, which requires the introduction of gauge potential fields. These are then identified as the connection (rotational gauge) on a Poincaré frame bundle over a manifold *M*, and the tetrad fields (translation gauge). The Einstein equations are then obtained by extremizing the Lagrangian with respect to the gauge potentials. In Lasenby et al. (1998), "displacement" and rotational gauge invariance is imposed on a matter Lagrangian defined on the Dirac algebra $\mathscr{D}$, and this leads to the introduction of potential gauge fields defined on $\mathscr{D}$ that generate the Einstein equations (plus an equation for torsion). In this theory, gravity is conceived as a force described by geometric functions defined on the Dirac algebra.

The second option is to attempt to transcribe *GR* as a theory governing fields in a curved spacetime directly into the *GA* formalism. To accomplish this, one can make use of Hestenes and Sobczyk's (1984, Chapter 4) notion of a *vector manifold*: a collection of 1-vector elements of $\mathscr{G}$. A vector manifold $\mathscr{M}$ can be considered as a curved surface embedded in a larger flat space (associated with $\mathscr{G}$). The extrinsic geometry of $\mathscr{M}$ can be defined in terms of objects in the "embedding space" $\mathscr{G}$, and an intrinsic (Riemannian) geometry can be defined in $\mathscr{M}$ by projecting the relevant quantities in $\mathscr{G}$ onto $\mathscr{M}$. In particular, a curvature tensor can be defined as a geometric function on $\mathscr{M}$ and this then allows the transcription of the Einstein equations as equations governing geometric function fields defined on $\mathscr{M}$[38].

5.2. Interpretation

In what sense does the *GA* formalism do away with the manifold *M* of the tensor formalism? Note that, for classical field theories in Minkowski spacetime, including the *GA* gauge theory of gravity of Lasenby et al. (1998), the *kinematical* role of *M* as a point-set for tensor fields to quantify over is explicitly played by the subalgebra $\mathscr{D}^1$ of 1-vector elements of the Dirac algebra $\mathscr{D}$, in so far as physical fields in the *GA* formalism are represented by geometric tensor functions that quantify over 1-vectors. The *dynamical* role of *M* as a set of points imbued with differentiable and topological properties on which derivative operators may be defined is also played by $\mathscr{D}^1$ with its associated vector derivative ∂. On the other hand, a case could be made that the object in the *GA* formalism that plays both the kinematical and dynamical roles of *M* is the Dirac algebra $\mathscr{D}$ in its entirety. Recall that $\mathscr{D}$ is the direct sum $\mathscr{D}^0(=\mathbb{R})+\mathscr{D}^1+\mathscr{D}^2+\mathscr{D}^3+\mathscr{D}^4$. Geometric tensor functions in $\mathscr{D}$ quantify over $\mathscr{D}^1$ and take values in any of these subalgebras of $\mathscr{D}$. Hence physical fields, in this sense, are represented simply by elements of $\mathscr{D}$. Moreover, the vector derivative operator $\partial \in \mathscr{D}^1$ is only well defined as a derivative operator due essentially to the differentiable properties of $\mathscr{D}^0$[39]. The claim then is that $\mathscr{D}$ comes as a self-contained package: to use any one aspect of it in formulating a classical field theory in Minkowski spacetime requires making use of $\mathscr{D}$ in its entirety. (Arguably, this is not the case in the tensor formalism in which *M* is considered as a "self-contained" mathematical object in its own right with additional structures defined on it as the need arises.)

[38]As Doran, Lasenby, and Gull (1993) note, one drawback of this approach is that the Einstein equations in their tensorial form only determine the local curvature of *M* and, in general, say nothing about its global properties. In contrast, a vector manifold, as an embedded surface, has a well-defined global extrinsic curvature. Hence to fully accommodate vector manifolds into *GR*, the Einstein equations should be modified to specify such extrinsic properties. Furthermore, there are topological issues associated with both options of incorporating *GR* into the *GA* formalism, due to the well-behaved (topologically) features of vector spaces *vis-á-vis* differentiable manifolds.

[39]In addition to a vector ($\mathscr{D}^1$) derivative, higher-grade derivatives associated with each of the other subalgebras of $\mathscr{D}$ can be defined. The general theory of such multivector derivatives is presented in Hestenes and Sobczyk (1984, p. 54).

To make this a bit more explicit, consider, once again, *CED* in Minkowski spacetime. In the *GA* formalism, a dynamical model for *CED* in Minkowski spacetime may be given by $(\mathscr{D}, \partial, F, J)$, where $\mathscr{D} \subset \mathscr{G}$ is the Dirac algebra, ∂ is the vector derivative of $\mathscr{D}$, and the electromagnetic bivector $F \in \mathscr{D}^2$ and the current density vector $J \in \mathscr{D}^1$ satisfy the *GA* formulation of the Maxwell equations (5a). Here, the Dirac algebra in its entirety replaces (M, η_{ab}) as the object encoding the properties of spacetime.

How might a semantic realist take the *GA* formulation of classical fields at its face value? Unlike the Einstein algebra case, *GA* comes pre-packaged with an intended interpretation. The objects of a geometric algebra, and the Dirac algebra in particular, are interpreted as multivectors. One option for a semantic realist is to include them as the fundamental geometric entities in the ontology of classical field theories. This perhaps suggests a relationalist's view of spacetime as arising from the algebraic relations between multivectors in the Dirac algebra. Alternatively, the algebraic structuralist of Section 4.2 may claim that the concrete representations of a geometric algebra $\mathscr{G}$ should not be read literally, but rather the structure defined by $\mathscr{G}$. Such a structuralist will claim that spacetime has the structure inherent in the abstract real Clifford algebra $\mathscr{C}_{(1,3)}$.

6. Spacetime as structure

The above review of alternative formalisms indicates that classical field-theoretic physics can be done without a 4-dimensional differentiable manifold, at least for most theories of interest. Minimally, this suggests that, if we desire to read classical field theories at their "face value", differentiable manifolds need not enter into our considerations: manifold substantivalism is not the only way to literally interpret a classical field theory. What does this suggest about the ontological status of spacetime? In particular, if we desire to be semantic realists with respect to classical field theories, what attitude should we adopt toward the nature of spacetime? One initial moral that can be drawn from the preceding discussion is that "fundamentalism" is in the eye of the beholder. In particular, all the alternative formalisms discussed above *disagree* on what the essential structure is that is minimally required to kinematically and dynamically support classical field theories.

6.1. Against fundamentalism

Note first that the relations between the tensor formalism and the alternative formalisms reviewed above may be summarized as follows. Projective twistor space $\mathbb{PT}$ encodes the *conformal structure* $(M, \Omega\eta_{ab})$ of Minkowski spacetime (i.e., the metrical structure up to a multiplicative constant Ω), with limited extensions to curved spacetimes. The dynamics of physical fields is encoded by geometrical structures on $\mathbb{PT}$ and its extensions. An Einstein algebra directly encodes the *differentiable structure* on M (i.e., the points of M imbued with differentiable and topological properties), and then encodes physical fields as derivations on this structure[40]. The Dirac algebra directly encodes the *metrical structure* (M, η_{ab}) of Minkowski spacetime, and then encodes physical fields and their dynamics as geometric functions on this structure (i.e., maps from $\mathscr{D}^1$ to subalgebras of $\mathscr{D}$).

A manifold substantivalist is a ''point set fundamentalist''. In the tensor formalism, this may seem a natural way to literally interpret spacetime: The point set of the manifold is the fundamental mathematical object, on which additional structures supervene. In particular, the moves to differentiable, conformal, and metrical structures are accomplished by adding more properties to the point set. On the other hand, proponents of alternative formalisms may claim that the manifold gives us *too much* as a representation of spacetime. In particular, they may charge one or more of the features of M with the status of surplus mathematical structure in the context of classical field theories.

Proponents of twistors may claim that conformal structure is what is essential. They may claim that both the point set and the differentiable structure of M are surplus: The point set can be reconstructed via the Klein Correspondence from twistors, while the differentiable structure is encoded in geometric/algebraic constructions over an appropriate twistor space. Moreover, twistor advocates will attempt to rewrite classical field theories in a conformally invariant way, hence they will also consider metrical structure as surplus.

Proponents of Einstein algebras may claim that differentiable structure is minimally sufficient to do classical field theory and view the point set of M as surplus structure, and conformal and metrical structure as derivative.

Finally, proponents of geometric algebra may claim that metrical structure gives us everything we need for field theory, and view the point set, and the differentiable and conformal structures of M as surplus. The point set is no longer needed to support fields, and the role played by differentiable structure is encoded directly in the Dirac algebra (in particular, in $\mathscr{D}^0$). There is also a precise sense in which conformal structure is derivative of $\mathscr{D}$: It turns out that twistors, as well as 2-component spinors, can be realized in the Dirac algebra. Lasenby et al. (1993) indicate how this is achieved by the following correspondences for the 2-spinor spaces $\mathbb{S}$, $\mathbb{S}'$ and twistor space $\mathbb{T}$:

$$\mathbb{S} = \{\forall\psi \subset \mathscr{D} : \psi = \kappa\tfrac{1}{2}(1+\sigma_3), \quad \text{for any } \kappa \in \mathscr{P}^+\}$$

$$\mathbb{S}' = \{\forall\psi \subset \mathscr{D} : \ \psi = -\omega \mathrm{i}\sigma_2\tfrac{1}{2}(1-\sigma_3), \quad \text{for any } \omega \in \mathscr{P}^+\}$$

$$\mathbb{T} = \{\forall Z \subset \mathscr{D} : \ Z = \phi + r\phi\gamma_0 \mathrm{i}\sigma_3\tfrac{1}{2}(1-\sigma_3), \quad \text{for any } \phi \in \mathscr{D}^+\}$$

[40] An original Geroch–Einstein algebra encodes local differentiable structure, whereas its commutative and non-commutative extensions may be said to encode global differentiable structure.

where $\mathscr{P}^+$, $\mathscr{D}^+$ are the even Pauli and Dirac subalgebras, and $r = \gamma_\mu x^\mu$[41]. The *GA* fundamentalist then may argue that, if spacetime is encoded by the Dirac algebra $\mathscr{D}$, then $\mathbb{S}$, $\mathbb{S}'$ and $\mathbb{T}$ are less fundamental than spacetime in the sense of being contained within $\mathscr{D}$. The main point, however, is that this cuts both ways: In the spinor formalism, Minkowski vector space (as encoded in $\mathscr{D}$) may be said to be derivative of $\mathbb{S}$ in the sense that it isomorphic to the real subspace $\mathrm{Re}(\mathbb{S} \times \mathbb{S}')$; and, of course, in the twistor formalism, the points of (compactified) Minkowski spacetime $\mathbb{M}^c$ can be derived from geometric relations in $\mathbb{T}$.

The conclusion, then, is that what counts as fundamental and what counts as derivative, from a mathematical point of view, depends on the formalism.

6.2. *For structuralism*

The debate between these fundamentalisms revolves around what the essential structure of spacetime is that is necessary to support classical field theories: a point set, or differentiable, conformal, or metrical structures. But it does not revolve around how this structure manifests itself: in particular, what it is predicated on; or, in general, the nature of the basic mathematical objects that are used to describe it. This suggests adopting a structural realist approach to spacetime ontology.

Such spacetime structuralism, as motivated here, depends on prior semantic realist sympathies. It says: If we desire to be semantic realists with respect to classical field theories; i.e., if we desire to interpret such theories literally, or take them at their "face value", then we should be ontologically committed to the structure that is minimally required to kinematically and dynamically support mathematical representations of physical fields. Just what this structure is depends explicitly, for a semantic realist, on the formalism one adopts, as indicated above. Note, however, that this is not to say that essential structure is a matter of convention, in so far as the formalism one adopts generally is not a matter of pure convention. Rather, in the context of classical field theory, it will be influenced by inter-theoretical concerns; concerns, for instance, over which formulation of quantum field theory one adopts, or which approach to quantum gravity one adopts. Thus ultimately, the essential structure of classical field theory is empirical in nature, in so far as, ultimately, which extended theory (quantum field theory, quantum gravity) is correct is an empirical matter. What

[41] In the transcriptions for $\mathbb{S}$ and $\mathbb{S}'$, κ and ω are the *GA* realizations of $SU(2)$ spinors and the factors $(1+\sigma_3)$ and $(1-\sigma_3)$ essentially realize chiral operators in $\mathscr{D}$ (the factor $i\sigma_2$ in $\mathbb{S}'$ realizes Hermitian conjugation). Thus elements of $\mathbb{S}$ and $\mathbb{S}'$ may be thought of as right- and left-handed spinors. (More precisely, they are right- and left-handed Weyl spinors in the Weyl representation of the Dirac operator algebra.) In the transcription for twistor space $\mathbb{T}$, a twistor in the *GA* formalism is realized as a position-dependent Dirac 4-spinor (in the Weyl representation). See Lasenby et al. (1993) for details.

the spacetime structuralist cautions against (in the here and now) is adopting an "individuals-based" ontology with respect to this structure. Conformal structure, for instance, can be realized on many different types of "individuals": manifold points, twistors, or multivectors, to name those considered in this essay. What is real, the spacetime structuralist will claim, is the structure itself, and not the manner in which alternative formalisms instantiate it.

As a form of realism with respect to spacetime, spacetime structuralism thus can be characterized by the following:

(a) It is not *substantivalism*: It is not a commitment to spacetime points.
(b) It is not *relationalism*: It does not adopt an anti-realist attitude toward spacetime[42].
(c) Rather, it claims spacetime is a real structure that is embodied in the world.

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[42]A traditional relationalist claims spacetime does not exist independently of physical objects (be they particles or fields). In this (perhaps limited) sense, relationalists are anti-realists with respect to spacetime. A spacetime structuralist claims that spacetime does exist independently of physical objects; but as a structure and not in the form of particular instantiations of that structure.

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Chapter 4

Minkowski Space-Time: A Glorious Non-Entity

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Abstract

It is argued that Minkowski space-time cannot serve as the deep structure within a "constructive" version of the special theory of relativity, contrary to widespread opinion in the philosophical community. This paper is dedicated to the memory of Jeeva Anandan.

1. Einstein and the space-time explanation of inertia

According to Einstein, special relativity (SR) and Newtonian mechanics share a defect. They both violate the *action–reaction principle*.

Leibniz held that a defining attribute of substances was their both acting and being acted upon. It would appear that Einstein shared this view. He wrote in 1924 that each physical object "influences and in general is influenced in turn by others." (Einstein, 1924, p. 15) It is "contrary to the mode of scientific thinking", he wrote earlier in 1922, "to conceive of a thing … which acts itself, but which cannot be acted upon."[1] Einstein's view was that the space-time continuum in both Newtonian mechanics and SR is such a thing. In these theories space-time upholds only half of the bargain: it acts on material bodies and/or fields, but is in no way influenced by them. It was a source of satisfaction for

[1]Einstein (1922, pp. 55–56). For a recent discussion of the action–reaction principle in modern physics, see Anandan and Brown (1995) and Brown (1996).

Einstein that in developing the general theory of relativity (GR) he was able to eradicate what he saw as this embarrassing defect of his earlier special theory.

In this section and the next we are not interested in exploring whether the action–reaction principle is well motivated. Rather, our concern is to investigate whether Einstein was correct to view SR and Newtonian mechanics as violating the principle. Our view is that he was not.

In order to assess Einstein's reasoning, one first needs to be clear about what kind of actions by space-time on matter Einstein thought are involved in SR and Newtonian mechanics. Although he did not describe them in these terms, it is evident that he had in mind the roles of the four-dimensional absolute affine connection in each case, as well as that of the conformal structure in SR. The connection determines which paths are geodesics, or straight, and hence determines the possible trajectories of force-free bodies. The null cones in SR in turn constrain the possible propagation of light.

> The inertia-producing property of this ether [Newtonian space-time], in accordance with classical mechanics, is precisely *not* to be influenced, either by the configuration of matter, or by anything else. For this reason, one may call it "absolute". That something real has to be conceived as the cause for the preference of an inertial system over a non-inertial system is a fact that physicists have only come to understand in recent years .... Also, following the special theory of relativity, the ether was absolute, because its influence on inertia and light propagation was thought to be independent of physical influences of any kind .... The ether of the general theory of relativity differs from that of classical mechanics or the special theory of relativity respectively, insofar as it is not "absolute", but is determined in its locally variable properties by ponderable matter. (Einstein, 1924)

It was Einstein's view, then, both that the inertial property of matter can be explained, and that this explanation is to be given in terms of the action of a real entity on the particles ("that something real has to be conceived as the cause for the preference of an inertial system over a non-inertial system").

At this point it might be useful to be quite explicit about what it is that this supposed action of space-time is supposed to explain. Consider the case of Newtonian mechanics. Any two isolated systems, each obeying Newton's laws, are systematically related, despite their isolation. The preferred time parameters defined by the relative motions of their constituents, together with Newton's laws, march in step, and the two spatial reference frames defined by their motions and Newton's laws are in uniform translatory motion with respect to each other. Why is this?

It seems that Einstein thought that the answer that Newtonian mechanics gives appeals to the action on matter of the space-time connection: the affine geodesics are to be thought of as rather like ruts or grooves in space-time that guide the free particles along their way[2]. Less picturesquely, one is to view the

[2]Of course, this is a metaphorical way of putting things, since nothing *moves* along a space-*time* geodesic.

universal coordinate systems in which our two isolated systems both obey Newton's laws as those coordinate systems adapted to the real, primitive spatio-temporal structures. The flatness of these structures in (traditional formulations of) Newtonian mechanics accounts for the existence of such global coordinate systems, with respect to which Newton's laws take their standard, non-generally covariant form. And the fact that each system obeys Newton's laws separately with respect to these coordinate systems is accounted for by the fact that these material systems are *constrained by the local laws* to be adapted in the right way to the real inertial structure in their localities.

It is our impression that the view that we here attribute to Einstein has come to be the orthodox understanding of inertial structure in Newtonian mechanics and SR. Whether or not this is the case, the view has certainly been explicitly endorsed, as the following quote from Nerlich illustrates well:

> … without the affine structure there is nothing to determine how the [free] particle trajectory should lie. It has no antennae to tell it where other objects are, even if there were other objects …. It *is because space-time has a certain shape that world lines lie as they do*. (Nerlich, 1976, p. 264, original emphasis)

In GR, of course, the action–reaction principle is reinstated because the space-time metric field (which encodes both the affine and the conformal structure) is dynamical, being a solution to Einstein's field equations, which couple matter degrees of freedom to the metric. Space-time is influenced by matter, just as it influences matter. However, far from providing a final verdict vindicating the space-time explanation of inertia, consistent with the action–reaction principle, we see GR as providing a rather different lesson.

In the early 1920s, when he wrote the above comment, Einstein had still not discovered an important aspect of his theory of gravitation — the fact that the field equations themselves underpin the geodesic principle. This principle states that the world-lines of force-free test particles are constrained to lie on geodesics of the connection. It follows from the form of Einstein's field equations that the covariant divergence of the stress-energy tensor field $T_{\mu\nu}$ — that object which incorporates the "matter" degrees of freedom — vanishes.

$$T^{\mu}_{\nu;\mu} = 0 \tag{1}$$

This result is about as close as anything that is in GR to the statement of a conservation principle, and it came to be recognised as the basis of a proof, or proofs, that the world-lines of suitably modelled force-free test particles are geodesics[3].

[3]See, for example, Misner, Thorne, and Wheeler (1973, Section 20.6, pp. 471–480). A fascinating account of the early history of independent discoveries of the geodesic theorem is found in Havas (1989).

The fact that these proofs vary considerably in detail need not detain us. The first salient point is that the geodesic principle for free particles is no longer a postulate but a theorem. The second point is that the derivations of the geodesic principle in GR also demonstrate its limited validity.

A defender of the space-time explanation of inertia might see the derivability of the geodesic principle simply as showing that there is only one way to combine particles and the metric field consistently. On this view, the result does nothing to undermine the space-time explanation of inertia. The fact that the geodesic principle need not be separately postulated does not by itself diminish the explanatory role that space-time can play.

Our view, however, is that there are reasons to be sceptical of the claim that space-time plays the sort of explanatory role envisaged by Nerlich. Our reasons are given more fully in the next section. At this point we simply wish to note that if the space-time explanation of inertia is indeed the pseudo-explanation that we take it to be then, in light of the geodesic theorem, GR is in fact the first in the long line of dynamical theories, starting with the Aristotelian system and based on that profound distinction between natural and forced motions of bodies, that offers a genuine explanation of inertial motion.

2. The nature of absolute space-time

The second point made in the previous section about the derivations of the geodesic principle was that they demonstrate its limited validity. In particular, it is not enough that the test particle be force-free. It has long been recognised that spinning bodies for which tidal gravitational forces act on its elementary pieces deviate from geodesic behaviour[4]. What this fact clarifies is that it is not simply *in the nature* of force-free bodies to move in a fashion consistent with the geodesic principle. It is not an essential property of localised bodies that they

[4] See Misner et al. (1973, p. 480; ex. 40.8, 1120–1121; and Section 40.9, pp. 1126–1131). These authors refer briefly on p. 480 to the complications that quantum physics is likely to introduce to the question of geodesic behaviour. We note that the familiar picture of light tracing out the null cones of space-time is also probably only approximately valid (though the approximation is usually extremely good) as a result of quantum physics. Since 1980, studies have been made of the propagation of photons in QED in curved space-times, in the esoteric regime where the scale of the space-time curvature is comparable to the Compton wavelength of the electron. Here, vacuum polarisation causes the vacuum to act both as a dispersive and birefringent optical medium. In particular the propagation of photons as determined by geometric optics is controlled by an effective metric that differs from the space-time metric $g_{\mu\nu}$. For a recent review paper, see Shore (2003).

run along the ruts of space-time determined by the affine connection, when no other dynamical influences are at play. In Newtonian mechanics and SR, the conspiracy of inertia (the coordination of the motions of isolated systems) is a postulate, and its putative explanation by way of the affine connection is a postulate added to a postulate.

Interestingly, in interpreting space-time as acting on matter, Einstein and Nerlich part company with Leibniz, and even with Newton. For both Leibniz and Newton, absolute space-time structure is not the sort of thing that acts at all. In our view, Leibniz and Newton are right about this. Newtonian mechanics and SR do not represent, *pace* Einstein, violations of the action–reaction principle, because the space-time structures in both cases are neither acting nor being acted upon. Indeed we go further and agree with Leibniz that they are not real entities in their own right at all.

It is well known that Leibniz rejected the reality of absolute Newtonian space and time, principally on the grounds that their existence would clash with his principles of Sufficient Reason and the Identity of Indiscernibles. Non-entities do not act, so for Leibniz space and time can play no role in explaining the mystery of inertia.

Newton seems to have agreed with this conclusion, but for radically different reasons. In his pre-*Principia* manuscript *De Gravitatione*, Newton affirms the reality of space, but denies it is a substance, claiming that it has "its own manner of existing" (Newton, 1962). One of his chief reasons for denying space substantiality is precisely that he held that it does not act. In explanation of Newton's view here we can do no better than to quote Stein's recent commentary on the relevant passage:

> [Newton] says that although philosophers do not traditionally define substance as "a being that can *act* upon something," they in fact all tacitly hold such a definition — "as for instance is plain from this, that they would easily concede extension to be a substance like a body if only it could move and could exercise the actions of a body; and on the other hand, they would by no means concede a body to be a substance if it neither could move nor arouse any sensation or perception in any mind whatever." To be noted well, then: (a) the definitive criterion of substantiality is the ability to act; (b) one of the characteristics that belongs to the essential nature of *bodies*, to their character as substances, is their ability to arouse perceptions in a mind. (Stein, 2002, pp. 266–267)[5]

[5]It is worth stressing that, aside from the fact that Newton viewed the existence of space to be a necessary consequence of the existence of anything, its lack of causal influence is Newton's sole reason for refraining from calling space a substance. It is therefore at least misleading to deny that Newton was a substantivalist in the contemporary sense of that term.

Newton, then, certainly did not see absolute space as providing some kind of quasi-causal explanation of the coordinated behaviour of free bodies. Rather, he postulated the existence of absolute space and time in order to provide a structure, necessarily distinct from ponderable bodies and their relations, with respect to which it is possible systematically to define the basic *kinematical* properties of the motion of such bodies. It is now known, however, that this job can be done without postulating any background space-time scaffolding, and that at least a significant subset — perhaps *the* significant subset — of solutions to any Newtonian theory can be recovered in the process[6].

We have still to state our reasons for being sceptical of the putative role the affine connection plays in explaining inertia, at least according to Nerlich. Recall Nerlich's remark above to the effect that force-free particles have no antennae, that they are unaware of the existence of other particles. That is the *prima facie* mystery of inertia in pre-GR theories: how do all the free particles in the world know how to behave in a mutually coordinated way such that their motion appears extremely simple from the point of view of a family of privileged frames? Our problem with the space-time story is that to appeal to the action of a background space-time connection in which the particles are immersed — to what Weyl called the "guiding field" — is arguably to enhance the mystery, not to remove it. For the particles do not have space-time feelers either. In what sense is the postulation of the 4-connection doing more explanatory work than Molière's famous dormative virtue in opium? (We return to this question below.)

At this point the reader might worry about the analogy with electromagnetism. Do charges need 'antennae' to feel the electromagnetic field? Clearly not, and yet the idea that the field acts on charges is unproblematic. It is sufficient that particles have charge, which couples to the field as described by the Lorentz force law. Why can we not regard the geodesic equation similarly, as describing how massive particles couple to the connection?

In our view there are important disanalogies. For one thing, mass is not a coupling constant. It does not indicate the strength of the particle's coupling to the connection. More importantly, the geodesic principle itself provides the backdrop against which it makes sense to talk about the action of

[6]The discovery was made by Julian Barbour and Bruno Bertotti (Barbour and Bertotti, 1982; Barbour,1994). For discussion see Belot (2000) and Pooley and Brown (2002). For a discussion of the alternative explanation of inertia offered by Barbour and Bertotti's theory, and a contrast with the orthodox story, see Pooley (2004).

the electromagnetic field on a charged particle. Causal talk is legitimate in this context because we can make sense of certain counterfactuals. In the absence of the electromagnetic field, the particle's trajectory would have been a certain geodesic. The action of the field on the particle is precisely to cause deviation away from such geodesic motion. But it is now clear that there can be no such analogue in the case of the action of the connection. It makes no sense to ask what the motion of the particle would have been in its absence.

It is of course non-trivial that inertia can be given a *geometrical* description, and this is associated with the fact that the behaviour of force-free bodies does not depend on their constitution: it is universal. But again what is at issue is the arrow of explanation. In our view it is simply more economical to consider the 4-connection as a codification of certain key aspects of the behaviour of particles and fields[7].

3. The principle versus constructive theory distinction

In recent years there has been increasing discussion of the role that thermodynamics played as a methodological template in Einstein's development of SR, and of his characterization of SR as a "principle" theory, as opposed to a "constructive" theory like the kinetic theory of gases[8].

The distinction is not a categorical one, nor must a principle theory be bereft of any constructive elements. What we have effectively argued in Section 1 is that Einstein's comments in the 1920s on the role of the Newtonian and SR "ethers", or space-times, indicate that he came to interpret inertial structure as a genuinely constructive element in these theories. (In our view it is unwarranted to attribute the same view to Einstein around 1905.) However, relativistic effects such as length contraction and time dilation are another matter. It is clear that in 1905, and for many subsequent years, Einstein regarded their derivation in SR as akin to the derivation in thermodynamics of, say, the existence of entropy as a thermodynamic coordinate — as being, that is to say, a necessary condition

[7]One faces a similar choice in parity-violating theories: do orientation fields play an explanatory role in such theories, or are they simply codifications of the coordinated asymmetries exhibited by the solutions of such theories? See Pooley (2003, pp. 272–274).

[8]An excellent characterisation of the principle-constructive distinction is found in Balashov and Janssen (2003, p. 331). We have much to say about their paper in what follows. For other recent discussions of the role played by the distinction in the history and philosophy of SR, see Brown and Pooley (2001) and Brown (2003, 2005).

for the validity of certain phenomenological principles that themselves have only empirical robustness as their justification[9].

We have discussed elsewhere Einstein's recognition of the fact that constructive theories have more explanatory power than principle theories, as well as the misgivings that he expressed, particularly late in his life, about the appropriateness of his separation of kinematical and dynamical considerations in the 1905 paper (Brown & Pooley, 2001). What we wish to consider here is the question of the possibility of a fully constructive rendition of SR, and in particular the possibility of a constructive explanation of the 'kinematical' effects associated with length contraction and time dilation.

The issues surrounding this question have been discussed recently by Balashov and Janssen (2003). As will soon become clear, we take a different view to them about what might constitute a constructive version of SR. However, before addressing this issue directly, we want to return briefly to the claim that principle theories lack the explanatory power of constructive theories, for this, too, is an issue addressed by Balashov and Janssen.

Balashov and Janssen see no problem with the idea that Einstein's original principle-theory presentation of SR can be held to explain the phenomenon of length contraction. They write: "Understood purely as a theory of principle, SR

[9]It is widely known that the fullest account given by Einstein of the claim that SR has the nature of a 'principle-theory' was in an article on relativity theory he was commissioned to write in 1919 for The Times of London (Einstein, 1919). Should it be thought that the popular nature of the publication and/or its date lessen the degree to which Einstein's claim is to be taken seriously, two points might be borne in mind. First, the claim is entirely consistent with the story of Einstein's pre-1905 struggles with the constructive approach to electrodynamics and the theory of the electron — which were based largely on the difficulties posed by the emergence of Planck's constant (see below, pp. 11ff). Second, the methodological analogy between SR and thermodynamics was mentioned by Einstein on several occasions prior to 1919. In a short paper of 1907 replying to a query of Ehrenfest on the deformable electron, he wrote:

> The principle of relativity, or, more exactly, the principle of relativity together with the principle of the constancy of velocity of light, is not to be conceived as a "complete system", in fact, not as a system at all, but merely as a heuristic principle which, when considered by itself, contains only statements about rigid bodies, clocks, and light signals. It is only by requiring relations between otherwise seemingly unrelated laws that the theory of relativity provides additional statements. … we are not dealing here at all with a "system" in which the individual laws are implicitly contained and from which they can be found by deduction alone, but only with a principle that (similar to the second law of the theory of heat) permits the reduction of certain laws to others. (Einstein, 1907)

In a letter to Sommerfeld in 1908, Einstein wrote:

> The theory of relativity is not more conclusively and absolutely satisfactory than, for example, classical thermodynamics was before Boltzmann had interpreted entropy as probability. If the Michelson–Morley experiment had not put us in the worst predicament, no one would have perceived the relativity theory as a (half) salvation. Besides, I believe that we are still far from having satisfactory elementary foundations for electrical and mechanical processes. (Einstein, 1993, p. 50)

explains this phenomenon if it can be shown that the phenomenon necessarily occurs in any world that is in accordance with the relativity postulate and the light postulate.'' They concede that, in contrast to constructive-theory explanations, such a principle-theory explanation will ''have nothing to say about the reality behind the phenomenon'' (2003, p. 331).

Later in their paper, which is a critical review of aspects of William Lane Craig's recent writings in defence of presentism (Craig, 2000a, 2000b, 2001), they take explicit issue with two claims that they attribute to Craig: (i) that SR in its 1905 form fails to provide a theory-of-principle explanation of phenomena such as length contraction and, (ii) that theory-of-principle explanations in general are deficient (2003, p. 332). We side with Craig on both counts, although it should be stressed that we endorse (i) for reasons quite different to those that motivate Craig. Before outlining our reasons for rejecting the idea that Einstein's 1905 derivation of the Lorentz transformations can provide any sort of explanation of length contraction we mention Balashov and Janssen's main reason for contesting (ii)[10].

It rests, simply, in their noting that (ii) applies equally to thermodynamics: ''That in and of itself, we submit, places the relativity interpretation [i.e. Einstein's 1905 presentation of SR] in very good company'' (2003, p. 332). It is certainly true that Einstein's original derivation of SR is in good company, but this company is not necessarily a company rich in explanatory resources. Balashov and Janssen are prepared to admit that Einstein thought that principle theories were ''inferior'' to constructive theories, but this rather general claim might seem to miss the very point of Einstein's articulation of the constructive versus principle theory distinction, and his citation of thermodynamics as a paradigm example of a principle theory. Einstein's view (one that we share) was that principle theories were 'inferior' specifically in their explanatory power. His contrasting thermodynamics, as a principle theory, with statistical mechanics, as a constructive theory, was supposed to illustrate precisely that:

> It seems to me … that a physical theory can be satisfactory only when it builds up its structures from *elementary* foundations. (Einstein, 1993)[11]

> … when we say we have succeeded in understanding a group of natural processes, we invariably mean that a constructive theory has been found which covers the processes in question. (Einstein, 1982, p. 228)

[10] They also note that principle-theory derivations of particular phenomena fit the covering law model of explanation, but, as they rightly concede, this ''might just be another nail in the coffin of the covering law model''. (Balashov & Janssen, 2003, p. 332)

[11] It is clear to us that in his 1908 letter, by the term ''elementary foundations'' Einstein means the building blocks of a constructive theory (see footnote 3, which contains the sentences from the letter that follow on immediately from the sentence just quoted). However, Stachel appears to think that the term refers to principles akin to those of thermodynamics (Einstein, 1989a, p. xxii).

It is certainly not the case that Einstein viewed principle theories as inferior in other respects. As Balashov and Janssen rightly note, their founding principles often enjoy particularly strong empirical confirmation. Einstein is well known for having had greater confidence in the laws of thermodynamics (and, for the same reason, in SR) than in any other laws of physics.

An examination of the status of length contraction in the context of Einstein's 1905 treatment of SR will illustrate the way in which principle theories fail to be explanatory. Recall that in this derivation the first conclusion drawn from the two fundamental postulates is the invariance of the speed of light, that it has the same constant value in all inertial frames. This gives the 'k-Lorentz transformations', the Lorentz transformations up to a velocity dependent scale factor, K. What has, in effect, been shown is that if the speed of light as measured with respect to frame F' is to be found to be the same value as when measured with respect to the 'resting frame' F, then rods and clocks at rest in F' had better contract and dilate (with respect to frame F) in the coordinated way that is encoded in the K-Lorentz transformations. One then appeals to the relativity principle again — the principle entails that these coordinated contractions and dilations must be exactly the same function of velocity for each inertial frame —, along with the principle of spatial isotropy, in order to narrow down the deformations to just those encoded in the Lorentz transformations[12]. What has been shown is that rods and clocks must behave in quite particular ways in order for the two postulates to be true together. But this hardly amounts to an explanation of such behaviour. Rather things go the other way around. It is because rods and clocks behave as they do, in a way that is consistent with the relativity principle, that light is measured to have the same speed in each inertial frame.

We now return to the question of what might constitute a constructive version of SR. It is useful in this connection to start by recalling that Einstein had not adopted the principle theory route to SR by chance. He was familiar with Lorentz's semi-constructive efforts in the 1890s to account for the null result of the 1887 Michelson-Morley experiment in terms of a postulated shape deformation suffered by solid bodies as a result of motion through the luminiferous ether. But by 1905 Einstein had convinced himself for a number of reasons that

[12]The importance of this second application of the relativity principle (together with spatial isotropy) in Einstein's 1905 logic was stressed in Brown (1997) and particularly in Brown and Pooley (2001). Janssen points out that in 1905 Einstein "found part of another result that had been found by Poincaré, namely, that the Lorentz transformations form what mathematicians call a *group*" (Janssen, 2002a, p. 428). But it is important to realize that it is appeal to the relativity principle that justifies the fact that the coordinate transformations form a group. The group property is essentially a postulate in Einstein's reasoning, not a theorem.

a systematic understanding of the non-Newtonian behaviour of moving rods and clocks based on the study of the forces holding their constituent parts together was, at that time, far too ambitious.

Note that Einstein did not reject the approach initiated by Lorentz primarily because it violated the relativity principle. Although Lorentz believed in a preferred inertial frame, by 1904 the kinematics of his theory of the electron was consistent with the relativity principle. His theorem of corresponding states was based on the assumption that no experiment could be performed that would exhibit the presence of the ether, at least as regards effects that were up to second order in v/c; for all predictive purposes Lorentz's theory of the electron had become compatible with the relativity principle. What instead concerned Einstein was the confused state of understanding — exacerbated by his own revolutionary hypothesis of light quanta! — of the stability of matter in terms of the dynamical forces operating at the atomic and molecular levels[13].

By the late 1940s, a much better picture, at least in broad terms, of the cohesion of matter was available. Even so, in his 1949 *Autobiographical Notes* (Einstein, 1969), Einstein's reservations about quantum mechanics apparently prevented his re-examining the constructive route to SR, despite his now articulating clear misgivings about key aspects of his 1905 principle theory approach. But what is especially striking is this. We saw in Section 1 that in 1922 Einstein referred to the SR "ether" as having an "influence on light propagation", but in the 1949 *Notes* he warns against imagining that space-time intervals "are physical entities of a special type, intrinsically different from other variables ('reducing physics to geometry', etc.)".

Since the 1920s there has been a small minority of voices — including those of Pauli, Eddington, Swann, Bell, Jánossy and Dieks — defending, to a greater or lesser extent, the importance of a *constructive*, non-geometric picture of the kinematics of SR that makes no commitment to the existence of a preferred inertial frame. We have added our voices to this little-known tradition (see Brown, 1993, 1997, 2003, 2005; Brown & Pooley, 2001). Recently we dubbed the approach, following a remark of John Bell (1976, p. 77), the "Lorentzian pedagogy". This label has proved to have several unfortunate and highly misleading features, the worst being that any position named after Lorentz risks being

[13]The role that Einstein's own 1905 light quantum hypothesis played in undermining his confidence in a constructive approach to relativistic kinematics is clearly spelt out in Einstein (1969); for further discussion see Brown and Pooley (2001) and Brown (2005, Chapter 5).

misinterpreted as an endorsement of a preferred frame[14]. A more appropriate label would be the *dynamical interpretation*[15].

But as one of us has noted (Brown, 1997) the 'space-time theory' approach developed principally by philosophers in North America in recent decades — the view of SR that is encapsulated in Friedman's 1983 book *Foundations of Space-Time Theories* — also could be interpreted as a constructive theory in Einstein's sense, where it is precisely the Minkowski geometry that provides the explanatory deep structure. An explicit defence of this position has recently been given by Balashov and Janssen, to which we now turn.

4. The explanation of length contraction

How *are* we to explain length contraction in SR? One needs to be careful about what, exactly, is taken to stand in need of an explanation.

Balashov and Janssen's (2003, p. 331) initial characterization of the constructive-theory explanation of the space-time interpretation runs as follows:

> length contraction is explained by showing that two observers who are in relative motion to one another and therefore use different sets of space-time axes disagree about which cross-sections of the 'world-tube' of a physical system give the length of the system.

Here we are asked to contemplate a single rod. What is to be explained is how it is possible that this single rod comes to be assigned two different lengths when measured with respect to two inertial frames. Note that the relativity of simultaneity — that two different cross-sections of the rod are involved — plays a crucial role[16].

[14]The remaining unfortunate features are these. First, the pedagogic dimension offered by Bell's simple atomic model displaying motion-induced relativistic contraction is not the whole story, as Bell himself recognized (see also Brown & Pooley, 2001). Second, as has been argued recently in Brown (2003, 2005), the term "FitzGeraldian pedagogy" would be historically more appropriate. Finally, in so far as there is a connection with Lorentz's thinking, it is only his post-1905 formulation of the electron theory, in which Lorentz had learnt from Einstein how correctly to interpret the Lorentz transformations (see Janssen, 2002a, p. 8) that is relevant — but shorn of the privileged frame!

[15]Such an approach does not appear (under any label) within the recent taxonomy of interpretations of SR produced by Craig, and endorsed, with qualification, by Balashov and Janssen.

[16]In a recent manuscript, Petkov claims to show that "no forces are involved in the explanation of the Lorentz contraction" (Petkov, 2002, p. 6); see also (Petkov, this volume). His argument involves consideration of essentially the same scenario considered by Balashov and Janssen. And, of course, those who believe (like us) that in some explanatory contexts it is correct to invoke forces would not do so when comparing one cross-section of the world tube of a rod with another cross-section of the same rod. Rather, forces are relevant, for example, when comparing, *relative to a fixed inertial frame and standard of simultaneity*, two otherwise identical rods that are in different states of motion relative to this frame of reference.

In an unpublished manuscript Saunders, (2003), Saunders considers two rods, R and S, in relative inertial motion. Specific features of Minkowski geometry are appealed to in an explanation of why, *relative to surfaces of simultaneity orthogonal to the world-tube of* R, S is shorter than R whereas, *relative to surfaces of simultaneity orthogonal to the world-tube of* S, it is R that is shorter than S[17].

In our opinion these constitute perfectly acceptable explanations (perhaps the only acceptable explanations) of the explananda in question. But it is far from clear that they qualify as *constructive* explanations[18]. What is being *assumed* in both cases is that the rod(s) being measured, and the rods and clocks doing the measuring, all satisfy the constraints of Minkowskian geometry. The explanations point out that if objects obeying these constraints have certain geometrical features, then it follows, as a simple consequence of the mathematics of Minkowskian geometry, that they will have certain other features.

The geometrical features of the objects that are assumed, and appealed to, in these explanations are similar in status to the postulates of principle theories. They do not, *directly*, concern the details of the bodies' microphysical constitution. Rather they are about aspects of their (fairly) directly observable macroscopic behaviour. And this reflection prompts an obvious question: *why* do these objects obey the constraints of Minkowski geometry[19]? It is precisely this question that calls out for a constructive explanation. What sort of an answer might be given?

The following quote from Friedman helps to delineate the options. In discussing Poincaré's preference for "the Lorentz–Fitzgerald version of an 'aether' theory" over Einstein's formulation of SR he writes:

> … the crucial difference between the two theories, of course, is that the Lorentz contraction, in the former theory, is viewed as a result of the (electromagnetic) forces responsible for the microstructure of matter in the context of Lorentz's theory of the electron, whereas this same contraction, in Einstein's theory, is viewed as a direct reflection — independent of all hypotheses concerning microstructure and its dynamics — of a new kinematical structure for space and time involving essential relativized notions of duration, length, and simultaneity. In terms of Poincaré's hierarchical conception of the sciences, then, Poincaré locates the Lorentz contraction (and the Lorentz group more generally) at the level of experimental physics, while keeping Newtonian structure at the next higher level (what Poincaré calls mechanics) completely intact. Einstein, by contrast, locates the Lorentz contraction (and the

[17] An analogous scenario is considered by Janssen (2002b, pp. 499–500).

[18] It should be stressed that Saunders does not claim that the explanation he sketches is a constructive-theory explanation.

[19] Note that this question arises for someone with no prior expectations about how bodies in motion 'should' behave; *pace* Balashov and Janssen (2003, p. 340), the question need not be understood as asking "why do these objects obey the constraints of Minkowski geometry *rather than those of Newtonian space-time*?"

> Lorentz group more generally) at precisely this next higher level, while postponing to the future all further discussion of the physical forces and material structures actually responsible for the physical phenomenon of rigidity. The Lorentz contraction, in Einstein's hands, now receives a direct *kinematical* interpretation. (Friedman, 2002, p. 211–212)

The talk of a preference for one theory over the other might suggest that we are dealing with two incompatible, rival viewpoints. On one side one has a truly constructive space-time interpretation of SR, involving the postulation of the structure of Minkowski space-time as an ontologically autonomous element in the models of the phenomena in question. In this picture, length contraction is to be given a constructive explanation in terms of Minkowski space-time because complex material bodies are constrained (somehow!) to "directly reflect" its structure, in a way that is "independent of all hypotheses concerning microstructure and its dynamics".[20] If one were to adopt such a viewpoint there would seem to be little room left for the alternative viewpoint, according to which the explanation of length contraction is ultimately to be sought in terms of the dynamics of the microstructure of the contracting rod.

In fact, it is not clear that Friedman has these two opposing pictures in mind. Although he claims that *Poincaré* keeps Newtonian structure at the level of 'mechanics', if one is committed to the idea that Lorentz contraction is the result of the forces responsible for the microstructure of matter then one should, in our opinion, believe that Minkowskian, rather than Newtonian, structure is the appropriate kinematics for mechanics. In our view, the appropriate structure is Minkowski geometry *precisely because* the laws of physics, including those to be appealed to in the dynamical explanation of length contraction, are Lorentz covariant. Equally one can postpone (as Einstein did) the detailed investigation into the forces and structures actually responsible for the phenomena that are paradigmatic of space-time's Minkowskian geometry without thereby relinquishing the idea that these forces and structures are, indeed, "actually responsible" for the phenomena in question and, hence, (we go further in suggesting) for space-time having the structure that it has.

Saunders is critical of the Lorentzian pedagogy because he takes it to *require* that the investigation of dynamical phenomena is to be referred to a single (though arbitrary) frame of reference. It is true that Bell was concerned to extol the virtues of working wholly within a single frame. But on this score his point

[20]The thesis that Minkowski space-time cannot act in this way as an *explanans* in a constructive version of SR was put forward in Brown (1997) and further defended in Brown and Pooley (2001) and Brown (2003).

was primarily a pedagogic one. His point was not that one is required to work in a single framed, but that one always *can* work in a single frame. In particular, he was concerned to show that, if one knew the laws of physics with respect to a given frame one could, at least in principle, *derive* how they should be described with respect to other frames[21]. Bell believed that exploiting the perspective one gains from working with respect to a single frame best allows one to discern the great continuity that exists between relativity and the physics that predated Einstein's 1905 paper. As such, the single-frame perspective is a useful antidote to misapprehensions about relativity that arise when one focuses solely on the discontinuities.

But focus on describing all phenomena with respect to a single frame is just one part of Bell's message. Moreover, it is not that part which forms the essential element in the position we have called the dynamical interpretation. What is definitive of this position is the idea that constructive explanation of 'kinematic' phenomena involves investigation of the details of the dynamics of the complex bodies that exemplify the kinematics.

And it seems that Saunders agrees on this score. Given a word-line that represents the possible trajectory of the end point of a small rod, and given a single point that is meant to represent the other end of the rod at some particular moment, there is, from the point of view of Minkowski geometry, a particularly natural construction of a second curve through the single point. The two curves together define the possible world-tube of an extended body, a world-tube that, from the point of view of Minkowski geometry, is particularly natural. According to Saunders "it is this construction that needs a dynamical underpinning: why do stable bodies, sufficiently small in size, have world-tubes with this geometry?" Saunders (2003). This, we claim, is precisely the type of question that the dynamical interpretation of SR seeks to address. Little hangs on whether the dynamical underpinning is spelled out with respect to a particular frame, or whether the solution is given in some sophisticated, coordinate independent way. What is important is that particular laws — a

[21]If the laws known with respect to a given frame are in fact (though possibly not known to be) Lorentz covariant, one will derive that the rods and clocks at rest in another frame will be contracted and dilated relative to one's own: one will derive that a Lorentz transformation is the correct coordinate transformation relating the two frames. One can then go on to investigate how phenomena in general are to be described relative to this frame, and to derive that these descriptions will obey laws of exactly the same form as do descriptions with respect to one's own frame. One will have thereby derived the fact that the laws satisfy the relativity principle (see Bell, 1987, pp. 75–76; cf. Swann, 1941, Jánossy, 1971 and Brown, 2005, chapter 7.)

specific quantum field theory — could be solved and the solutions shown to have the requisite geometrical properties[22].

We have been arguing that the truly constructive explanation of length contraction involves solving the dynamics governing the structure of the complex material body that undergoes contraction. There are, of course, many contexts in which such an explanation may not be appropriate, contexts that call for a purely geometrical explanation. What we wish to stress is (i) that such geometrical explanations are not constructive theory explanations in Einstein's sense and (ii) that there *are* contexts, and questions, to which the dynamical story is appropriate.

There is one final, important, area of disagreement between us and Balashov and Janssen to map out. But before we do so, it will be instructive to acknowledge that in many contexts, perhaps in most contexts, one should not appeal to the *details* of the dynamics governing the microstructure of bodies exemplifying relativistic effects when one is giving a constructive explanation of them[23]. *Granted that there are stable bodies*, it is sufficient for these bodies to undergo Lorentz contraction that the laws (whatever they are) that govern the behaviour of their microphysical constituents are Lorentz covariant. It is *the fact that the laws are Lorentz covariant*, one might say, that explains why the bodies Lorentz contract. To appeal to any further details of the laws that govern the cohesion of these bodies would be a mistake.

Elsewhere we have dubbed this view the "truncated" Lorentzian pedagogy (Brown & Pooley, 2001, p. 261). It is worth making two points about it. First, to explain why there are any bodies at all that conform to Minkowskian geometry one needs to appeal to more than Lorentz covariance. One needs to

[22]It is perhaps worth mentioning here one common objection to any approach that seeks to reduce non-dynamical space-time structure, such as that of SR, to the symmetries of the laws governing matter. According to the objection such an approach is constrained to use special coordinates (in which the laws take their canonical form) because otherwise the geometric structure, in the form of the Minkowski metric and its connection coefficients, appears explicitly in the laws.

Two things should be said in response to this objection. First, the objection surely is not that defenders of the reductive account are okay so long as they place restrictions on admissible coordinate systems. If the reductive account is tenable at all, then it can countenance the use of arbitrary coordinate systems. (Perhaps it could be argued that the supporter of the reductive account faces an obligation to provide an alternative formulation of the laws as written with respect to arbitrary coordinates, in which the secondary status of the geometrical structure is clear.) Second, even if one is inclined to take the appearance of the Minkowski metric in the laws when written generally covariantly as a reason to afford it a primitive ontological status, one is still obliged to tell some story about how and why material systems reflect its structure in their macroscopic behaviour. What could this story be, other than the dynamical one? (In a recent discussion, Butterfield also recognises the existence of such an obligation, which, in his terminology, is an obligation to answer to the "consistency problem" (Butterfield, 2001, Section 2.1.2).)

[23]We thank Michel Janssen for reminding us of this point.

demonstrate the possibility of stable material configurations, and the constructive explanation of this will involve a more complete dynamical analysis. Second, one might be tempted to deny that explanations which appeal to an explanans as non-concrete as the *symmetries* of the laws are genuinely constructive explanations. In other words, it turns out that there are even fewer contexts than one might have at first supposed in which length contraction stands in need of a constructive-theory explanation.

5. Minkowski space-time: the cart or the horse?

But if it is often sufficient to appeal to Lorentz covariance to give a dynamical explanation of length contraction, is that where explanations should stop? It is here that Balashov and Janssen see a further, constructive role for the geometry of space-time. They ask:

> … does the Minkowskian nature of space-time explain why the forces holding a rod together are Lorentz invariant or the other way around? Our intuition is that the geometrical structure of space(-time) is the *explanans* here and the invariance of the forces the *explanandum*. To switch things around, our intuition tells us, is putting the cart before the horse. (Balashov & Janssen, 2003, pp. 340–341)

The same issue was raised some years ago in Brown (1993) and, particularly, Brown (1997), but there the opposite view to Balashov and Janssen's was taken as to what was to be regarded as the cart and what the horse.

It is worth recalling that Balashov and Janssen's target is the particular neo-Lorentzian interpretation of SR advocated by Craig. This is an interpretation in which space-time structure is supposed to be Newtonian and in which there is supposed to be a preferred frame, consistent with Craig's commitment to a tensed theory of time. Balashov and Janssen's claim is that the space-time interpretation has a definite explanatory advantage over this neo-Lorentzian interpretation when it comes to the Lorentz covariance of the laws governing the behaviour of matter:

> In the former, Lorentz invariance reflects the structure of the space-time posited by the theory. In the latter, Lorentz invariance is a property accidentally shared by all laws effectively governing systems in Newtonian space and time ….
>
> In the neo-Lorentzian interpretation it is, in the final analysis, an unexplained coincidence that the laws effectively governing different sorts of matter all share the property of Lorentz invariance, which originally appeared to be nothing but a peculiarity of the laws governing electromagnetic fields. In the space-time interpretation this coincidence is explained by tracing the Lorentz covariance of all these different laws to a common origin: the space-time structure posited in this interpretation (Janssen [1995], [2002]) …. No matter how the argument is made, the point is that there are brute facts in the neo-Lorentzian interpretation that are explained in the space-time interpretation. As Craig (p. 101) writes (in a different context): 'if what is

> simply a brute fact in one theory can be given an explanation in another theory, then we have an increase in intelligibility that counts in favor of the second theory.'

We agree that in Craig's neo-Lorentzian interpretation of SR, and according to our preferred dynamical interpretation, the Lorentz covariance of all the fundamental laws of physics is an unexplained brute fact. This, in and of itself, does not count against the interpretations: all explanation must stop somewhere. What is required if the so-called space-time interpretation is to win out over the dynamical interpretation (and Craig's neo-Lorentzian interpretation) is that it offers a genuine explanation of Lorentz covariance. This is what we dispute. Talk of Lorentz covariance "reflecting the structure of space-time posited by the theory" and of "tracing the invariance to a common origin" needs to be fleshed out if we are to be given a genuine explanation here — something akin to the explanation of inertia in general relativity (see Section 1). Otherwise we simply have yet another analogue of Moliere's dormative virtue.

In fact, Balashov and Janssen's own example can be turned against them. Craig's neo-Lorentzian interpretation is precisely an example of a theory in which the symmetries of space-time structure are not reflected in the symmetries of the laws governing matter. Balashov and Janssen do not question the coherence of this theory (as we would). Rather they seek to rule it out on the grounds of its explanatory deficiencies when compared to their preferred theory. This shows that, as matter of logic alone, if one postulates space-time structure as a self-standing, autonomous element in one's theory, it need have no constraining role on the form of the laws governing the rest of content of the theory's models[24]. So how is its influence on these laws supposed to work? Unless this question is answered, space-time's Minkowskian structure cannot be taken to explain the Lorentz covariance of the dynamical laws.

From our perspective, of course, the direction of explanation goes the other way around. It is the Lorentz covariance of the laws that underwrites the fact that the geometry of space-time is Minkowskian. It is for this reason that we can rule out the sort of mismatch between space-time symmetries and dynamical symmetries that are a feature of Craig's interpretation, and that so trouble Balashov and Janssen.

Balashov and Janssen acknowledge that some of their readers will have this 'relationist' intuition. Remarkably they claim that this does not weaken their point! In a footnote, they admit that, for the relationalist, the Lorentz covariance of the laws "in a sense does seem to explain" why space-time structure in Minkowskian. (We, of course, see no reason for their qualifications

[24]See in this connection Brown (1993). It might be useful to recall here the example of the approach to Einstein's field equations in GR based on the introduction of a spin-2 field on flat Minkowski space-time (for references, see Preskill & Thorne, 1999, pp. xiii–xiv). The operational significance of the background space-time in this theory is not the same as that in SR.

here.) But, they go on to assert that the relationalist should nonetheless view, for example, the Euclidean nature of space as explaining why the forces holding Cyrano's nose together are invariant under rotations rather than *vice versa* (Balashov & Janssen, 2003, p. 341, footnote 11; cf. p. 340). As far as we can see, this amounts to bald assertion. We happily concede that there are many contexts in which the Euclidean nature of space is the appropriate explanation of the behaviour of Cyrano's nose. But we insist that there are others in which it is appropriate to appeal to the Euclidean symmetries of the forces at work to explain the same behaviour. And we simply deny that the Euclidean nature of space can ever be cited as a genuine explanation of these symmetries; *this* would be to put the cart before the horse.

A more sustained discussion of Minkowski space-time's providing a putative common origin for the "unexplained coincidence" in Lorentz's theory that both matter and fields are governed by Lorentz covariant laws, is to be found in Janssen's detailed recent analysis of the differences between the Einstein and Lorentz programs (Janssen, 2002a). It is also covered in his wider investigation of 'common origin inferences' in the history of science (Janssen, 2002b, pp. 497–507). In our view, neither of these papers succeed in clarifying how space-time structure can act as a "common origin" of otherwise unexplained coincidences. One might, for example, go so far as to agree that all particular instances of paradigmatically relativistic kinematic behaviour are traceable to a common origin: the Lorentz covariance of the laws of physics. But Janssen wants us to go further. He wants us to then ask after the common origin of this universal Lorentz covariance. It is his claim that this can be traced to the space-time structure posited by Minkowski that is never clarified.

For example, immediately after making this claim in Janssen (2002b), he writes:

> In Minkowski space-time, the spatio-temporal coordinates of different observers are related by Lorentz transformations rather than Galilean transformations. Any laws for systems in Minkowski space-time must accordingly be Lorentz invariant.

There is a dangerous ambiguity lurking here. The state of affairs described in the first sentence cannot be held to *explain* the Lorentz covariance of the laws (surely the claim that Janssen intends). But one can take the state of affairs described in the first sentence as *evidence for* the Lorentz covariance of the laws[25]. The passage quoted is true only if one understands it as making such an

[25]Cf. Janssen's own distinction between 'explanatory' and 'evidentiary' uses of "because" (Janssen, 2002b, p. 456).

evidentiary claim. And as such, it is (essentially) an unexceptionable statement of Einstein's 1905 reasoning[26].

We hope to have made it clear why we do not believe that Minkowski space-time can play the constructive explanatory role that Balashov and Janssen would have it serve. What needs to be stressed is that this conclusion is appropriate not only for those who adopt an eliminative relationalist stance towards the ontology of space-time, and not only in the context of theories with fixed, absolute space-time structure. As we argued in Brown and Pooley (2001), even when one's ontology *includes* substantival space-time structure, the symmetries of the laws governing material systems are still crucial in such structure gaining operational chronogeometric significance. As we wrote elsewhere:

> Despite the fact that in GR one is led to attribute an independent real existence to the metric field, the general relativistic explanation of length contraction and time dilation is simply the dynamical one we have urged in the context of special relativity. (Brown & Pooley, 2001, p. 271)[27]

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[26]It is also worth noting that a curious picture of Einstein's pre-Minkowskian work emerges in Janssen (2002a). Janssen stresses that "In Einstein's special theory of relativity the Lorentz invariance of these different laws [of matter and fields] is traced to a common origin" (p. 6) and that "Einstein recognized that Lorentz invariance reflects a new space-time structure" (p. 9). But Janssen himself acknowledges that in 1905 Einstein never talks about space-time, and that his initial reaction to Minkowski's geometrization of his 1905 theory was negative (p. 9). The careful reader of Janssen's study would be forgiven for thinking that Einstein misunderstood his own theory in 1905, or at least its real point of departure from Lorentz's program. Our position, on the other hand, is that Einstein knew pretty well what he was doing in 1905. In providing a principle theory approach to deriving the Lorentz transformations, and hence the non-classical behaviour of rods and clocks, he was re-systematizing, and giving a different emphasis to, aspects of the work of Lorentz and Poincaré, but not providing a revolutionary new stance. For Einstein himself, the real revolution in his 1905 *annus mirabilis* was his light quantum hypothesis, as is well known. It has been aptly noted by Staley (1998, pp. 272–274) that despite the fact that physicists seldom distinguished between Lorentz's and Einstein's formulation of the electron theory in the years immediately following 1905, Einstein did not seek to redress this situation — indeed he even referred to "the theory of Lorentz and Einstein" in 1906 (though admittedly in somewhat special circumstances).

[27]A somewhat different point of view is found in Dieks (1984), where it is argued that general relativity has a special role to play in providing a constructive account of length contraction. This is because, according to Dieks, general relativity explains in turn why the constructive laws such as Maxwell's equations are valid in particular frames of reference. A more systematic defense of the opposing view that GR appeals to the same considerations as does SR in accounting for length contraction and time dilation is found in Brown (2005, Chapter 9).

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PART II: TIME, BECOMING AND RELATIVITY: COMPATIBILIST POSITIONS

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Philosophy and Foundations of Physics
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Chapter 5

The Irrelevance of the Presentist/Eternalist Debate for the Ontology of Minkowski Spacetime

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Abstract

I argue that the debate between the so-called presentists and eternalists either lacks substance or is merely pragmatical. Consequently, I show that such a debate has no implications whatsoever both for our understanding of Minkowski spacetime and for notions like change, persistence and becoming. In particular, becoming should *not* be construed as presupposing an *ontological* asymmetry between past (or present) and future, but as the successive occurrence of timelike-related events, an issue related to the various arrows that have been taken to mark the asymmetry of time.

1. The presentism/eternalism Debate and its Ramifications in Current Philosophy of Time

First and foremost among the examples of a misguided metaphysical use of an apparently meaningful notion is given by the *pseudo-predicate* "is real", which, in current philosophy of time, is very often invoked to create distinctions or

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debates whose genuinity or clarity, on closer analysis, turns out to be quite difficult to defend.

One of such distinctions is that between *presentists*, claiming that only the present "is real", and *eternalists*, claiming that the future and the past are "as real as the present". As an illustration of this debate and of its current importance, consider the following passage, taken from a very authoritative and recent contribution to the metaphysics of persistence in time:

> According to eternalism, past and future objects and times are just **as real as** currently existing ones. Just as distant places are no less real for being spatially distant, distant times are **no less real** for being temporally distant .... According to presentism, on the other hand, only currently existing objects **are real**. Computers, but not dinosaurs or Mars outposts, **exist** (Sider, 2001, p. 11, boldface added).

This debate has gained respect and momentum via considerations taken from spacetime theories. In particular, since the geometrical formulation of the special theory of relativity, it has been frequently argued that (i) not only does this theory decidedly favor eternalism over presentism, but that (ii) it is even incompatible with the latter view[1]. And apart from, but not independent of, its connection with the ontological interpretation of Minkowski spacetime, the alleged metaphysical divide between presentism and eternalism has been linked with metaphysical issues concerning the nature of *persistence in time*[2], the nature of *change* and the nature of *becoming*. Just to sketch the connection between the presentist/eternalist debate and becoming, which is easier to present, the received view on becoming has it that only the presentists can make room for its mind-independence, or for an objective coming into being of future events in the present. Given that for the eternalists all events, past, present and future, "are equally real", there cannot be any room for a coming into being in the present of *previously unreal events* and becoming must be mind-dependent or purely subjective (see Gale, 1967, p. 16). In this view, "the unreality of the future" is therefore regarded as a necessary condition for a mind-independent, *ontological* becoming: in the block-view of the universe, very often associated with the eternalist perspective "forced upon us" by the relativity of simultaneity and the special theory of relativity, we are told that any event *tenselessly coexists* with any other event, so that nothing can ever come to exist in a spacetime model like

[1]See among others, Putnam (1967), Rietdijk (1966, 1976), and Saunders (2002). For a different view, see Stein (1968, 1991), Weingard (1972), and Craig (2000). I have myself contributed to the debate in Dorato (1995).

[2]In a rough characterization of the problem of change and persistence in time, we could raise the following questions: do entities persist (or change) in time by *perduring*, i.e., by having different *temporal parts* at different times (event-ontology) or by *enduring*, i.e., by remaining identical to themselves and being wholly present in time while instantiating different properties at different times (things ontology)? The best recent overview of this debate is in Sider (2001).

Minkowski's, that is still regarded as the arena for all processes described by contemporary quantum field theories (except for the gravitational interaction)[3].

In the following, I will argue that the debate between presentists and eternalists either lacks a clear formulation or is merely *semantical*. In any case, my conclusion is rather skeptical and antimetaphysical, since I submit that the presentism/eternalism debate should be regarded as having no implications whatsoever both for our understanding of the ontology of Minkowski spacetime and for notions like *change*, *persistence* and *becoming*, which, if they have to be mind-independent, must certainly be regarded as being *ontological* notions. Consequently, we should resist the temptation of invoking the special theory of relativity or the structure of Minkowski spacetime in order to try to adjudicate between a metaphysical view in which only the present is real and a view in which past, present and future are equally real.

2. The lack of contrast class for the expression "the reality of the future (past)"[4]

As I see it, the main trouble raised by the claim that "the future is real" is that this claim has no "contrast class". What I mean by this expression has been wonderfully clarified by Austin more than 40 years ago: "the function of the word 'real' — he wrote — is not to contribute positively to the characterization of anything but to exclude possible ways of being not real — and these ways are both numerous for particular kinds of things, and liable to be quite different for things of different kinds" (Austin, 1962, p. 70)[5]. Taking Austin's hint, the important question to be answered in order to ascertain the existence of a genuine, ontic disagreement between presentists and eternalists is the following: "how could the future or the past *fail* to be real"? If, as Sider has it, according to the presentist "only currently existing objects are real", it follows that there must be a clear sense in which non-currently existing objects are unreal. (What above is referred to as the contrast class of "is real"). But what, exactly, is being denied by the presentist's implication that the future "is not real" or simply "does not exist", above and beyond the platitude that it does not exist *now*?

Let us look at some cases in which there is a clear contrast class between "real" and "not real". We understand the difference between: "this is real

[3]General relativity is of course more fundamental than the special theory, but we still do not know how to connect it with quantum field theory.

[4]For simplicity and in discussing the presentist's position in relation to the issue of becoming, I will limit my considerations to the ontological status of the *future*, but the same considerations apply, symmetrically, also to the past.

[5]Reference to Austin in this context has been brought to the fore also by Yuval Dolev, who, independently of me, has argued on a similar line in the paper presented at the Montreal conference. See also Savitt, this volume, and Dolev, this volume.

coffee" in contrast to "this is a pure surrogate" (Ersatz), or "this is a *real* disaster" in contrast to "the problem is not so serious", or "this is the real color of the painting", in contrast to "this is the surface color" or "this is a real horse" in contrast to a picture of a horse.

In our case, however, we seem to be in a different predicament: *if* "the reality of the future" simply means that "*there will be events occurring after now*" (what else could it mean?), there seems to be no plausible way in which the future could be unreal as the presentist has it, unless we had evidence for an immediate end of the universe! Since there is no contrast class between a real future and an unreal future as in the examples of the previous paragraph, it is hard to make sense of the debate in question, namely, to see how presentists and eternalists as described by Sider could disagree. Note, furthermore, that if the difference between the presentists and the eternalists must have *ontological* significance, any recourse to the indefiniteness of truth-value of future-tense propositions *vis à vis* the definiteness of present-tense propositions will not be of much help, since this indefiniteness has a mere *semantic* significance. Explaining something ontological with a semantic move is unsatisfactory, since presentists and eternalists can agree that some future-tense propositions may lack now a definite truth-value for epistemic reasons, while agreeing that some future event or other will occur, thereby agreeing that the future "is real". Claiming that the *origin* of, or the reason for assuming, the semantic difference between present-tense and future-tense propositions is ontological is of course a mere *petitio principii*, since we want to know what such an ontic difference amounts to.

When the eternalist claims that "the future is as real as the present" — a misleading way to state the position, but expedient for showing that the debate with the presentists is genuine — all that she must be understood to be affirming is that "there will be future events". There is nothing particularly interesting about such claims, as soon as we emphatically add that they do not imply that "the future (whatever will be the case), or any particular future event E, exists now".

In other words, even if, for some descriptive purposes, it can be useful to *represent* the whole history of the world as being somehow completely "given", with time viewed as a wholly spacelike dimension within a four-dimensional block, we should not forget that once we are given a particular event *in* time (a point in the block), the eternalist *can* (and *should*) distinguish between events that, relative to that point, have already occurred, and events that will occur[6]. *If* the successive occurring of events — in which becoming consists[7] — is a

[6]Whether this distinction is local or global will depend on details about the spacetime structure we are considering.

[7]See Dorato (2002, 2006), and Savitt (2002). Dieks is now independently arguing in favor of a similar view.

mind-independent feature of the universe, it is not legitimate to conflate a "static" representation with the thing (time) that is being represented[8].

The antecedent of the conditional *must* be granted simply because also in Minkowski spacetime timelike-separated events are objectively, invariantly timelike-related, and events, *by definition*, *occur or happen*. They do so, so to speak, *a priori*. If any two events *are* tenselessly timelike separated, and a reasonable arrow of time can be assumed, one event will happen after the other, and this suffices to assume the mind-independence of (tenseless) becoming: the fact that in a block-view pairs of timelike-separated events *exist at their location*, as one often hears, does not mean that they are all simultaneous, but simply that one event of the pair occurs and then the other does. And the events' very being is their occurring.

Summarizing, the representation in which all events are given, and time is like an extra-dimension of space is a mere picture; the thing being represented, however, is the "real" world or the real spacetime, characterized by events objectively and mind-independently following one another in time. No sensible eternalist will argue that the events along the temporal dimension of the universe are all simultaneous with each other (as in a *Totum Simul*), *because otherwise such events could not occur, as they actually do, in temporal succession*. But if events occur in succession, then there is form of becoming consisting of such successive occurrence, and events cannot coexist simultaneously as they do in space.

I want to suggest that it is only a misleading interpretation of the "as-real-as-claim" in Sider's quotation above that creates the impression of a "real" difference between eternalism and presentist[9]. In other words, *it is only if the eternalist interprets the "future-as-real-as-the-present-claim" as the absurd view that all events are simultaneous with each other that a difference with the presentist would be available*. Once this absurdity is rejected, how can the presentist avoid any form of existential commitment to future events? We have seen that if the presentist accepts as true that "it will be the case that some object or other exists", where "exists" is present tense, then she will be committed to the same view allegedly defended by her enemy, the eternalist, namely, "the reality of the future". The only way to avoid a collapse of the presentist's position on the eternalist one seems to consists in arguing that "it will be the case that something or some event E exists" does *not* amount to an existential commitment to that something, because the quantifier is inside the scope of the tense operator **F** ("it will be the case that"). It is not by chance that this is exactly the line taken by Sider (2004)[10], which will be discussed in the following.

[8] In a paper presented at the Montreal conference, a similar point has been stressed also by Richard Arthur. See Arthur (this volume).

[9] I am not suggesting that Sider is guilty of this misinterpretation.

[10] I thank Theodore Sider for permission to refer to a paper in progress.

Before going to that move, however, if we agree with the defenders of the genuinity of the debate that the presentist has to deny any sort of tensed existential commitment to future events or objects, then we must recognize that she is in a bad predicament. I take it, in fact, that the presentist cannot be interpreted as denying that, as of the present moment, the world will have some future or other, or, equivalently, as affirming that the world will end after the present moment. If I am right about this, if the end of the world is not what is at stake, at least in this reading there seems to be no genuine "contrast class" between the presentist and the eternalist about the ontological status of the future, i.e. no real ontological difference between them.

This diagnosis, of course, will be judged to be too quick by the antiskeptic. However, I think that I have eliminated from the possible candidates at least *one* sense of "being unreal", referred to future events: if the contrast class concerned *eschatology*, the belief that what we call "the same persisting world" annihilates after each present instant, is luckily being constantly refuted by experience. So we should abandon it in light of induction and admit, presentists and eternalists alike, that there will be some future, but should not cash this belief in terms of the misleading expression "the reality of the future", because in this case we would have no plausible contrast class for "real".

2.1. Occasionalism to the rescue?

Let us see whether it is possible to make sense of the view that the future is unreal in some alternative way. A first attempt is to try to engage in some wildly speculative occasionalist metaphysics, following the footprints of Descartes:

> "for it is quite clear to anyone who carefully considers the nature of time that the same power and action are needed to conserve anything at each individual moment of its duration as would be required to create that thing anew if it were not yet in existence. Hence, the distinction between conservation and creation is only conceptual, and this is one of the things evident by the natural light"

(Descartes, 1644/1985, Vol. II, p. 33). The presentist could then affirm that presentism entails or means that at each instant what we call "the world" is created anew, and duration in time or persistence of the *selfsame* world is an illusion. Consequently, if we identify a different world with each different instant of time, it would be true to claim, at each time, that there is no future, since "future" might be indexical to each instantaneous world, as "actual" is in Lewis's theory of possible worlds (Lewis, 1986). In each present moment, each world, or better, world-slice, would have no future, since a different world would be created at each different instant of time.

In spite of the fact that this move is not incoherent, I will assume that presentists should not go so far as rediscovering the heavy metaphysics of continuous creation just to save their own theory: the remedy seems worse than the disease. And besides, what would prevent one from using the future-tense operator to refer to the different world that will be created after the present and claim that "*there will be* an act of creation of a different world"?

If anything, this reference to occasionalism has the merit of reminding us of a possible *theological* origin of presentism (apart from the important role of tenses in ordinary language): if God creates (or recreates) the world all at once (or at each instant of time), then there must be the same objective present across all the universe.

3. A second blow at the debate: the pluralistic nature of existence

Another, more promising way to defend the view that there exists genuine disagreement between presentists and eternalists is resort to existential quantification, and forget about the alluring but vacuous charm of "is real". Not by chance, Sider's quotation above ends with the claim that for presentists, dinosaurs and Mars outpost do not *exist*. Nevertheless, Sider adds, in order to have genuine disagreement, we must make sure that presentists and eternalists do *not* mean different things when referring to existence (Sider, 2001, p. 15).

However, to use Sider's examples, the question whether dinosaurs and human outposts on Mars are in the domain of quantification of the true theory of the world, in a broadly Quinean sense, may not admit a univocal answer, or better, it may have an answer depending on our descriptive aims. We must live with the fact that, at least in the philosophical literature, "existence", or "there exists", *is* ambiguous between tensed and tenseless existence.

> Def_1. Event *e* exists in a *tensed* sense of "existence" just in case it exists now.
>
> Def_2. Event *e* exists in a *tenseless* sense just in case it existed, exists now, or will exist.
> $\mathrm{Def}_{2\mathrm{Alt}}$. Alternatively, and equivalently, *e* exists in a *tenseless* sense just in case it exists at a particular time–place by occupying a region of spacetime.

Attempts at arguing that there is just a univocal sense of existence, as if we had a broadly Quinean criterion of ontological commitment with no further qualification, seem to be contradicted by the fact that, for example, for the platonist *mathematical* existence is not *physical* existence, given that the former is abstract and the latter is concrete, spatiotemporally extended existence[11]. If we did not distinguish between mathematical and physical existence, we would not be able to distinguish those philosophers having a naturalistic position about mathematical existence from the platonists, who believe that there are also non-natural, non-spatiotemporally extended entities (namely, the mathematical ones). The *mode* of existence is fundamental in the enterprise of

[11]This is a response to an objection raised by an anonymous referee.

ontology: paraphrasing Aristotle's famous words about being, also "of existence one can speak in many ways".

This remark also serves to attack the sweeping generalization according to which "if there is no genuine ontological distinction between presentists and eternalist then no ontological debate is genuine" (Sider, 2001, pp. 16–17). Perhaps the debate between actualists and possibilists[12] falls in the same category as the presentists/eternalists one, but other ontological debates can rely on clearer ways of articulating their positions. "Are mathematical entities real or not"? gets translated, for instance, into "are mathematical entities abstract or purely mental or fictional"? These questions are different from the issues dividing eternalists and presentists (and possibilism from actualism) since they admit a well-posed contrast class (compare Sider, 2001, pp. 16–17).

Analogously, given the existence of a philosophical debate whether as of the present moment "dinosaurs exist" or not, the temptation to think that (a) two different senses of existence are in play, and (b) the dispute between presentists and eternalists should be cashed as being about which of the two is more fundamental, is very strong. In the next section, I will explore this possibility and show that, put it in these terms, the debate between presentists and eternalists is purely *semantical*, *and has no ontological consequences*. As such, it cannot have any import on our understanding of the ontology of Minkowski spacetime, of becoming, of the nature of change or of persistence in time.

4. A debate on which of the two senses of existence is more fundamental?

Let us go back to the definitions given above:

> Def_1. Event *e* exists in a *tensed* sense of "existence" just in case it exists now.
>
> Def_2. Event *e* exists in a *tenseless* sense just in case it existed, exists now, or will exist.

As we can see, the use of "there exists" presupposed by the first definition is to be contrasted with the one presupposed by the second. The first definition just refers to what exists in the present or exists now, leaving aside problems about the nature and ontological status of the present; the second uses the disjunction "was or is now or will" and has the purpose of capturing the distinction between *concrete and abstract existence*. The contrast class of the second definition, the

[12]According to Sider, *possibilism* is defined as the view that "reality also contains merely possible things" (Sider, 2001, p. 12), while modal *actualism* decrees that reality only contains actual entities. One may wonder what it means to claim that, for the possibilist, *merely possible things are real*, if "real" also implies actual, since at this point, by letting "possible" mean "non-actual", we would have that "non-actual things are actual"! And if the meaning of "real" does not entail "actual", then possibilism amounts to the triviality that "possible things are possible". Once again, the dispute seems merely verbal, and dependent on how we want to define "real".

legitimacy of its use, lies in the class of abstract, non-spatiotemporally extended entities, like sets, functions or classes, whether they exist, as platonists have it, or are just fictions. In both cases, Def_2 is needed because we need a distinction between concretely existing entities and abstract/fictional "entities", which are not in spacetime.

As hinted above, a defender of the view that the contrast between eternalists and presentists is genuine could claim that "there exist dodos" is false for the presentist and true for the eternalist, because they disagree about the meaning of the existential quantifier, or put it differently, disagree about which of the two senses of "existence" is more fundamental[13].

The presentists tell us that tensed existence is more fundamental (after all, in most natural languages it is certainly more entrenched) and therefore "there are human outposts on Mars" *is* false. The eternalist will immediately note that the statement in question "is false *now*" (false at a certain instant of time), but that it might be true that "there will be outposts on Mars". The presentist will say that "is false now" is redundant because "*is* false" already presupposes "is false now", since the italicized copula is tacitly but fundamentally *tensed*[14].

Note, however, that even granting that the tensed sense of existence and the tensed copula are more fundamental than the tenseless ones will not help much against the assault of the skeptic. First of all, as long as truth is relativized to instants of time, it seems difficult to deny a commitment to the future existence of outposts for both the presentist and the eternalist (assuming there will such outposts on Mars). Of course, the presentist can deny that any past or future-tense statement is true, so the debate is now captured in terms of presence or absence of definite truth values, but we have already seen why this semantic move is not to be recommended. Second, if we recall that the presentist is committed to the unreality of *any* future (past) event, the claim whose truth-value is to be evaluated is not a particular one about the presence of human outposts on Mars, but rather one concerning whether it will be the case or not that something will occur or will exist". In this latter case it is difficult to imagine how the presentist could consistently deny it without falling into the position that we have already refuted, namely, that there is no future because the world will end. The more fundamental character of "there exist" (tensedly) does not exclude commitment to the existence of the future (of some future event) in such a way as to dissolve any alleged ontological divide.

In a nutshell, the main problem in this second way of capturing the debate seems to revolve around the meaning of "more fundamental". If, in a moderate

[13]This is the way in which, for instance, Huw Price cashes the debate between presentists and eternalists (oral communication).

[14]I owe this suggestion to the presentist John Bigelow, during a discussion of a version of this paper, which I presented in Sidney.

and tolerant reading of "more fundamental", "the greater degree of fundamentality" of tensed existence does not entail that the other, tenseless sense of existence is outlawed, then presentists and eternalists will agree that "it will be the case that some event *e* occurs (tensedly)". This either entails "*e* will occur", or it entails that *e* exists tenselessly on the basis of the following definition.

$\mathrm{Def}_{2\mathrm{alt}2}$ "*e* tenselessly exists just in case *it was the case that e* exists (tensedly), or *e* exists (tensedly) or it will be the case that *e* exist (tensedly)". In both cases, there seems to be no disagreement between presentists and eternalists.

If, instead, the reading of "more fundamental" were more radical and intolerant, a presentist might end up refusing the legitimacy of *any* tenseless sense of existence. In this latter case, however, it would be hard to see on which ground presentists could regard Def_2 as meaningless, given that it is not *prima facie* inconsistent. Furthermore, also presentists need to distinguish between an event existing in spacetime and fictional entities like Pegasus, and banning Def_2 would deprive them of an indispensable linguistic resource. While a future event *f will be* in spacetime (supposing that it will occur, so as to leave irrelevant epistemic worries about warrant aside), Pegasus's flight toward the Sun has not occurred, is not occurring now and will never occur.

Note that once the two senses of existence are admitted, *presentism*, if it commits itself to the future existence of something, *becomes either a triviality or a contradiction*. If the presentist denied that "any future event *exists* (alternatively, *is* real)" by relying on the tensed sense of existence (exists = exists now) or on the tensed copula, she would be peddling a triviality: "the future is not real or does not exist $=_{\mathrm{def}}$ what will exist ('the future') is not existing now (is not now occurring)".

But if, on the other hand, the sense of existence in "does not exist" is tenseless (alternatively, the copula "is" in "is real" is tenseless), the minimalist assumption that the world will not end leads to a contradiction. Supposing that at least something will exist or occur (has existed, has occurred), that something is (tenselessly) existent in virtue of Def_2, and it cannot be (tenselessly) non-existent as presentism has it. Recall that, according to Def_2, the claim "e does not exist" in a tenseless sense means that "*e* did not exist *and* does not exist now *and* will not exist". Once again, presentists are forced to say that literally there will be no future at all after the present (there was no past), that the world has an end after now, because as soon as they admit that something will occur (has occurred), then they must admit that that something exists (tenselessly). And we have already seen that this apocalyptic position is too absurd to be considered as a plausible defense of presentism.

It could be suggested that the distinction between presentists and eternalists has to do with the determinateness or fullness of attributes of future events: the former denying that all future events are determinate, the latter admitting it. But if the possession of an attribute (a property) by an object at a time–place is an event, then we are back at step one: the presentist would deny the existence of future events that the eternalists would admit.

5. Platonism and presentism

Consider the following example due to Sider. An eternalist believing in sets would endorse the claim that there exists (tenselessly) a set containing a dinosaur and a computer, but the platonic presentist will reject the disjunction[15]: "it was the case that (($\exists x$) (x is a set containing a dinosaur and a computer)), or it is the case that (($\exists x$) (x is a set containing a dinosaur and a computer)) or it will be the case that (($\exists x$) (x is a set containing a dinosaur and a computer))". Since at no time computers and dinosaur coexist, according to Sider the eternalist believes in something that the presentist denies, namely the existence of the above set (Sider, 2001, pp. 15–16).

This argument is not as convincing as may appear at the outset. Sider notes that in order to give the example all its force, both parts must accept the principle that sets exist only if their members *exist* (Sider, 2001, p. 16). Otherwise, there would be no difference between the eternalist and the presentist, since both could admit the existence of sets whose members never existed. But why should presentists endorsing the existence of sets *qua abstracta* accept the *highly restrictive principle* according to which such an existence depends on the *temporal coexistence* of their members or on the simultaneity of their time-slices? It would be strange to let sets exist only on the condition that their members coexist at the same time, since, after all, sets, *if* they exist, are abstract entities, whose members may well lack any temporal extension at all: think of sets of numbers or of functions. It would be odd to require that sets of numbers exist only if their members coexist in time, since numbers do not exist in time at all and even more *ad hoc* to introduce a criterion for the existence of sets of concrete objects, which has no correspondence in the case of sets whose members are abstract.

Summarizing, to the effect that sets are abstract entities, and the word "set" in our example does not simply stand for the concrete "object", which results from the disconnected sum or "fusion" of a computer with a dinosaur, we seem to be introducing an implausible constraint. Since a set containing a computer and a dinosaur is neither a computer nor a dinosaur nor both, if it exists, it is *abstract*, and abstract objects are not located in time by definition. So the disjunction "there was a set composed by a computer and a dinosaur, or there is a set composed by a computer and a dinosaur or there will be a set composed by a computer and a dinosaur" looks like a misapplication of tensed language in a

[15]John Bigelow is an example of a presentist that is a realist about mathematical objects: this combination seems to be consistent.

domain to which it does not belong. It follows that also the presentist believing in sets *should* accept, along with her alleged enemy the eternalist, that there exists (atemporally) a set containing a computer and a dinosaur, because the object in question (the set) does not exist in a tenseless sense, but rather in an *atemporal* sense, even though its two members never coexist at the same time.

It remains to be seen whether presentists can use the future (and past) tense operators without any commitment to the existence of the past and the future. To my knowledge, the philosopher who has gone furthest in defending this possibility is Theodore Sider (who is no presentist), and who claims that existential quantifiers inside the scope of the tensed operators carry no existential commitments. I will now briefly explore this possibility to conclude the paper.

6. Tensed existence and nested quantifiers

Recently, Sider has presented a more sophisticated argument against the skeptic about the genuinity of the debate between presentists and eternalists. Consider the claim that "it is possible that unicorns exist":

$$\diamond((\exists x)(\mathrm{U}x)) \tag{1}$$

Sider notes that in modal actualism (1) does not imply the existence of unicorns, because within this position, *possibilia* do not exist: within actualism, the presence of the existential quantifier inside the scope of the modal possibility operator by itself does not commit one to existence claims. For the possibilist, on the contrary, (1) implies existence, by definition of possibilism. Sider tries to establish a parallel between (1) above and "it will be the case that (label it with *F*) there exist outposts on Mars" (O)

$$F((\exists x)(\mathrm{O}x)) \tag{2}$$

which, according to him, would not carry any existential commitment, if one is presentist and will do so on an eternalist metaphysics.

First of all, one should agree with Sider that (1) does not commit an actualist to the existence of unicorns, a remark that seems to entail that the meaning of the embedded quantifier is going to depend on one's prior metaphysical commitments. However, if symbols, logical and mathematical alike, do not carry their interpretation on their sleeves, ably resorting to logic as Sider (2004) does in the rest of his paper may not be sufficient to settle metaphysical disagreement.

Two arguments can be provided against Sider's claims that (1) and (2) are fully analogous and that "it will be the case that some event *E* exists" does *not* amount to an existential commitment to *E*, because the quantifier is inside the scope of the tense operator.

First, (1) cannot be invoked to defend the legitimacy of denying ontological commitment to future existence in (2) since, despite the formal and semantical analogy, the case of the actualism/presentism dispute is *different* from the one that is our concern in this paper. While we know what it means for an actualist (or for the famous "person in the street") to claim that unicorns do not exist (or that they are simply logically possible entities), namely, that they are not spatiotemporally extended, we still lack a clear meaning for the claim that the future (the past) does not exist, except the "apocalyptic" interpretations rejected above. In a word, using the terminology introduced above, (1) has a contrast class that (2) lacks and this suffices to show that the two cases are to be treated differently: (1)'s existential commitment, unlike (2)'s, depends on a clearly describable metaphysical difference.

Second, if the meaning of $F((\exists x)(\mathrm{O}x)$ can be spelled out as "there will be a moment of time in which there are outposts on Mars", the commitment to the future instant is unavoidable.This claim seems to express the following intuition: the presentist still needs to refer to past (future) objects by claiming, for instance, that Newton lived in England and wrote the *Principia*, or that "Uncle Robert will ring the bell at noon". Frankly, I cannot see how one can use this tensed language in ordinary language without implying that Newton existed or the event in question will occur (it will be the case that it occurs). And even if we decided to change or revise the standard implications or implicatures of ordinary tensed language — by trying to argue that they do *not* imply what they seem to imply, namely, the tenseless existence of future and past events, that should therefore be accepted by "presentists" and "eternalists" alike — the argument that tenses are more natural and fundamental because more entrenched in our linguistic practice would boomerang against the presentist. This language, in fact, does entail commitment to at least some past and future events: "Newton wrote the *Principia*" as well as "Uncle Robert will ring within 10 minutes".

A second argument that Sider uses in order to show that $F(\exists x{:}Gx)$ (there will be an x such that Gx) is not existentially committing to future events is given by the fact that while two restricted "eternalist" quantifiers over future events commute, two iterated tensed operator do not, because they presuppose an evaluation point in time (Sider, 2004, p. 9). If we say that at some point in the future, there will exist an H and that at some moment after that there will exist a G such that ϕ – $F((\exists x{:}Hx)\ F(\exists y{:}Gy))\phi$ — we are clearly not claiming that at some point in the future, there will exist a G and that at some moment after that, there will exist an H such that ϕ – $F((\exists y{:}Gy)\ F(\exists x{:}Hx))\phi$. Suppose that $(\Sigma_F\ x{:}Gx)\phi$ stands for "Some future G is ϕ" and $(\Sigma_F x{:}Hx)\phi$ stands for "Some future H is ϕ", then $(\Sigma_F x : Gx)(\Sigma_F x : Hx)\phi$ is logically equivalent to its commutated expression $(\Sigma_F x : Hx)(\Sigma_F x : Gx)\phi$.

From the fact that the corresponding restricted tenseless quantifiers commute, Sider concludes that the tensed operator F and P, when they precede an existential quantifier, are not themselves quantifiers. However, from this argument one can only derive at best that the two symbolic expressions ($\Sigma_F x{:}Gx$) and $F(\exists x{:}Gx)$ have a different inferential content, and therefore a different use. But one can grant that without being forced to admit that $P\exists xQx$ or $F\exists xQx$ do not entail an existential commitment to past and future events!

I am not doing justice to the complexity of Sider's (2004) and I cannot do it here: what is completely obscure to me is why the translation of the formula $F((\exists x\ Gx)\ F(\exists x\ Hx))\phi$ — namely, "at some point in the future, there will exist an G and that at some moment after that, there will exist a H such that ϕ" — is *not* a quantified one, and does not commit the presentist to the existence of a future *G* and a future *H*. I must also add that I am in favor of the use of any technical resource (logic included) in order to argue in favor of a particular metaphysical thesis; however, a display of technicalities to show that "it was (will be) the case that there is (present tense) an eclipse" does not commit one to the past existence and the future existence of an eclipse seems to me wholly misguided.

I hope that it is clear from what I have written so far that I am not attacking the presentist and defending the eternalist's position. I am simply arguing that the presentist has no way to deny commitments to future (past) events, and that therefore, when the two senses of existence are carefully distinguished, her position cannot be distinguished meaningfully from the allegedly opposed one, the eternalist's.

Furthermore, it is important to stress that my conclusion does not depend in any way on the possibility that tensed and tenseless theorists of time have a genuine disagreement over the nature of the present, regarded as a mind-independent property by the former, and as a subjective element denoted by an indexical by the latter. Suppose "being present" is a mind-independent property of events: the presentist must still claim that some event *E will be* present if the world does not come to an end, and therefore that, in the tenseless sense of existence, *E* exists by being part of spacetime or by being occurring somewhere and somewhen after the present moment, while, of course, not existing now. There seems to be no way for the presentist to distinguish her position from the eternalist's insofar as the dispute is construed as involving the existence or reality or the unreality non-existence of the future (past).

By invoking Carnap's teaching, we could state the above in a single sentence: *the presentist/eternalist debate originates from an illicit transformation of a pragmatic difference into an ontological gap*. Therefore, we should say that sometimes we rely on the tensed sense of existence, and then we take a perspectival attitude toward it; at other times, for different, mostly scientific purposes, we rely on a tenseless sense of existence and we look at reality from "nowhen", by counting as (tenselessly) existent any past, or present or future event. This pragmatic attitude is also essential in showing the compatibility between Minkowski spacetime and the theory of becoming mentioned above and briefly developed in the following section.

7. Consequences for the philosophy of time and the ontology of Minkowski spacetime

If my skeptical conclusions on the presentist/eternalist debate are correct, various noteworthy consequences on the philosophy of time must be drawn. The most obvious one is that if the debate between presentists and eternalists is not genuine, the various attempts to use the theory of relativity and in particular the features of Minkowski spacetime to vindicate one position (eternalism) over the other become completely otiose. Likewise, those attempts at modifying the theory of relativity to make it compatible with presentism (through the addition of a privileged frame, of a now, and so on) must suffer the same fate[16].

In particular, granting that the previous sections have offered a correct diagnosis of the status of the presentist/eternalist debate, our understanding of becoming must also undergo a radical change. For instance, despite their disagreement about how to interpret Minkowski spacetime, Putnam (1967) and Stein (1991) seemed to agree that the problem of making room for objective becoming in Minkowski spacetime was linked to the possibility of having an indefinite or unreal future. So, even though Putnam claimed that the future of any event *e* of Minkowski spacetime had to be regarded as ‘‘wholly real’’, while Stein argued that *if* there is becoming, then for any event *e* in Minkowski spacetime there are at least some other events that count as ‘‘indefinite’’ relative to *e*, *they shared the wrongheaded view that the true divide between the friends and the foes of becoming concerned the ontological status of future events*[17].

However, we have seen that there cannot be any genuine disagreement about this point. Consequently, becoming is not to be understood as the becoming real or determinate in the present of previously unreal events: if there is becoming, it is crucial to acknowledge that *the asymmetry it imposes on the structure of time both in Stein as well as in Clifton and Hogarth's theorems cannot be interpreted as ontological, as that between the real and the unreal, but simply physical or structural*, in strict connection with the various asymmetries constituting the arrow of time (Horwich, 1987). Since this view of becoming has been fully developed in another paper of mine (Dorato, 2006), here I will have to content myself with very sketchy remarks, while referring the reader to Tim Maudlin (2002), who defends the same view in a different context[18].

[16]See Rakic (1997).

[17]To be fair with Stein, he did not defend becoming, but simply its compatibility with Minkowski spacetime.

[18]For a recent survey on the arrow of time, see Albert (2001).

The reason for connecting becoming with the issue of the arrow of time lies in the conclusions of the only two theorems available in the literature: not by chance, the two possible candidates for a becoming relation definable in terms of the structure of Minkowski spacetime, *past timelike connectibility* and *past causal connectibility* (Clifton & Hogarth, 1995) are *asymmetric*, the asymmetry being inherited from the causal relation or the temporal precedence relation. Clearly, if the asymmetry of becoming is not of an ontic type for the reasons given above, the same arguments will apply also to the asymmetry of causation and temporal precedence. But since the last two relations *are* asymmetric, and their asymmetry cannot have an ontic nature, it must concern the issue of the arrow of time, namely, the explanation of the origin and nature of temporally asymmetric or irreversible phenomena *in* time (Horwich, 1987). And the asymmetry of becoming — the fact that, given the big bang and the big crunch, it is an objective fact of the matter which of the two ways "time goes", i.e. which way the succession of events goes, from the Big Bang to the Big Crunch or just the opposite, relative to a cosmic time function — might play an important role in explaining the other asymmetries in time, physical or not[19].

It could be objected that we have not yet considered all the possible ontological theories about time, since what we could refer to as "the empty view of the future" — namely, the view according to which the past is real, while the future is not[20] — could provide a serious alternative between presentism and eternalism. The empty-view theorist, however, can at best give epistemic or pragmatic reasons to claim that the past is real while the future is not (we have traces of the past and not of the future, we act for the sake of the future and not of the past, we know more about the past than about the future, etc.), but if her view has to be read ontologically, as it is in her intentions, then it is hard to offer reasons against a commitment to the simple claim that *something in the future will occur*. We can simply run through the same arguments presented before. If so, then the empty-view theorist (sometime called "possibilist") will accept the tenseless sense of existence on the basis of which an event is real if it will exist, exists now or has existed. Excluding that the event in question is present or past, and assuming that it will exist, then it exists tenselessly on the basis of Def_2 and is therefore real in the tenseless sense also for the empty-view theorist, as it is for the presentist and for the eternalist.

[19]The *physical* asymmetries are linked to the growth of entropy in the vast majority of closed systems, to the prevalence of retarded rather than advanced radiation, and to the violation of parity and charge conjugation in weak interactions, while the philosophical asymmetries are linked to the knowledge, action, counterfactual, and causal asymmetries.

[20]For this view, see Dorato (1995) and Tooley (1997).

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Chapter 6

Presentism and Eternalism in Perspective

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> [H]ere … the assertions, which are set in opposition to one another, through mere misunderstanding, can both be true.
> (Kant, *Prolegomena to Any Future Metaphysics*, §53)

Logicians have frequently dwelt upon the equivocation of 'is' as between the "is of identity" on the one hand, and the "is of predication" on the other. The temporal equivocation of 'is' has, however, been little heeded. Yet it is quite clear that there are several very distinct possibilities:

(i) The "atemporal *is*" that means "is *timelessly*." ("Three *is* a prime number.")
(ii) The "*is* of the present" that means "is *now*." ("The sun *is* setting.")
(iii) The "omnitemporal *is*" that means "is *always*." ("Copper *is* a conductor of electricity.")
(iv) The "transtemporal *is*" that means "is *in the present period*." ("The earth *is* a planet of the sun.")

So begins a paper by Nicholas Rescher, "On the Logic of Chronological Propositions," that appeared in *Mind* in 1966. I will assume with Rescher that 'is' (and other verbs as well, including the verb 'exists'), is temporally equivocal in much the way he sketches, although Rescher's sense (iv) will play no role in the considerations to follow. I will argue that the temporal equivocation of 'is' (and other verbs as well, including the verb 'exists'), has not been sufficiently heeded to this day by showing in Sections 1 and 2 that current attempts to define the supposed opposition between two positions in the ontology of time, presentism, and eternalism, fail primarily because they do not take proper account of this equivocation[1]. In Section 2, I will show how these two views *can* be formulated, but they will not be contradictory. Both would be true provided space-time structure is what classical physics and common sense take it to be.

Before turning to the main discussion, it will be useful to clarify a few preliminary matters. First, another 'is' distinct from those above should be distinguished, the *detensed* 'is'. To say that x is (detensed) Φ is to say that either x was Φ or x is Φ or x will be Φ, where the verb in each disjunct is tensed. Generally, for any verb V, to say that x Vs (detensed) is to say that either x has Vd or x is Ving or that x will V. I call this a *detensed* verb since there is no contrasting past or future tense of this verb[2].

Second, in contexts where it is necessary or helpful to disambiguate, I will use bold face type and indicate tensed verbs by writing them in lower case, detensed verbs by capitalizing the first letter, and atemporal (or tenseless) verbs by writing them entirely in capital letters.

Finally, one should note that in the context of the presentism/eternalism debate, expressions like 'x is real' and 'x exists' tend to be used interchangeably, even if they diverge in other contexts[3].

1. Presentism or eternalism?

In the contemporary debate in philosophy of time it is typically supposed that there is some thesis that presentists affirm and that eternalists deny. For instance, Ted Sider says, "Presentism is the doctrine that only the present is real … . A presentist thinks that everything is present; more generally, that, necessarily, it is always true that everything is (then) present"[4]. Sider continues

[1]Others have also used this equivocation in related ways. Recently, at least Broad ("Ostensible Temporality," Chapter 35 of Volume II of Broad's *Examination of McTaggart's Philosophy*, first published by Cambridge University Press in 1938 and reprinted, with the same pagination, by Octagon Books in 1976.), Smart (Smart, J. J. C., *Philosophy and Scientific Realism* (New York: The Humanities Press, 1963)), Sellars ("Time and the World Order" in *Minnesota Studies in the Philosophy of Science*, Volume III, edited by Herbert Feigl and Grover Maxwell (University of Minnesota Press, 1962), Section 3), Quine (*Word and Object* (The MIT Press, 1960), p. 170), Dorato (*Time and Reality: Spacetime Physics and the Objectivity of Temporal Becoming* (CLUEB, 1995), Section 6.1), and Mellor (*Real Time II* (Routledge, 1998), Chapter 7) have employed a tensed/tenseless verb distinction in discussions of time.

[2]One might also reasonably consider this verb tensed because it is a disjunction of tensed verbs. This is the view of E. J. Lowe in "Tense and Persistence" in *Questions of Time and Tense*, edited by R. Le Poidevin (Oxford University Press, 1998). For a charming introduction to the complexity of tense as seen by a linguist, see David Crystal's "Talking about Time" in *Time*, edited by Katinka Ridderbos (Cambridge University Press, 2002).

[3]One might even think there is a distinct 'is' of existence in this neighborhood, though it is not often encountered.

[4]"Presentism and Ontological Commitment", *The Journal of Philosophy* **96** (1999): 325–326.

by pointing out that presentism is opposed to eternalism:

> *Presentism* is the temporal analogue of the modal doctrine of *actualism*, according to which everything is actual. The opposite view in the philosophy of modality is *possibilism*, according to which nonactual things exist; its temporal analogue is *eternalism*, according to which there *are* [emphasis added] such things as merely past and merely future entities.[5]

How is one to understand the verb 'are' in the clause defining eternalism? Is it Rescher's second sense, so that eternalists are supposed to hold that, say, Isaac Newton **is**, **exists**, or **is** real? Such a reading risks making one pole of the opposition, eternalism, false in light of the obvious facts and hence reducing the debate to triviality.

Isaac Newton was born in 1642 and so, in the manner of speaking usually employed in discussing the presentism/eternalism issue, came into existence then. He died in 1727, and so, in that same manner of speaking, he ceased to exist then. Newton (like Elvis) once **did**, but **does** not now, **exist**. It is possible to deny or doubt this fact. One might for one reason or another be a skeptic with respect to the past or a fallibilist with regard to historical claims, but I mention these views only to set them aside as not relevant to the alleged metaphysical dispute[6].

Granted these common facts about Newton's birth and death, then, if one reads eternalism as saying that Isaac Newton **exists**, then one reads it as an obviously false view. I'll take it as a working hypothesis that there is an interesting philosophical difference between presentism and eternalism and that a characterization of these views that makes one either obviously true or obviously false (i.e., either logically true or self-contradictory or true or false in light of such obvious facts as those about Newton indicated above) likely misses the philosophical point.

Suppose, we shift from the tensed to the detensed reading of 'are' in the quote from Sider and understand the last clause to say that eternalism is the view that there **Are** such things as merely past and merely future entities. If eternalism is supposed to affirm that there either **were** or **are** or **will be** (say) merely past entities (like Isaac Newton), then presentism is supposed to deny this claim,

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[5] *Ibid*., p. 326.

[6] A more sophisticated strategy is not to deny the common facts about Newton that I cited but rather to deny that they can be stated. If one believes that the proposition expressed by

(1) Isaac Newton was born in 1642

must contain Isaac Newton and that Isaac Newton does not exist, then one must believe that (1) expresses no proposition. All I can say in response to this view is that the conclusions follow from presentism and certain current views about language and propositions. Like a good Duhemian I can point out that one may retain presentism and the common sense view that (1) is literally true by bracketing the other claims about language and propositions. I aim in this paper to examine presentism and eternalism neat and not those views plus a philosophy of language.

rendering *it* (in light of the plain facts I cited above) obviously false. Again, we have not found a suitable way to express these views.

If we turn to Rescher's sense (i) and suppose that eternalism is the view that there **ARE** such things as merely past and merely future entities, matters become murky[7]. Perhaps, one should take the idea that this verb is timeless quite literally and suppose that entities **ARE** simply not in time at all. On this *narrow* or restrictive view of tenseless verbs it is meaningless (or ill-formed or perhaps at best false) to claim that there **ARE** (or **ARE** not) such things as merely past, present, or future entities because these narrowly construed tenseless verbs cannot have temporal entities as subjects. Tenseless verbs understood so narrowly seem singularly ill-adapted to express or distinguish metaphysical views like presentism and eternalism.

Suppose, then, that tenseless verbs apply to temporal as well as non-temporal entities. One might admit as meaningful or truth-valued sentences like 'Socrates **SITS** at t' or possibly even just 'Socrates **SITS'**, along with sentences like 'Three **IS** greater than two'. But how is one to understand these sentences? One suggestion I find useful is that we think of the tenseless verbs in such sentences as like ordinary tensed verbs but lacking all temporal information (just as ordinary verbs lack spatial information), while compatible or consistent with the addition of temporal information[8]. On this understanding of tenseless verbs, the claims 'Isaac Newton **EXISTS** in 1666' and 'Isaac Newton **EXISTS'** are well-formed[9].

This *broad* tenseless verb is *prima facie* distinct from the detensed verb, since the latter applies *only* to temporal entities. The broad tenseless verb in contrast supplies a univocal sense in which both I and the number three can be said to **EXIST**. It should also not be difficult to distinguish tenseless from tensed verbs. For instance, one might require that tenseless verbs be non-indexical with respect to time, to use a term introduced (as far I am aware) by Philip Percival[10]. What this requirement means is that the truth conditions of a token of a type sentence containing a tenseless verb do not depend on the token's temporal

[7]If there are only two senses or shades of the copula, the tensed and the detensed versions sketched above, then my negative thesis has just been established. Refusing to explore the possibilities for an additional tenseless sense would limit arbitrarily the tools one might use to try to fashion a traditional presentism/eternalism distinction.

[8]Following Mellor in *Real Time II*, Chapter 7, Section 3.

[9]Since verbs are placeless, we have no trouble in recognizing that although 'It is windy' is well-formed, we cannot assign it a truth-value until we know of what place it is being asserted. Similarly, if the verb is genuinely tenseless in the sense indicated, then in some cases, like 'Socrates **SITS**', we cannot assign it a truth-value until we know of what time it is being asserted. Mathematical propositions, on the other hand, do not need this temporal specification.

[10]In "A Presentist's Refutation of Mellor's McTaggart," which appeared in *Time, Reality, and Experience*, edited by Craig Callender (Cambridge University Press, 2002), p. 101.

location (in contrast to the truth conditions of tokens of sentences containing a tensed verb)[11]. This independence of temporal location is clear when the subjects or *relata* are not temporal entities; but, if the requirement is to be met generally, it must also hold for assertions concerning mere temporal entities as well, else we import covertly features of the tensed verb into a context from which they are overtly excluded.

What temporal entities can be said to **EXIST** in this new broad sense? One would think that a minimal commitment is that at least the things that **exist EXIST**, else this broad tenseless verb risks becoming empty[12]. To return to my running example, in 1666 one could have said truly 'Isaac Newton **EXISTS**' since in 1666 one could say truly 'Isaac Newton **exists**'. *If* the tenseless verb is non-indexical with respect to time[13], however, it must *now* be true to affirm

(2) Isaac Newton EXISTS,

although of course it is now false to claim

(3) Isaac Newton **exists**.

There may be much about tenseless verbs that is obscure, but it does seem clear that if the (broad) tenseless verb is as I have characterized it, there are interesting philosophical payoffs. First, presentists and eternalists as such cannot now differ with respect to the truth of (2) without differing about an obvious fact, since we have agreed that Isaac Newton was alive during his *annus mirabilis*, 1666. Furthermore, consider the following sentence as one on which presentism and eternalism might be supposed to differ:

(4) Everything that **EXISTS** exists.

As long as one can instantiate the quantifier in the universally quantified conditional (4) with Isaac Newton, then the truth of (2) and the falsity of (3) renders (4) false. Anyone, whether presentist or eternalist, who understands the tenseless verb in the way I have described and who allows instantiation of the

[11]In the language of David Kaplan's "Demonstratives" (in *Themes from Kaplan*, edited by J. Almog, J. Perry, and H. Wettstein (New York and Oxford, Oxford University Press, 1989)), tenseless verbs have a fixed character whereas tensed verbs (if, e.g., the present tense verb is thought of as having an implicit indexical 'now') have a context-sensitive character.

[12]Looking ahead to sentence (4), without this minimal commitment presentists would not be able to claim that all present entities **EXIST**, slimming their ontology to perhaps some proper subset of present entities.

[13]If the broad tenseless verb is *not* non-indexical with respect to time, then it is difficult to distinguish it from the ordinary (present) tensed verb.

universal quantifier with Newton must agree that (4) is false[14]. If one understands tenseless verbs in some other way that yields a different result, one is obliged to present, to describe in detail, this alternative[15].

We have now examined the three most promising ways of construing verbs without finding a satisfactory distinction between presentism and eternalism[16], but there seems to be more complexity to contemporary attempts to make the distinction than I have so far acknowledged. I will argue that this apparent additional complexity serves merely to camouflage rather than remedy the problems that I have just indicated. Formal language is introduced that directs one's attention away from the linguistic sleight-of-hand (or confusion) that occurs under its cover.

2. Quantifiers or tense operators?

In the metaphysics of modality there is, as Sider pointed out above, a distinction to be made between actualism and possibilism. Actualism is the view that "the only things that exist are objects that exist in the actual world"[17], whereas "realism about unactualized possibles [i.e. possibilism] is exactly the thesis that there are more things than actually exist"[18]. Since it is claimed that time is like modality[19], it is claimed that an analogous distinction can be made between presentism and eternalism.

[14]If one does not allow instantiation with respect to past or future objects like Newton but only with respect to (say) presently existing objects, then of course *both* eternalists and presentists will agree that (4) is true. Questions about the ranges of quantifiers will be addressed below.

[15]One ought to be able to say, for example, whether such a verb is non-indexical with respect to time and, if not, how it differs from the usual tensed verb.

[16]Recently, there seems to be a tendency in the literature to follow attempts to distinguish presentism from eternalism with arguments defending against claims of trivialization like those above. In addition to Sider's arguments, one might see footnote 3 in Ned Markosian's "A Defense of Presentism" in *Oxford Studies in Metaphysics*, Volume 1, edited by D. Zimmerman (Oxford University Press, 2004), footnote 1 in Matthew Davidson's response to Sider "Presentism and the Non-Present" *Philosophical Studies* **113** (2003): 77–92, and Section II of H. Scott Hestevold and William R. Carter's "On Presentism, Endurance, and Change" in *Canadian Journal of Philosophy* **32** (2002): 511–542. (I commented along the above lines on an earlier draft of Hestevold and Carter's paper at the Pacific Division meeting of the APA in Seattle, Washington in March of 2002.) And there are papers by Thomas Crisp and Peter Ludlow forthcoming in *Oxford Studies in Metaphysics*, Volume I, that look at the move to trivialize the presentism/eternalism issue in detail but in ways I do not find convincing.

[17]Michael Loux's introduction to *The Possible and the Actual* (Cornell University Press, 1979), p. 48.

[18]David Lewis in *Counterfactuals* (Basil Blackwell, 1973), p. 86.

[19]Section 3.7 of Markosian's "A Defense of Presentism" for an extended defense of this claim. For an argument that the analogy fails, see Ulrich Meyer's "The Presentist's Dilemma" in *Philosophical Studies* **122** (2005): 213–224.

The analogy between time and modality is a formal one. Temporal logics have been developed in which the operators and semantics are analogous to the operators and semantics of modal logics. The analogy has been fruitful, but formal analogies do have limits. The differential equation that governs the motion of a mass at the end of a vertical spring has exactly the same form as the equation that governs the variation in charge in a particular simple series electrical circuit[20]. This analogy too has been fruitful (in analog computing), yet mass is quite different from charge and each obeys different laws.

How is the formal similarity between presentism/eternalism and actualism/possibilism supposed to help in formulating a non-trivial presentism/eternalism distinction? Let me quote from footnote 1 of Matthew Davidson's paper, cited above:

> Presentism is to be understood in a manner analogous to the manner in which actualism is understood, where actualism is the view that necessarily, whatever there is exists actually. The universal quantifier in the statement of actualism is "loosed" so that it may range over possibilia. Similarly, with presentism, the universal quantifier in the statement of the view is "loosed" so that it may range over past and future objects. Both presentism and actualism employ unrestricted quantification in their definitions to avoid the trivially true/obviously false objection. Unfortunately, when this is pointed out to those who think presentism is either trivially true or obviously false, they tend not to understand the notion of unrestricted quantification.

Despite the widespread invocation of unrestricted quantification in this literature[21], there is good reason for doubting its utility in the present context. While it is easy to see that the notion of restricted quantification can be given a precise meaning (quantification over some set **D'** which is a proper subset of some given set **D**), if the set **D** is to capture the idea of unrestricted quantification, it should be the set that contains everything — everything, that is, that exists. But in what sense is 'exists' being used in the last sentence? One has choices, I have shown, but once a choice is made and **D** is specified unambiguously, the remaining questions are typically not philosophical questions[22]. Contra Davidson, my claim is not that the notion of unrestricted quantification cannot be understood, but that once it is understood — once it is specified

[20]The analogy is spelled out in Sections 3.7 and 3.8 of Boyce and DiPrima's *Elementary Differential Equations and Boundary Value Problems*, 4e (John Wiley and Sons, 1986).

[21]Here, for one, the second sentence of Markosian's "A Defense of Presentism": "According to Presentism, if we were to make an accurate list of all the things that exist — i.e., a list of all the things that our most unrestricted quantifiers range over — there would be not a single non-present object on the list."

[22]For instance, if the sense is '**exists**', then there may be a question whether or not ivory-billed woodpeckers **exist**, but that is not a philosophical question. It is true that in the tenseless sense, there are philosophical questions about what sets **EXIST**, but this is not the sort of question at issue here.

unambiguously — the standard way of trying to distinguish presentism from eternalism evaporates[23].

Since the 'exists' that occurs in the presentism/eternalism debates is connected (as noted above) to the notion 'is real', one should also bear in mind J. L. Austin's observation that

> … a definite sense attaches to the assertion that something is real, a real such-and-such, only in the light of a specific way in which it might be, or might have been *not* real … . This, of course, is why the attempt to find a characteristic common to all things that are or could be called 'real' is doomed to failure; the function of 'real' is not to contribute positively to the characterization of anything, but to exclude possible ways of being *not* real — and these ways are both numerous for particular kinds of things, and liable to be quite different for things of different kind.[24]

Austin does not think that 'exists' is in all contexts just like 'is real'. He writes, "'Exist', of course, is itself extremely tricky. The word is a verb, but it does not describe something that things do all the time, like breathing, only quieter — ticking over, as it were, in a metaphysical sort of way. It is only too easy to start wondering what, then, existing *is*"[25]. We need not emulate Austin by trying to uncover all the trickiness of 'exist'. What we need to see is that, as another dimension of this debate, 'exist' has a definite meaning only when it is (tacitly or overtly) contrasted with some way in which a thing (or event or whatever) may fail to exist — a thing may have existed formerly or be going to exist eventually or be merely possible or fictional or imaginary or … . When the contrast class is specified, then, I claim, there has not been exhibited an existence claim about which presentists and eternalists need disagree. You **exist** or are real, as opposed to Newton, because he once **existed** but does not now. Newton exists or (much better) is real, as opposed to Santa Claus (i.e., Newton **Exists** or **Is** real, as opposed to Santa Claus), because Santa Claus is imaginary. Ned Markosian thinks that Newton "is in the same boat as Santa Claus"[26], but I suggest that always indicating the proper contrast class will provide us with enough boats to allow them to sail separately.

To put the point of this argument another way: if the notion of "the real" (*simplicter*, one might say — the real as such and not as opposed to some way of

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[23]Sider (in his *Four-Dimensionalism* (Oxford University Press, 2001), pp. xvi and pp. 15–17 especially) *assumes* that the notion of an unrestricted quantifier is well-defined. Richard Cartwright ("Speaking of Everything" in *Noûs* **20** (1994): 1–20) vigorously defends the view that "any objects there are can simultaneously be the values of the variables of a first-order language." (This quote is from page 2 of that paper.) All involved in the presentist/eternalist debate should, however, bear in mind Cartwright's warning: "When we talk of the ontological commitments of a theory, we are in uncertain territory. It nonetheless seems clear that if it is said that such-and-such objects are the values of the variables of a first-order language, nothing — or next to nothing — is thereby implied as to the ontological commitments of theories expressible in the language" (p. 6).

[24]Austin, J. L., *Sense and Sensibilia* (Oxford, 1962), p. 70.

[25]*Sense and Sensibilia*, p. 68.

[26]"A Defense of Presentism", Section 3.7.

failing to be real) is ill-defined without specification of a contrast class, as Austin so persuasively argued, then so is the notion of a domain for "our most unrestricted quantifier" without some specification of its contrast class (some specification beyond, of course, the equally empty "the non-existent")[27]. And in fact the "loosed" quantifier of the presentist, as I understand Davidson's characterization of it above, ranges over what **Exists** but not over possibilia, abstract entities, or fictional entities.

It will be useful, though, to waive this general argument for a moment and see what can be done by way of another approach to understanding of "unrestricted quantification". As a first step, we can certainly understand quantification. Quantifiers are syntactic strings in formal languages that are, on the one hand, intended to be formal precizations of bits of English (or whatever natural language is at issue) but are also given meaning, given a semantics, when they are assigned some domain of objects **D** in which they are interpreted according to certain well-known rules for assigning truth values. But all precizations of natural language expressions come with *caveats*, as all who have taught logic know. The material conditional in classical propositional logic roughly corresponds to one use of 'If ... , then ... ' but not to others. So, similarly, for the existential quantifier and 'exist'[28].

How might we then understand "loosed" or unrestricted quantification? We can get some idea of the intended domain **D** for an unrestricted quantifier from David Lewis when he says:

> Our idioms of existential quantification may be used to range over everything without exception, or they may be tacitly restricted in various ways. In particular, they may be restricted to our own world and things in it.[29]

To what expression in English, then, does this unrestricted quantifier (more-or-less) correspond? To one either found or invented by Lewis:

> You might think that strictly speaking only this-worldly things *really* exist; and I am ready enough to agree; but on my view this 'strict' speaking is *restricted* speaking, on a par with saying that all the beer is in the fridge and ignoring most of all the beer there is. When we quantify over less than all there is, we leave out things that (unrestrictedly speaking) exist *simpliciter*.[30]

[27] In his paper forthcoming in *Oxford Studies in Metaphysics*, Volume I, Peter Ludlow argues from some linguistic principles for what he calls (NLQR) — [All] Natural Language Quantification is Restricted. I take Austin's argument to be an argument for (NLQR) as well.

[28] And so my remark that focusing on the existential quantifier tends to camouflage the fact that it is being related to an expression in English that has many shades of meanings. One can no more equivocate between the senses of 'exist' sketched above in interpreting the existential quantifier than one can use '$\supset$' for both material and counterfactual conditionals or 'v' for both inclusive and exclusive disjunction.

[29] *Counterfactuals*, p. 86.

[30] *On the Plurality of Worlds* (Basil Blackwell, 1986), p. 3.

Lewis' unrestricted quantifier is intended to include but not be restricted to our own world. Let me remind you of what he understands our world to be.

> The world we live in is a very inclusive thing. Every stick and every stone you have ever seen is part of it. And so are you and I. And so are the planet Earth, the solar system, the entire Milky Way, the remote galaxies we see through telescopes, and (if there are such things) all the bits of empty space between the stars and galaxies. There is nothing so far away from us as not to be part of our world. Anything at any distance at all is to be included. Likewise the world is inclusive in time. No long-gone ancient Romans, no long-gone pterodactyls, no long-gone primordial clouds of plasma are too far in the past, nor are the dead dark stars too far in the future to be part of this same world.[31]

If this term ('exists *simpliciter*') is invented by Lewis who is explaining how it is to be understood, then, I claim, it cannot be used to make a non-trivial distinction between presentism and eternalism. My point can be made most clearly by considering the arguments in a recent paper by Hestevold and Carter[32]. They begin their discussion of presentism with the standard general form of the allegedly characterizing sentence:

> P_1 Necessarily, if x exists, then x presently exists.[33]

They reject various readings of the first occurrence of 'exists' in P_1. In particular, they reject the detensed verb, which yields:

> P_4 Necessarily, if x presently exists, x did exist, or x will exist, then x presently exists.

They reject P_4 because (if I may substitute my own running example for theirs) Isaac Newton did exist but he does not presently exist. The detensed verb '**Exist**' ranges over our world (or at least the spatiotemporal part of it) and that range includes (at least, on page 496 of their paper) Newton.

On page 499 they offer their own supposedly non-trivial version of presentism:

> P_6 Necessarily, if x exists simpliciter, then x presently exists.

But according to Lewis, since everything in our world and in all other possible worlds exists *simpliciter*, P_6 should be understood as follows:

> P'_6 Necessarily, if x presently exists, x did exist, x will exist, or x possibly exists, then x presently exists.

If P_4 is trivially false, then it is hard to see how P_6 (i.e., P'_6) could not also be trivially false for (at least) the same reason. If '**Exists**' cannot do the job, then 'exists *simpliciter*' cannot do the job either.

[31] *Ibid.*, p. 1.

[32] H. Scott Hestevold and William R. Carter's "On Presentism, Endurance, and Change" in *Canadian Journal of Philosophy* **32** (2002): 511–542.

[33] I will use the same labels as they when citing labeled propositions from their paper.

I have been reading Lewis as if he were introducing a new technical term or unfamiliar locution ('exist simpliciter') and explaining to us how it is to be understood. Perhaps this reading is incorrect[34]. Perhaps we are expected to understand antecedently 'exists simpliciter' and Lewis is best understood as telling us what he thinks so exists, as presenting a theory of what so exists. If so, then I have at least tried to provide one way to understand 'exist simpliciter' with the broadly construed tenseless verb '**EXIST**' described above. If this suggestion is accepted, then Hestevold and Carter's P_6 and P'_6 are trivially false for the same reason that Proposition (4) above is false. If this suggestion is not accepted, then we are owed some explanation of the meaning of 'exist simpliciter' by those who think that it is (1) distinct from the present tense '**exist**', the detensed '**Exist**', and both the narrow and broad senses of the tenseless '**EXIST**' described above and (2) can be used to make a significant presentism/eternalism distinction.

There is one further line of argument that must be addressed, for it might seem to expose as naive the use that I've been making of the supposedly obvious facts about Isaac Newton. Consider a paragraph from Sider's paper that begins, "Where possibilists and eternalists speak with quantification, actualists and presentists make do with irreducible sentence operators"[35]. Perhaps, there are some subtle scope distinctions with tense operators that allow one to find an assertion affirmed by a presentist and denied by an eternalist (or vice versa). Indeed, that is just what Sider suggests.

Presentists, according to Sider, can acknowledge the obvious facts about Newton consistent with their view by using tense operators:

(5) $\underline{\text{was}}$ (there is an x such that $x =$ Newton).

Since the existential quantifier (So presentists speak with quantifiers too!) is within the scope of the tense operator, this sentence does not carry a commitment to the present existence of Newton. Of course, eternalists, like presentists, need not deny (5).

But in addition to (5) eternalists (and eternalists only, presumably) supposedly *can* say

(6) There is an x such that $\underline{\text{was}}$ ($x =$ Newton).

This sentence does carry a commitment to the present existence of Newton, and so presentists must deny it. Or must they? Which 'is', exactly, is supposed to be used in the initial existential quantifier in (6)? If the 'is' is present tense, certainly presentists will deny it, but then I see *no reason* why eternalists should

[34] As Michael Nelson pointed out to me.

[35] "Presentism and Ontological Commitment", p. 326.

affirm (6) understood in this way, despite Sider's claim. There need be nothing existing now that was identical to Newton. If you concoct some mereological tale in which (e.g.) presently existing but scattered atoms of Newton's body can be said to have been Newton, then you have imagined a situation in which presentists would be constrained to join eternalists in affirming (6).

If the 'is' in (6) is the detensed verb, then eternalists should certainly affirm (6), but so should presentists. If the 'is' is '**IS**', then the verb in the quantifier is non-indexical with respect to time whereas the tense operator within its scope must form sentences whose truth value is responsive to their temporal location. It does not seem possible to provide a coherent interpretation for such a sentence, so eternalists and presentists alike should pronounce (6) so understood ill-formed.

I believe that we have now exhausted the possibilities for making the presentism/eternalism distinction in the usual way, though superficially different variations on these basic themes may well turn up. One might then conclude that the issue is an empty one, but I shall not. What I shall do is look at the distinction in a new and (I hope) illuminating way[36].

3. Presentism and eternalism

After these negative arguments, I would like to take two positive steps toward re-defining the presentism/eternalism debate. The first stems from the observation that those who defend presentism rarely, if ever, indicate what they take the present to be, aside from sometimes indicating that they intend the temporal rather than the spatial present. It is, of course, obvious what the present consists in *if* one assumes as background space-time structure that which is implicit in common sense or classical physics — say Galilean space-time, **G**[37]. The present is a particular set of simultaneous events in **G**, the ones occurring now[38].

[36]In addition to the paper by Ulrich Meyer cited above in footnote 19, I have recently discovered a third paper arguing at length for the triviality of the usual way of construing the presentism/eternalism debate, Lawrence Lombard's "Time for a Change: A Polemic Against the Presentism/Eternalism Debate" forthcoming in J. Keim Campbell, M. O'Rourke, and H. Silverstein (Eds.), *Time and Identity: Topics in Contemporary Philosophy*, Volume 6, (Cambridge, MA: The MIT Press). Neither of these admirable papers proposes a positive reconstruction of the debate along the lines to be indicated in Section 3.

[37]As described in Chapter 3 of Robert Geroch's *General Relativity from A to B* (The University of Chicago Press, 1978). The structure is often called *neo-Newtonian space-time*.

[38]Sider offers an assumption that entails that there can be no such set as **G**. He writes "I am assuming that the presentist assumes that it is always the case that sets exist only if their members do" (*op. cit.*, p. 327). I know of no presentist who explicitly makes this assumption and see no reason why presentists need to treat abstracta this way as opposed to regarding them as atemporal or sempiternal. (A computer cannot be in a room when it does not exist. Is it also the case that it cannot be in a set when it does not exist?)

At this point philosophers divide into two camps. One camp is willing to follow modern physics in thinking that, no matter what we do not know yet about space-time, we have abundant evidence that the space-time of our universe is not Galilean space-time. Such philosophers are deprived of a notion of observer-independent simultaneity and hence the familiar presence of common sense.

Philosophers in the second camp resort one way or another to an instrumentalist interpretation of relativistic space-time theories. I can only note here the sprawling debate concerning instrumentalism and realism in scientific theories and indicate my partiality to the realist side. I prefer to derive metaphysical insights from our most well-confirmed theories rather than import them into. The constructive point I hope to get across, though, is that from a realist perspective it becomes clear that one has to state what eternalism and presentism are *relative to some background space-time theory*. If a proper presentism/eternalism distinction has eluded formulation, perhaps a partial explanation of why this is so lies in the fact that those engaged in the debate have typically left out of consideration one term in a relational notion.

As a step toward my second point, let me try to state presentism and eternalism assuming provisionally Galilean space-time as background space-time structure[39]. An adequate characterization of presentism in classical space-time structures might go as follows, where the events *e* are taken to be instantaneous events.

CP1 Spacetime is a set of events, G, having the structure of Galilean spacetime.
CP2 In particular, Galilean spacetime can be foliated uniquely into hyperplanes of simultaneity, which are equivalence classes of simultaneous events.
CP3 The present for an event *e* is the hyperplane of simultaneity that contains *e*.
CP4 Hyperplanes of simultaneity occur successively.[40]
CP5 An event e **exists** iff it **occurs**.

Eternalists would replace CP5 with

CE5 An event *e* **Exists** iff $e \in G$.[41]

[39]Ultimately this assumption must be abandoned in light of the evidence supporting the special and general theories of relativity. Ultimately then, classical presentism and classical eternalism, insofar as *both* are committed to CP1–CP4, must also be abandoned. What analogous or successor metaphysical positions can be defined in, say, Minkowski space-time is a question for another paper, but my views are congruent with ideas expressed in the papers of Richard Arthur and Dennis Dieks in this volume.

[40]Note that CP4 is not, strictly speaking, necessary for the characterization of presentism. It describes the passage of time and presupposes an oriented manifold.

[41]Characterizing eternalism coherently is at least as difficult as characterizing presentism. Frequently, eternalists are said to hold a static view of time in which events "timelessly coexist" (as in Barry Dainton's text *Time and Space* (McGill, Queen's University Press, 2001), Chapter 1). This latter expression inevitably carries the spurious implication that all real (point) events are simultaneous. I hope that CE5 finesses at least that problem. Mauro Dorato points out some other possible misunderstandings in Chapter 6 of *Time and Reality: Spacetime Physics and the Objectivity of Temporal Becoming* (CLUEB, 1995).

If the distinction between (classical) presentism and eternalism comes to the difference between CP5 and CE5, then the two views are compatible. One should not hastily conclude, however, that alleged difference between these venerable positions has been shown to be *merely* verbal. The difference between CP5 and CE5 reflects a difference in perspective as well as a difference in language. Presentists adopt a point of view that is close to temporal experience, confronting the actually occurring, as opposed to merely past or future, events. Eternalists consider the totality of actual, as opposed to merely possible or otherwise non-historical, events. The latter perspective seems necessary for physics, for the determination of the geometric structure of space-time. The former perspective is, as it were, that of those living inside the structure contemplated by the latter from "outside". Michael Dummett beautifully captures this contrast, though in another context[42]:

> What the [eternalist] would like to do is to stand in thought outside the whole temporal process and describe the world from a point which has no temporal perspective at all, but surveys all temporal positions at a single glance: from this standpoint — the standpoint of the description which the [eternalist] wants to give — the different points of time have a relation of temporal precedence between themselves[43], but no temporal relation to the standpoint of the description — i.e., they are not being considered as past, as present or as future. The [presentist] takes more seriously the fact that we are immersed in time: being so immersed, we cannot frame any description of the world as it would appear to one who was not in time, but we can only describe it as it is, i.e., as it is now.[44]

Each perspective is compelling, unless it errs by thinking that it is the only point of view worth taking. But since these perspectives are formally compatible, one might be tempted to wonder whether there is a way to have both. I believe the answer is *yes*, but I am not able to give a complete account of the reconciliation. What I can do is point out that such reconciliation might be viewed as a chapter in one or another of the naturalistic metaphysical programs of our time. One could view this reconciliation, for instance, as part of Wilfrid Sellars' attempt to fuse what he calls the manifest and the scientific images into one truly textured image, as one fuses two similar but distinct images into an image with depth in a stereoscopic viewer[45]. Or one might see it as a step toward what Abner Shimony calls *closing the circle*.

[42]In order to adapt the extract from Dummett to the present context, I have substituted 'eternalist' for 'realist' and 'presentist' for 'anti-realist'.

[43]My note. Once one abandons classical space-time structure, then it is *not* true that every pair of distinct "points of time" stand in a relation of temporal precedence. In Minkowski space-time, there are pairs that stand in such a relation only relative to a choice of inertial frame.

[44]From p. 369 of Dummett's "The Reality of the Past" as reprinted in *Truth and Other Enigmas* (Harvard University Press, 1978). The paper first appeared in the *Proceedings of the Aristotelian Society*, n.s., Volume LXIX, London, 1969, pp. 239–258.

[45]See his "Philosophy and the Scientific Image of Man" in *Science, Perception, and Reality* (The Humanities Press, 1963), pp. 1–40.

> The program [of closing the circle] envisages the identification of the knowing subject (or more generally, the experiencing subject) with a natural system that interacts with other natural systems. In other words, the program regards the first person and an appropriate third person as the same entity. From the subjective standpoint the knowing subject is at the center of the cognitive universe, and from the objective standpoint, it is an unimportant system in a corner of the universe.[46]

I believe that philosophy of time should aim at a coherent naturalistic picture of the experiencing subject with its felt time in an experienced universe with its spatiotemporal structure. If this view is correct, then the victory of either side in the dialectic described in Section 1 of this paper will result in a one-sided and shallow account of time.

This view is not unprecedented. J. Robert Oppenheimer wrote, "These two ways of thinking, the way of time and history and the way of eternity and of timelessness, are both part of man's effort to comprehend the world in which he lives. Neither is comprehended in the other nor reducible to it"[47]. Oppenheimer's view was motivated by the phenomenon of "complementarity" in quantum mechanics, the impossibility of simultaneous measurement of certain pairs of observables in one experimental set-up, whereas my view is motivated by considering the peculiarities of time and the sorts of naturalism mentioned in the previous paragraphs. So there is at least a difference of source and aim, if not content, here.

General differences, like those between those who think that presentism and eternalism contradict rather than complement each other, won't be settled by crisp arguments but by exhibiting the advantages of one's views. I'd like to end then by showing how the dual perspective I favor can deal with two important arguments. The first is Michael Dummett's version of McTaggart's "proof" that time is unreal[48]. Dummett, after examining some of the more usual ways of construing McTaggart, supposes that McTaggart's argument shows that "reality must be something of which there exists in principle a complete description" (p. 503). If reality is temporal, then Dummett takes McTaggart to require (a) that complete descriptions of reality are temporally neutral or remain the same through time, but yet (b) that complete descriptions of reality must contain temporally token-reflexive sentences like "The event M **is** happening"[49].

[46]In p. 40 of "Reality, Causality, and Closing the Circle" in Abner Shimony, *Search for a Naturalistic World View*, Volume I (Cambridge University Press, 1993).

[47]*Science and the Common Understanding* (Simon & Schuster, New York; 1953, 1954), p. 69.

[48]"A Defense of McTaggart's Proof of the Unreality of Time" *The Philosophical Review* **69**(4) (October, 1960): 497–504.

[49]While Dummett does not explicitly state (a), he objects to the existence of a complete description of reality by pointing out that, if it is temporal, "There would be one, as it were, maximal description of reality in which the statement 'The event M is happening' figured, others which contained the statement 'The event M happened,' and yet others which contained 'The event M is going to happen'." Some principle in the neighborhood of (a) must underlie this remark in order for it to be an objection to the existence of a complete description of reality.

But (a) and (b) on the face of it make contradictory demands on the notion of a complete description of reality. The requirement that a complete description of space contain the token-reflexive sentence "Object M is here" is not compelling, yet it is the dual for space of the demand that Dummett's McTaggart makes for time. It is my hypothesis that this (unreasonable) demand is made because it appeared that, short of this kind of complete description, one was forced to choose between the partial descriptions of the Eternalist, which leaves out such facts as "Event M is happening now," and that of the Presentist, which seems to leave out all the other facts about events not simultaneous with M[50]. If, as I have argued, these two perspectives are not opposed but complementary, then one can conjure a description of a temporal reality from a fusion of the two views that is consistent and not obviously incomplete.

My second example, an appealing and powerful argument presented by Craig Callender, criticizing what he calls "hybrid views" of time. He wrote:

> Hybrid views acknowledge that the world may be thought of as an existent four-dimensional entity, like B-theorists, but retain the idea that there is something special about present times, like A-theorists. Because hybrid theories accept that a four-manifold is the arena of world history, they cannot — on pain of coherency — analyze becoming in terms of the coming into existence of events. It simply doesn't make sense to say an existent event comes into being.[51]

The sort of presentist I have invoked above does believe that, since an event's existence is its occurrence, an event comes into being when it **occurs**. But if the existence of an event for an eternalist is simply its being in G, then an implication of my contrast between eternalism and presentism is that it is perfectly coherent for an Existent (in the eternalist sense as a member of G) event to come into being in the presentist sense (that is, to occur at its allotted instant).

If hybrid (or synthetic or fusion) theories manage in this way to be coherent, then, I suggest, they may be just what is needed in philosophy of time. If such theories can draw upon both the internal and external perspectives, they have the resources needed to tackle two fundamental questions of philosophy of time — the (external) question as to the nature or structure of space-time itself and the (internal) question as to how, in such a structure, one can account for the experience of creatures like us. More, like a theory of quantum gravity or an account of our perceptual or cognitive processes and resources, may be required for complete answers to these questions, but we cannot make do with less.

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[50]Relativistic complications will have to be dealt with eventually, but need not be in the context of this argument.

[51]p. S590 of "Shedding Light on Time," Callender's contribution to the symposium "Prospects for Presentism in Spacetime Theories" in *Philosophy of Science*, Supplement to Vol. 67, No. 3 (2000).

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Chapter 7

Minkowski Spacetime and the Dimensions of the Present

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Abstract

In Minkowski spacetime, because of the relativity of simultaneity to the inertial frame chosen, there is no unique world-at-an-instant. Thus the classical view that there is a unique set of events existing now in a three-dimensional space cannot be sustained. The two solutions most often advanced are (i) that the four-dimensional structure of events and processes is alone real, and that becoming present is not an objective part of reality; and (ii) that present existence is not an absolute notion, but is relative to inertial frame; the world-at-an-instant is a three-dimensional, but relative, reality. According to a third view, advanced by Robb, Čapek and Stein, (iii) what is present at a given spacetime point is, strictly speaking, constituted by that point alone. I argue here against the first of these views that the four-dimensional universe cannot be said to exist now, already, or indeed at any time at all; so that talk of its existence or reality as if that precludes the existence or reality of the present is a non-sequitur. The second view assumes that in relativistic physics, time lapse is measured by the time co-ordinate function; against this I maintain that it is in fact measured by the proper time, as I argue by reference to the Twin Paradox. The third view, although formally correct, is tarnished by its unrealistic assumption of point-events. This makes it susceptible to paradox, and also sets it at variance with our normal intuitions of the present. I argue that a defensible concept of the present is nonetheless obtainable when account is taken of the non-instantaneity of events, including that of conscious awareness, as (iv) that region of spacetime comprised between the forward light cone of the beginning of a small interval of proper time τ (e.g. that during which conscious experience is laid down) and the backward light cone of the end of that

interval. This gives a serviceable notion of what is present to a given event of short duration, as well as saving our intuition of the "reality" or robustness of present events.

1. The problem of the present

In classical physics, the world-at-an-instant was assumed to be a well-defined concept. Each such instantaneous world was thought to exist in three spatial dimensions, so that when threaded together along the time dimension they constituted (at least in the conception of H. G. Wells, building on ideas of Hinton and Newcomb[1]) a unique four-dimensional structure, absolute space-time. But in the Minkowski spacetime of Einsteinian Special Relativity, because of the relativity of simultaneity to the inertial frame chosen, there is no unique world-at-an-instant. Thus the classical view that there is a present, in the sense of a unique set of events existing now in a three-dimensional space, cannot be sustained. The two solutions to this difficulty most often promoted are

(i) the so-called "block universe" or "manifold" view, that the four-dimensional structure of events and processes is alone real, and that becoming present is not an objective part of reality: *the present is an illusion* (*or mere facet of subjective experience*); and

(ii) the "relativized present" view, that *present existence* is not an absolute notion, but *is relative to inertial frame*; the world-at-an-instant is a three-dimensional, but relative, reality.

According to a third view, the "punctual present" view, described by Robb, Čapek and Stein,

(iii) *what is present at a given spacetime point is* (strictly speaking) *constituted by that point alone*.

Against (i) I shall argue in Section 2 that the four-dimensional universe cannot be said to exist now, already, or indeed at any time at all, so that talk of its existence or reality as if that precludes the existence or reality of the present is a non sequitur. I then turn to an examination of (ii), the relativized present. I argue that this view, like Gödel's argument against the objectivity of time lapse, is vitiated by a misconception of the status of the time co-ordinate function in relativistic physics; this is illustrated by reference to the Twin Paradox, which demonstrates, so I argue, that time lapse is represented in relativistic physics by the proper time. This develops

[1] In his *Time Machine*, H. G. Wells (1895) alludes to Simon Newcomb's address on four-dimensional geometry to the New York Mathematical Society of 1893, published as Newcomb (1894), and elaborated on in Newcomb (1898, pp. 1–7). See Geduld (1987, pp. 32, 94, n. 14). But as Geduld points out (p. 93), Wells' conceptions are more indebted to those of Charles H. Hinton, "What is the Fourth Dimension?" in Hinton (1884–85).

the conception of becoming as taking place along a worldline and in proper time, sketched in Stein (1968) and Arthur (1982), and defended in elaborate detail by Clifton and Hogarth (1995). In Section 4 I argue that the punctual present view (iii), although formally correct, is tarnished by its unrealistic assumption of instantaneous or point-events, which makes it susceptible to paradox and sets it at variance with our normal intuitions of the present. Following a suggestion of Stein, I argue that a view more consistent with our experience of present events as ''at hand'' may be obtained by allowing for events extended in proper time, and once this is done a defensible conception of the present emerges:

(iv) the present of an object during an interval of its proper time π (e.g. that during which conscious experience is laid down) is that region of spacetime comprised within the forward light cone of the beginning of this (usually short) interval and within the backward light cone of the end of that interval.

2. The manifold, reality and becoming present

According to a view that has great currency among both philosophically inclined physicists and philosophers versed in physics, the present has no place in a scientific worldview. ''The universe'', writes Jack Smart, ''is a four-dimensional spacetime manifold. Present, past and future are all equally real'' (Smart, 1968, p. 255). Similarly, D. C. Williams writes in his classic paper, ''I believe that the universe consists, without residue, of the spread of events in spacetime … . The theory of the manifold is the very paradigm of philosophic understanding'' (Williams, 1951, pp. 132, 146). On this view, ''all events — past, present and future — are equally real'' (Davies, p. 260)[2]. That some events are occurring *now* means only that those events are occurring contemporaneously with the utterance of that observation[3]. But since it is equally true of any event that it is happening now at the time of its occurrence, this does nothing to mark out any one event from any other. Therefore, it is inferred, passage or becoming present is not a feature of objective reality.

There are two features of this argument on which I wish to concentrate: first, the sense in which it can truly be said that all events in the manifold are equally real; and second, once this sense is clarified, whether the inference to the unreality of the becoming of events can be sustained. I shall argue that it cannot, that the inference depends on a certain equivocation on the sense in which events can be said to exist.

[2]Cf. J. J. C. Smart (1968, p. 255): ''Present, past and future are all equally real''.

[3]''The term 'the present' is the conventional way of designating the cross-section of events which are simultaneous with the uttering of the phrase'' (D. C. Williams, in Westphal & Levenson, 1993, p. 137). ''When we say that an event … is present, we are saying that it is simultaneous with our utterance'' (J. J. C. Smart, 1968, p. 255).

Before I begin, however, I should first say something about the notion of "passage". When Smart, Williams and others object to becoming, one of their main targets is the notion of passage articulated by McTaggart (1908) in his work; and I believe they are correct to regard this notion of passage as indefensible. McTaggart (1908/1993), it will be remembered, supposed events to be laid out at certain positions in an antecedently given (absolute) time (p. 95), and demanded to know "What characteristics of an event are there which can change and yet leave the event the same event?" (p. 97). His answer is that only the A-determinations can change; that is, an event can only change in the sense that it begins by being a future event, becomes present and is then past (p. 97). Against this Williams and Smart objected that change is already built into the spacetime manifold, and that to suppose the manifold static and in need of motion is to commit a kind of paralogism. "There is passage", grants Williams (1951), "but it is nothing extra. It is the mere happening of things, their strung-along-ness in the manifold" (p. 137). This applies equally to H. G. Wells' conception of passage. According to Wells' Philosophical Inventor, "Our consciousnesses, which are immaterial and have no dimensions, are passing along the time-dimension with a uniform velocity from the cradle to the grave" (Wells in Geduld, 1987, pp. 33, 156). This conception is echoed by Hermann Weyl: "Only to the gaze of my consciousness, crawling upward along the life line of my body, does a section of this world come to life as a fleeting image in space which continuously changes in time"[4]. But such conceptions of a "moving present" are pure confusion. "There is clearly no room in the spacetime picture for movement through spacetime … . What would movement through time be? Change of time with respect to what?" (Smart, 1968, p. 256). Consequently, this notion of passage must be rejected.

But Smart, Williams and all those belonging to the category of "B-theorists", go further, and infer that temporal becoming should be abandoned altogether: events simply ARE, and do not need also to "become". Their argument, in a nutshell, is this: if we assume that the universe is a four-dimensional spacetime manifold and that this manifold is real, then the reality or existence of an event simply consists in its being contained in this manifold. It is therefore quite unnecessary to suppose that it also "becomes" or "becomes present"[5]. If an event already exists, it does not also need to come into being.

[4] Weyl (1949, p. 116). He had said almost exactly the same thing in his earlier *Mind and Nature* (Philadelphia, 1934), p. 76.

[5] An explicit version of this argument is given by Craig Callender, in the course of criticizing so called "hybrid theories": "Because [upholders of] hybrid theories accept that a four-manifold is the arena of world history, they cannot — on pain of incoherency — analyze becoming in terms of the coming into existence of events. It simply doesn't make sense to say an existent event comes into being" (quoted from Savitt, 2006, p. 126).

Here I think we need to be very careful about the slippery word "exists". There are many senses of the words "exists" and "is" that can be distinguished. For current purposes, the main ones to consider would appear to be these: (i) to exist atemporally, as in "3 is prime";[6] (ii) to exist at a given time or spacetime location; (iii) to exist at all times, or sempiternally; and (iv) to exist for a certain duration.

Now consider a point-event *a*. What does it mean to say that this event exists or is real? A straightforward answer would be this: an objectively existing event is whatever occurs at the place and time at which it is represented to occur, independently of anyone's subjective experience. This involves existence in sense (ii); for point-events, clearly, senses (iii) and (iv) do not apply. At any rate, concerning the claim that all events in a spacetime manifold exist or are equally real, we can say that this is so in sense (ii): each of them is represented as being real, in the sense of occurring at the particular location in the spacetime it occupies, independently of anyone experiencing it.

This will not, however, license an inference to the claim that all the events are *already* real. For such a claim makes an implicit reference to the time at which the event is being represented (by the word "represented" I mean "considered", "spoken of", "pictured in a spacetime diagram", etc. I am not using it in any obscure technical sense). That a future event is represented as existing obviously does not make it exist at the time it is being represented. This point is granted by both Smart and Williams. Says Williams of his "theory of the manifold", it "does not assert, therefore, that future things 'already' exist, or exist 'forever'" (p. 144); says Smart (1968), "Of course it could be misleading to say that according to the theory of relativity the future is 'already in existence'" (p. 226). Yet if there is no sense in which a given event "already" exists, it is hard to see the argument for the non-necessity of an event's becoming, which I summed up above in the words: "If an event already exists, it does not also need to come into being".

Nevertheless, according to Smart and Williams there is an appropriate sense in which an event exists, namely in its being contained in the four-dimensional manifold. It IS in the manifold, where I have put the "IS" in small capitals to denote that we are now using the atemporal "is", the "is" of sense (i) above. Thus if the manifold can be said to pre-exist in some sense, this will license an inference to the pre-existence of any of the events in it. But the conclusions we reached about the temporal existence of a singular event must apply *a fortiori* to

[6]I believe it can be seriously questioned whether the "is" in "3 is prime" is an "is" of existence. It appears rather to be an "is" of predication, which does not exist in a language like Swahili. But I am allowing it here on the principle of charity. It is usually referred to as connoting "tenseless existence", on which more below. Savitt (2006) also explores other possible meanings of "is", including the "detensed" "is", where "x Is Φ" means "x either was, is or will be Φ". See also Savitt (2002).

the four-dimensional manifold. If future events do not exist at the time they are being represented, then the whole spacetime manifold cannot be said to exist. The spacetime manifold cannot be thought of as a thing existing on a par with three-dimensional physical objects, which exist through time. To suppose that a four-dimensional object has this sort of existence is to commit a paralogism. But the paralogism does not reside merely in interpreting the word ‘‘exists’’ as ‘‘exists now’’, as is sometimes said — it runs deeper. The manifold not only can be said to exist now, *it does not exist at any time*[7]. Being four-dimensional, with time included as one of these dimensions, it simply does not have a temporal existence. This is why it is a mistake to talk of changing relations in the four-dimensional manifold, and equally a mistake to talk of the static view of spacetime. To quote Smart again: ‘‘And if there can be no change in spacetime, neither can there be any staying the same. As Schlick points out, it is an error to claim that the Minkowski world is static: it neither changes nor stays the same’’ (Smart, 1964, p. 13).

There is a valid sense, however, in which we want to say that the spacetime manifold exists over and above the events in it. To say that a spacetime manifold exists objectively is to say that the metrical, topological and ordering relations among the events ARE as depicted, where the word ‘‘ARE’’ is here being used atemporally, in sense (i) above[8]. It is the copula we use to assert facts, and is not to be confused with the ‘‘are’’ used to express duration in time. In the same way, if we say that event *a* IS before event *b*, we are stating a fact about their temporal relation. But it is a fallacy to speak of this relation as never changing or being ‘‘permanent’’, as does McTaggart[9], since these things can only be said of things existing in time. Neither point-events, nor temporal relations connecting them, nor four-dimensional objects like worldlines or indeed the whole of spacetime, can be said to exist through time (for a duration, or forever — senses (iii) and (iv) above), and only some events (a proper subset of those in the manifold) exist *at* any given time (sense (ii) above). One can grant that events EXIST in the sense of being contained in a manifold; but since a manifold can also only be said to EXIST in an atemporal sense (sense (i) above), we have not succeeded in identifying any sense of ‘‘exist’’ that will support the argument that since events already exist, they do not need also to become.

[7]Cf. the similar remark about time Leibniz made to Clarke: ‘‘Whatever exists of time and duration, being successive, perishes continually, and how can a thing exist eternally which (to speak exactly) does not exist at all?’’; Fifth Paper, §49; Westphal and Levenson (1993, p. 51).

[8]This formulation, it seems to me, is fully in keeping with what Nerlich wants to say about the reality of spacetime and spacetime structure (see Nerlich, 1994, 40ff.).

[9]‘‘If N is ever earlier than O and later than M, it will always be, and has always been, earlier than O and later than M, since the relations of earlier and later are permanent’’ J. M. E. McTaggart (1908, p. 96).

At this juncture an appeal is often made to a purported distinction between becoming present and the "tenseless occurrence" of events[10]. According to Adolf Grünbaum (1971), "Becoming is mind-dependent because it is not an attribute of physical events per se, but requires the occurrence of certain *conceptualized conscious experiences* of the occurrence of physical events" (p. 197). This seems to beg the question of the objectivity of becoming, since it is tantamount to *defining* the becoming of events as requiring a conscious mind. But Grünbaum and company equate this mind-dependent notion with "happening in the tensed sense", and contrast it with "occurring in the tenseless sense". The mind-dependence thesis, writes Grünbaum (1971), although it "does deny that physical events themselves happen in the tensed sense of coming into being apart from anyone's awareness of them", nevertheless "clearly avows that physical events do happen independently of any mind in the tenseless sense of merely occurring at later clock-times in the context of objective relations of earlier and later" (pp. 213–214).

Now, I submit that it is one thing to talk of verbs being used tenselessly, as when Grünbaum claims that "to assert tenselessly that an event exists (occurs) is to claim that there is a time or clock reading t with which it coincides" (p. 215). But it is quite another to claim that "events happen tenselessly", as Grünbaum alleges Minkowski to have asserted (p. 215). It seems to me that this whole notion of "tenseless occurrence" is a *contradictio in adjectivo*. An event occurs, happens or becomes exactly when it occurs, happens or becomes, independently of any minds or clocks. If we say an event OCCURS, using the verb "occurs" tenselessly, then this describes the way we have used the verb, not a variant kind of existence or occurrence. A tensed use of a verb gives implicit information about the time of utterance; a tenseless use does not. I therefore take the valid core of Grünbaum's intuition to consist in this: (i) events occur quite independently of coming into anyone's awareness of them; and (ii) one can represent an event as occurring at a certain location in the manifold without any implicit reference to the "now" at which the event is being represented. But this in no way validates a distinction between two types of occurrence of events, "tenseless occurrence" and "tensed occurrence". An event (*eventum*, the past participle of *evenire*, Latin for to come about or happen) is something that *has become*, both semantically and etymologically. An event cannot exist or occur without having become, since this would be to say that it could have become without having become, an evident self-contradiction. When we represent an event we therefore of necessity represent it as having become. Once we have represented all events

[10]This distinction perhaps has its origin, as Grünbaum suggests, in Bertrand Russell's (1915, p. 212) claim in his work, that "past, present and future arise from time-relations of subject and object, while earlier and later arise from time-relations of object and object". Quoted from Grünbaum (1971, pp. 215–216).

and all processes on a space-time diagram, we have represented all becoming, so it is unreasonable to look for something else to be superadded[11].

To sum up: the word ''exists'' can be used temporally in a sense appropriate to things existing at a time or through time. In this sense, all events can indeed be said to be equally real, i.e. as occurring (i.e. becoming) at the particular times or spatiotemporal locations they do independently of anyone's awareness. But the spacetime manifold itself does not exist in this temporal sense. The word ''exists'' or ''is'' can also be used atemporally, as when we say that ''event *a* IS before event *b*'', and events ''*a* and *b* ARE contained in the manifold''. But this atemporal ''is'' is inadequate to ground any notion of events *already existing*, which clearly requires a temporal sense of ''exists''. There is, therefore, no sense of ''exists'' which will support the argument that events do not need to come into existence since they (and the spatiotemporal relations among them) already exist in a four-dimensional manifold[12].

With this preface, let us look at some of the arguments from the relativity of simultaneity to the reality of all events in the manifold. That Einsteinian relativity rules out the idea of a unique, absolute present is easily seen: if the set of events that is simultaneous with a given event *e* depends upon the inertial reference frame chosen, and in fact is a completely different set of events (save for the given event *e*) for each choice of reference frame in inertial motion relative to the original, then there clearly is no such thing as *the* set of events happening at the same time as *e*. In the vivid example of Paul Davies, if I stand up and walk across my room, the events happening ''now'' on some planet in the Andromeda Galaxy are different by a whole year than those that would be happening ''now'' if I had stayed seated. (Davies, 1995, p. 70). This much is clear and uncontroversial. But from it Davies (1995) concludes: ''unless you are a solipsist, there is only one rational conclusion to draw from the relativity of simultaneity: events in the past and future have to be every bit as real as events in the present … . To accommodate everybody's nows, … events and moments have to exist all at once across a span of time'' (p. 71).

But this is by no means a rational conclusion to draw. Events ''exist all at once'' in a spacetime manifold only in the sense that one represents them all at

[11]Despite his championing of ''the theory of the manifold'' over the reality of becoming, D. C. Williams (1951, p. 464) makes essentially this point in his work; Westphal and Levenson (1993, p. 138) quotes: ''World history consists of actual concrete happenings in a temporal sequence; it is not necessary or possible that happening should happen to them all over again''.

[12]I take the view that if ''is'' or ''exists'' is being used atemporally, then it is a confusion to add a temporal qualification such as ''at time *t*'', a qualification which only makes sense for a temporal sense of ''exists''. Savitt (2006, p. 112) reports that this was the view of A. N. Prior regarding verbs used tenselessly, such as saying an event is to take place tomorrow: ''What place can a word like 'tomorrow' have in a strictly tenseless form?'' Savitt himself allows such temporal qualification of tenseless verbs.

once as belonging to the same manifold. But one precisely represents them as occurring at different times, or different spacetime locations, and if one did not, one would have denied temporal succession. The rational conclusion to draw, I submit, is that (according to Special Relativity) distant events that are simultaneous with some given event — for example, the event of my considering them — cannot be supposed to be "real" or "existent" for that event, e.g. existent for me at the spacetime location from which I am considering them.

More elaborate arguments along the same lines as Davies' had previously been given (in papers written independently at nearly the same time) by Putnam (1967) and Rietdijk (1966). Although the details of their arguments differ, both depend on a scenario that can be described as follows. We are asked to imagine two spatially distant inertial observers, O_1 and O_2, with one moving at an appreciable fraction of the speed of light with respect to the other. At a certain time according to the observer O_1's own inertial system, an event b that is happening to O_2 is "present" or "now" for O_1, and we may imagine O_1's being aware of this as the event a; but to O_2, the event happening to O_1 that is simultaneous with b in her inertial system is not the event a, but another event p. Yet it is easy to set the relative velocity in such a way that p is in the future for O_1 at the time that he is experiencing a. It follows that, if all those events are real which are present for a given observer in that observer's inertial system, then b is real for O_1 when he is experiencing a, and p is real for O_2 when she is experiencing b. Thus if xRy denotes "x is real for y" we have bRa and pRb, so that, if R is transitive, then pRa ("p is real for a") even though p is in the future for O_1 when he is experiencing a. We are forced to conclude, reasons Putnam, "that future things (events) are already real" (Putnam, 1967, p. 242), or as Rietdijk (1966) puts it, "that, being 'past' or 'present' for only one inertial system, an event can be shown to be determined in all other systems" (p. 342), so that "there is determinism" and "there is no free will" (p. 343).

Putnam, it should be said, acknowledges that simultaneity, although transitive within any given frame of reference, is not transitive between frames: "the relation 'x is simultaneous with y in the co-ordinate system of x' ... is not transitive" (pp. 242–243). So he does not claim that all events exist "at once" in the sense of being mutually simultaneous. Nevertheless, he argues, the assumption that "all things that exist now according to my co-ordinate system are real", in combination with the principle that "there are no privileged observers", requires the relation R to be transitive (p. 243). But if R is to be interpreted to mean that future events "already exist", as Putnam asserts, then this is to imply that they have, as of the earlier time, already occurred. A similar criticism applies to Rietdijk's conclusion: an event p can only be said to be "already 'past' for someone in our 'now'" (p. 341) at location a in the sense that it has already occurred at a. But such a claim amounts to a denial of temporal succession.

In each case, we are presented with an argument that begins with a premise that all events existing simultaneously with a given event exist or are real, and concludes that consequently all events in the manifold are real. But the conclusion only has the appearance of sustainability because of the equivocation analyzed above. If a point-event exists in the sense of occurring at the spacetime location at which it occurs, it cannot also have occurred earlier. But if the event only exists in the sense of EXISTING in the manifold, then the conclusion that it *already* exists earlier — that such a future event is "every bit as real as events in the present" (Davies), or "already real" (Putnam) — cannot be sustained. Thus, far from undermining the notion of becoming, their argument should be taken rather to undermine their starting premise that events simultaneous with another event are already real or already exist for it in a temporal sense. For to suppose that this is so, on the above analysis of their argument, inexorably leads to a conclusion that denies temporal succession.

3. The relativized present

Putnam and Rietdijk, of course, did not advance their arguments to support the case for idealism. In contrast, Kurt Gödel (1949) gives an argument whose intent is explicitly idealist: from the relativity of simultaneity he infers that the lapse of time is itself unreal. His argument runs as follows:

> Change becomes possible only through the lapse of time. The existence of an objective lapse of time, however, means (or at least is equivalent to the fact) that reality consists in an infinity of layers of "now" which come into existence successively. But, if simultaneity is something relative in the sense just explained, reality cannot be split up into such layers in an objectively determined way. Each observer has his own set of "nows", and none of these various systems of layers can claim the prerogative of representing the objective lapse of time. (pp. 557–558)

Here Gödel assumes that (i) objective time lapse must be construed in terms of the successive coming into existence of layers of "now", i.e. classes of simultaneous events; (ii) if time lapse is to be counted as objective, it must be invariant under change of inertial frame (although he expresses this in a needlessly subjectivist manner in terms of "each observer having his own set of 'nows'"). He then infers that, since (iii) the layers of now are not invariant; hence (iv) there is no objective time lapse in the sense he has defined it: the same event will be "real" or come into existence in one inertial system before or after it has come into existence in another.

Now I believe this to be a valid argument whose conclusion is self-contradictory. And, since I endorse the second premise about the frame invariance of time lapse, I believe it proves the first premise false. But many philosophers have not found this last statement self-contradictory, and are content to hold that the reality (in the sense of the coming-to-be) of an event is relative to the inertial frame selected. For instance, both Storrs McCall and Mario Bunge would endorse Gödel's first premise, construing objective time lapse in terms of the successive coming into existence of classes of simultaneous events[13]. But they would reject his equating of "objective" with "frame invariant" (premise (ii)), and therefore deny that there is anything contradictory about time lapse being relative to frame. They are thereby committed to the second of the construals of the present I detailed above: that present existence is not an absolute notion, but is relative to inertial frame; the world-at-an-instant is a three-dimensional, but relative, reality.

Gödel's first premise is, I believe, demonstrably false: it depends on a mistaken notion of time lapse in relativity theory. Since I have argued this at length elsewhere (2003), my exposition here will be correspondingly brief. Suppose, as does Gödel, that for each individual observer, "the existence of an objective lapse of time … is equivalent to the fact that reality consists in an infinity of layers of "now" which come into existence successively". That is, the time lapse between, for instance, two events in anyone's life history is given by the difference in the values of the time co-ordinate function in some particular inertial reference frame[14]. Now consider the classical "Twin Paradox", where one twin (H) stays at Home, stationary in his rest frame for 20 years, while his twin (A) speeds Away at six-tenths of the speed of light, turns around and then returns home at the same speed. Because of time dilation, twin A will find time running more slowly by a factor of $\gamma = (1-\beta^2)^{-1/2}$, where $v = \beta c$ and will therefore take only $\sqrt{(1-0.36)} = \sqrt{(0.64)} = 0.8$ times as long for each leg, and therefore 8 years for each. If we idealize for the sake of simplification, and treat the turnaround as instantaneous, when the twins meet again, twin H will be 20 years older, but twin A will have aged only 16 years. That is, the time lapse between

[13] In his, Mario Bunge (1967–68) defines time T as a mapping from the set of all ordered quadruples <event, event, physical reference frame, chronometric scale> onto the set of real numbers; see especially pp. 358, 359. Similarly but independently, Storrs McCall (1976) has defined time in terms of a mapping into "a set [T] of time co-ordinates (i.e. real numbers)" by a function h which, for each co-ordinate frame f which partitions the set U of spacetime points into simultaneity classes, "assigns each u of U a time" (1976, pp. 337–362, 356–357). More recently, McCall (1995, p. 158) has upheld this view "No frame-independent or hyperplane-independent pattern of illumination could possible represent temporal becoming … . Temporal becoming is frame-dependent". In his (2006) McCall argues that what the triangle inequality difference in lengths of the twins' paths "demonstrates is that elapsed time is not path-dependent, but frame-dependent" (p. 200).

[14] Rietdijk (1966), Putnam (1967) and Fitzgerald (1969) also assume that becoming must occur relative to a co-ordinate frame, with time lapse measured by the time co-ordinate function, as a premise in their reductio arguments against the reality of becoming [real or determinate]. For this reason I find Clifton and Hogarth's (1995) description of their (and Maxwell's) view as "a worldline dependent conception of becoming" (p. 356) very misleading. It is a frame-dependent view, as McCall rightly calls it.

parting and re-uniting will be 20 years for twin H, but only 16 years for twin A. Now, I shall not stop to explain how this apparent paradox is resolved, since this has been done many times elsewhere. But the point is that this time difference is a real effect; it is *not* an apparent effect, the result of there being something improper about A's timekeeping. The reality of the time dilation effect has been demonstrated, for example, by two scientists flying cesium clocks around the world on commercial jets.

But according to the construal of time lapse as relative to a particular inertial frame, this difference in time lapse for the two travelers is impossible! The time difference between the two events of parting and re-uniting reckoned according to H's rest frame is 20 years, and when they reunite the same time will have elapsed for both relative to this frame. If the time lapse is reckoned according to the rest frame of A on her outward journey, the difference would be 16 years: for 8 years she would have been stationary as twin H went off at $0.6c$ in the other direction, and then, instantaneously accelerated to a speed of almost $0.8c$ in the direction of twin H, she would have caught up with him 8 years later, and, again, the same time would have elapsed for both when they reunite. But *in neither frame could there be a difference in time lapse between the two events*, contrary to fact. The Gödelian view is unable to account for the fact that 20 years will have elapsed between parting and re-uniting for twin H, whereas only 16 will have elapsed for twin A, a fact that both will be able to verify perfectly objectively!

The mistake lies precisely in Gödel's construal of time lapse. If the quantity of time elapsed were measured by the time co-ordinate function in some given inertial reference frame, then, although this quantity would differ depending on what reference frame might be chosen (as in the above example), it could not differ for two processes — say, the life histories of two "observers" who happened to take different paths through spacetime. Since such histories are paradigm cases of processes for which time is elapsing, and yet a different time has elapsed for each, it follows that Gödel's first premise is wrong: co-ordinate time is not the correct measure of how much time has elapsed.

The reason, I believe, why this consequence has not been seen clearly by the defenders of the relativized present is that they assume that time lapse must be measured not by the time co-ordinate in some one inertial frame for the entire journey, but *by the time co-ordinate in the rest frame of each twin*. This is, for instance, how McCall defends the relativist view. Twin A, on this account, would reckon time elapsed by the time co-ordinate function t in her own rest frame on the outward leg, and then by the function t' in the different rest frame appropriate to the return leg. Since in this idealized case her journey is the sum of these two independent legs, and each leg is inertial, the time will be precisely as measured by her clock: 16 years.

But this is to adopt a different premise: we are no longer assuming that becoming takes place in some one inertial frame, but rather that *the frame must* *be selected and reselected in such a way that it is always the rest frame of the object under consideration*. Against this it must be objected that there is nothing in Special Relativity to dictate this privileged nature of the rest frame as being the only appropriate inertial frame. One is at liberty to choose any inertial frame to describe a given process: the centre-of-mass frame, the frame in which one or the other twin was initially at rest, etc.[15] Moreover, this solves the twin paradox by trading on an accidental feature of the above set-up, namely that each observer is in inertial motion at every point (excluding the singularity of the instantaneous acceleration). In a more realistic set-up, where one twin remained on a gently rotating reference frame while the other gradually accelerated then gradually decelerated on both legs, neither twin would have been at rest in an inertial frame at any instant of their journeys through time. Yet one could arrange this situation in such a way that there would be precisely the same difference in the readings on their clocks when they reunite on Earth. The clocks will measure time elapsed for each twin even though no part of their journeys is inertial.

The reason for this, in turn, is that the quantity of time elapsed for a given process (such as a clock keeping time) is measured by the *proper time*, a quantity that is calculated by taking the integral along the worldline of that process of the quantity

$$\tau = \int \mathrm{d}\tau, \quad \text{where} \quad \mathrm{d}\tau = \sqrt{(c^2\mathrm{d}t^2 - \mathrm{d}x^2 - \mathrm{d}y^2 - \mathrm{d}z^2)}/c$$

where x, y, z and t are the co-ordinates in some given inertial frame, and are considered as functions of the proper time τ.

The proper time so calculated is invariant to change of frame: it will come out the same no matter what inertial frame (with co-ordinate values x, y, z and t) is chosen. It therefore meets the criterion implicitly assumed by Gödel, namely that if time lapse is to be counted as objective, it must be invariant under change of inertial frame. Thus, the time taken for each twin to make the trip through spacetime from the point of A's departure to their eventual reunion is found by integrating the proper time along that twin's particular worldline, and this is so whether the line in question is piecewise straight, as in this case, or whether it is sometimes or even always curved. In the above case it comes out as 20 along H's straight worldline, and 16 along A's crooked one. (Because of the peculiar

[15]Suppose, for example, I throw a tennis ball very hard against a wall, and suppose the rebound instantaneous. What would be natural about describing this motion in the rest frame of the ball? Nothing physical would correspond to the fact that the "nows" of that frame do not completely cover my worldline as I watch it. It appears that this privileging of the rest frame is founded on a conception according to which each observer "inhabits an inertial frame" (namely her rest frame) (cf. McCall, 2006, p. 198). See Stein (1968), Myrvold (2003) and Arthur (2003) for a critique of such views.

metric of Minkowski spacetime, a straight line between two points connectible by a worldline is not the shortest but the *longest* interval between these two points). Proper time in general is not time according to the time co-ordinate in an inertial frame, or several such frames taken piecewise; it is calculated along the spacetime path, and is invariant to which reference frame is chosen to perform the calculation. As Kent Peacock (2006) has summarized this view, "The physiological difference between the twins is strictly a function of their elapsed proper times. Hence real physical changes are tied to *proper* time ... , not the time coordinate" (p. 255).

In sum, there is nothing in Special Relativity to impugn the reality of time, contrary to Gödel's intent. Instead, his argument now becomes a *reductio ad absurdum* against the construal of time lapse that is assumed in the account of becoming given by the proponents of the relativized present. To suppose that time lapse is given by the time co-ordinate function in some one reference frame is incompatible with there being a difference in time elapsed for the twins; to suppose that time lapse is calculated piecewise by adding inertial components of a journey is to ignore the fact that proper time is calculated by integrating along the path in any chosen inertial frame, and does not require that either twin perform inertial motion.

But this does not at all mean that temporal becoming is eliminated. Indeed becoming *is* represented on an Einstein–Minkowski diagram, since a process is nothing other than a sequence of events becoming, and in the Special Theory of Relativity every process is represented by a worldline[16]. That is, just as there is no invariant plane of simultaneity, there is no plane of becoming, no worldwide instant at which all simultaneous events come to be. But there is nevertheless a perfectly well-defined sequence of becoming along each and every worldline in spacetime. The proper time, calculated by integrating along such a worldline, is an invariant measure of time lapse. So construed, time lapse does not depend on reference frame, nor on the existence of inertial motions, nor on any considerations of what events are simultaneous with the experiences of an observer.

What is true, new and revolutionary is that these sequences of becoming do not match up: in Mauro Dorato's picturesque imagery, becoming on this view is like water flowing through "an uncorrelated, non-denumerable set of narrow creeks"[17]. This is how it is that twin A manages to travel 4 years into the future: twin H, and everything else at home, will be 20 years older, while twin A and

[16]Cf. Arthur (1982, p. 107): "... a proper time function [is] associated with each timelike line segment of spacetime (of a sufficiently smooth nature). It is this proper time which is understood to measure the rate of becoming for the possible process following this timelike line (or worldline)". Dieks (1988, p. 456): "Only time along worldlines (proper time) has an immediate and absolute significance as an ordering parameter of physical processes". See also Peacock (1992).

[17]Quoted by Barry Dainton (2001, p. 275) from Mauro Dorato, Time and Reality: Spacetime Physics and the Objectivity of Temporal Becoming (Bologna, CLUEB, 1995), p. 185.

everything with her will have aged only 16 years. In this sense, time will have passed more quickly for the stay-at-home twin H — contrary to Jack Smart's oft-repeated jibe at proponents of passage, it *does* make sense to talk of time passing more or less quickly. Yet when the twins are together again, despite the difference in their lifetimes, they will share the same present. But this cannot be the relativized present, for, by the above arguments, the objective lapse of time is *not* "equivalent to the fact that reality consists in an infinity of layers of 'now' which come into existence successively".

4. The punctual present

This brings me to the third of the construals of the present in relativity theory outlined in the introduction above. On this view, what is present at a given spacetime point is, strictly speaking, constituted by that point alone. This view was first articulated by Alfred A. Robb in 1911, writing within 6 years of Einstein's original 1905 paper, and only 3 years after Minkowski's[18]. Taking exception to Einstein's proposal that "events could be simultaneous for one observer but not simultaneous for another moving with respect to the first"[19], Robb "avoided any attempt to identify instants of time at different places"[20]. Instead, he concentrated on the "absolute relations" identified by Minkowski: one instant, or the event a happening at it, is *absolutely before* another, b, if a physical influence can be propagated from a to b[21]. As he showed in 1914, this means that — restricting temporal relations to these absolute ones only — a given event can be related to any in its future or past light cones, but cannot be so related to any event outside these cones (in what Minkowski called the "elsewhere"). Thus there is no linear time, because events do not occur in a serial order, but rather in a strict partial order, which Robb called a "conical order". As for simultaneity, Robb's theory had the immediate consequence that "*the only events which are really simultaneous are events which*

[18]Alfred Arthur Robb (1914); his work in 1936 is essentially a second edition of this book. Robb (1911) had previously published a draft of his theory in the short tract Optical Geometry of Motion, and later gave a simpler exposition without proofs of the theorems in his work in 1921.

[19]A. A. Robb (1936, p. 11); cf. (1921, p. v).

[20]This is Robb's description of his 1911 tract in 1914 (p. 3), in which he presents himself as opposing Einstein's relativism with an independent development of relativity theory deriving directly from the work of Larmor and Lorentz. I believe it is more accurate, though, to see Robb as deriving Einstein–Minkowski spacetime on the basis of the same absolute relations of before and after as delineated by Minkowski, defined in terms of the possibility of propagation of physical influence from one point to another. In this I follow John Winnie (1977).

[21]Robb (1914) tended to talk in terms of instants, rather than events, and even wrote of one's being "directly conscious" of them (p. 8). By "instant", therefore, I take him to mean an instantaneous event, a point-event, or what Broad (1938, p. 280) aptly called an "event-particle".

occur at the same place''. Thus ''*there is no identity of instants at different places at all*'', so that ''*the present instant, properly speaking, does not extend beyond here*''[22].

Robb's view was taken up by Milič Čapek (1966, 1975), and also by Howard Stein (1968) (although here without attribution to Robb) in their critiques of the arguments of Putnam and Rietdijk discussed above. ''Like Rietdijk'', objects Čapek (1975), ''Putnam retains the old notion of the universal present spread as a 'world-wide instant' across the whole universe, and uses this notion in order to conclude that, in a sense, *everything* is present'' (pp. 612–613). But this neglects ''the one essential idea of relativity that … 'Here-Now' can never be extrapolated to 'Everywhere-Now''' (p. 613). Similarly, Stein (1968) objected that ''in Einstein–Minkowski spacetime *an event's present is constituted by itself alone*'' (p. 15). Stein proceeds to object to the arbitrariness of Putnam's ''maintaining the implication 'present implies real''', suggesting we might as well insist on its converse, the presentist assumption that ''*only* things that exist now are real''. Then we would be ''led to conclude that *for any event, it and it alone, is real*'' (p. 18). Stein characterizes this position (resulting from combining the punctual present of relativity with presentism) as ''a peculiarly extreme (but pluralistic!) form of solipsism'' (p. 18). This recalls Davies' ''Unless you are a solipsist'', remark quoted above.

Of course, we are by no means obliged to uphold presentism. Indeed, once the worldwide instant is jettisoned, presentism loses much of its intuitive appeal. If to be real no longer means to come into existence in a worldwide plane of simultaneous becoming, then it is difficult to see what it does mean. Since whatever we perceive to be present has already become (real), Stein (1968) suggests replacing ''is real for'' by ''has become real for'':

> For an event — a man considering, for example — at a spacetime point *a*, those events, and only those, *have already become* (real or determinate), which occur at points in the topological closure of the past of *a* [i.e. in Minkowski spacetime, within or on *a*'s backward light cone]. (p. 14)

The justification for this is that

> At a spacetime point *a* there can be cognizance of — or information or influence propagated from — only such events as occur in the past of *a*. (p. 16)

On this view, what is real or actual at some specific spacetime point does not depend on the reference frame, since it is whatever *has occurred* at that point: and what has occurred at a spacetime point is what lies in its absolute past. This

[22] Robb (1914, pp. 6, 12, 13). This sentiment is later echoed by Broad in connection with his notion of ''absolute becoming'': ''But a literally instantaneous event-particle can significantly be said to 'become present'; and indeed, in the strict sense of ''present'' only instantaneous event-particles can be said to 'become present''' (Broad, 1938, p. 280).

tallies well with Robb's (1921) own definitions of his absolute relations of *before* and *after*:

> Thus if I can send out any influence or material particle from a particle P at the instant A so as to reach a distant particle Q at the instant B, then this is sufficient to show that B is *after* and therefore distinct from A. (p. 11)

It also tallies with Robb's (1936) rejection of solipsism: "A normal individual who is not a solipsist (and a solipsist could hardly be regarded as a normal individual) believes in the existence of more than his own self and his own perceptions, and one is accustomed to regard these perceptions, under normal circumstances, as representing things as real as one's self but in some sense external" (pp. 7–8). In other words, both Robb and Stein are inclined to count all events in the past of a given event as real. But this is "real" in the sense of "having become determinate for"; it does not imply that past events co-exist with those of the present. For co-existence, we need a mutual relation, "compresence" or "presentness to each other". As Stein points out, if this relation "is taken to mean that each has, for the other, already become", then in the classical case we recover the ordinary concept: because "topological closure of the past" includes the limiting condition of instantaneous interaction, two events will be compresent if and only if they are simultaneous[23]. But in the relativistic case, this definition will yield only the punctual present: to paraphrase Robb, the only events compresent with a given event are events which occur at the same place. Thus even if we reject presentism, Stein's definition of compresence still leads to the punctual present.

The punctual present, however, is very problematic. To say that what is compresent to an event, such as a person considering, is merely what shares the very same spacetime point is, to say the least, decidedly harsh on our normal intuitions of presentness. It also seems susceptible to a version of one of Zeno's paradoxes, since temporal becoming can no more take place in an instant than can motion. Therefore, if becoming takes place in the present and all that is present at some point is what is at that spacetime point, then, since there is no becoming in an instant, there is no temporal becoming[24]. Russell proposed something like this argument as an objection to becoming. This is curious, for his solution to Zeno's parallel argument against motion is that, although there is indeed no motion in an

[23]Here Stein's definition of the "topological closure of the past" of an event is such as to include the events on the backward null cone, i.e. those connectible to it by any process including a light ray *in vacuo*.

[24]Cf. Zeno's B4: "What is moving is moving neither in the place in which it is nor in the place in which it is not". Aristotle: "The now is not a part of time, because a part measures the whole and the whole must consist of its parts; time, however, does not seem to consist of nows". Physics iv.10, 218a6–218a8 (Aristotle, 1996, p. 103).

instant, this does not refute the reality of motion, since this consists in a body's having a different position at a later instant[25]. By parity of reasoning one might argue that, although a Zenonian argument shows that a process cannot be composed of point-events, it does not preclude there being a process whereby something becomes different at a later time from what it was at an earlier one.

This last consideration, in fact, points the way to an acceptable construal of becoming, and one that "saves the phenomenon" of our experience of the present too. This is achieved by recognizing that becoming occurs over a short (even arbitrarily short) duration; even the event of a person considering or apperceiving another event cannot be strictly instantaneous.

5. The extended present

In presenting their theory of the punctual present both Robb and Stein were careful to qualify their characterization of it with the phrases "properly speaking" and "strictly speaking". As they were both aware, the punctual present depends on the abstraction of "instantaneous" or "point-events", and in relating these to experience ("a man considering") it also assumes that the perceptions or awarenesses of such events themselves occur in a point. Obviously, these are the typical abstractions of a mathematical physicist, necessary for a strict understanding. But they are also responsible for the gulf between this theory and our palpable experiences of events. As has long been recognized, when we experience — to give a hackneyed example — the postman's knock, we hear it as a "rat-tat-tat", and not as a "rat", then a "tat", then another "tat"; and similarly with speech and phrases of music.

As several authors have pointed out, however, this discrepancy between theory and experience can be bridged by introducing the concept of the *specious present*[26]. The idea, as originally developed by William James, is that the present or now as we cognize it in practice is "no knife-edge, but a saddle-back with a certain width of its own"[27]. By this means, our intuitions of presentness as comprising brief processes and also as encompassing a considerable spatial extent can be preserved. For we do not have to restrict our notion of contem-

[25]"People used to think that when a thing changes, it must be in a state of change, and that when a thing moves, it is in a state of motion. This is now known to be a mistake. … Motion consists merely in the fact that bodies are sometimes in one place and sometimes in another, and that they are at intermediate places at intermediate times". Bertrand Russell (1929), "Mathematics and the Metaphysicians" (pp. 83–84).

[26]See in particular the discussions of H. A. C. Dobbs (1951). Dobbs builds on the speculations of Eddington (1946) in his work about the two-dimensionality of time, as well as Russell's (1948) discussion of the paradoxes associated with the specious present in his work.

[27]Broad (1938, 281ff.) is extremely critical of the idea of a specious present. But see Davies (1995, pp. 265–278) and Dainton (2001, pp. 96–109) for contemporary discussions.

poraneity to what is present to a *point-event* or *instant*, but can apply it to a small extended event of apperception. As Stein argues, a natural way of construing contemporaneity is in terms of *mutual communication or influence*. He writes:

> Let us consider a "specious present" π of some percipient being; and let us call an event *e* "contemporaneous" with π if signals — interaction — influence — can occur *mutually* between *e* and π. In the Newtonian case, the spatial extent of the set of events contemporaneous with a given specious present is infinite; and it is rather natural to see in this fact the precise correlate, in the physical theory, of the "intuitive" notion of a "present" throughout all of space. The situation in the relativistic case is significantly different … .[28]

Here, Stein is linking the notion of mutual communication with what the physics in question says about interaction. In the case of Newton's theory, gravitational interaction is assumed to be instantaneous. But there is a second strand in Stein's (1991) discussion, his "plausible anthropological hypothesis" that our "intuitive" notion of the present as grounded in mutual communication "first arises 'naturally' in the course of human development and socialization" (p. 159). If we pick up this strand instead, a different construal of interaction suggests itself. After all, perception does not occur by gravitation; what is relevant to the intuitive present is not the worldwide instant of Gassendi presupposed by Newton in his theory of gravity, but interaction of objects with perceivers, especially visual interaction. And, given the collapse of the worldwide instant entailed by relativity theory, Stein's suggestion permits us to redeem the notion of the present as having a spatial extent that is, in fact, extremely large.

In a lyrical passage, Stein compares his account of the spatially extended present with Schrödinger's answer to the question, "Why are atoms so small?" Just as Schrödinger transposed this into the more easily answerable question, "Why are we so large in comparison to atoms?", Stein tries to answer the question "Why is it that, in the geometry of spacetime, we are so long and thin?" — that is, why is it that the ratio in the Minkowski metric between the spatial extent of our bodies and the temporal length of the specious present is so exceedingly small? — by transforming it into the question, "Why is it that, during a specious present, light travels a distance that bears a very large ratio to the spatial extent of our bodies?" His answer is that, even though we know very little about the conditions for conscious awareness, we do know that "the things we perceive must possess a degree of stability (and must interact with us in stable patterns)" (p. 161). And in order for this to occur, it is necessary for there

[28] Stein (1991, p. 159). This amplifies on a point in a footnote in his earlier article: "for processes of more than instantaneous duration, a meaningful and intuitively satisfying notion of 'contemporaneity' can be defined: two such processes may be said to be contemporaneous if part of each is past to part of the other — in other words, if mutual influence ("communication") is possible between them" (Stein, 1968, p. 15, n. 14).

to be very many interactions between the thing perceived and the perceiver; this in turn requires that the moments of experience (specious presents) be long enough to enable there to be very many such interactions between an organism and its immediate environment[29]. It follows that the distance light can travel in such a specious present is very many times greater than the dimensions of our bodies. And this in turn explains why, if our intuitions concerning compresent bodies are laid down in such a time interval, we come to expect the present to have a very large spatial extent.

Accordingly, if a is the extended event of our becoming aware of some other extended event e during some short interval π of our proper time, then both a and e will be short processes, and accordingly both will be represented as segments of worldlines in a Minkowski diagram. Actually, it is more appropriate to talk in terms of short segments of worldlines than events, since the notion of interaction requires two temporal continuants, objects enduring through time, and thus tracing segments of worldlines in spacetime. (It is a strain on language if not ontology to talk of two events interacting with one another.) Now any segment of a worldline that is contained within the absolute past of the end of the worldline segment of proper duration π, but within the absolute future of the beginning of that segment, will represent the path of a process or enduring object with which the person perceiving could be in interaction during that time[30]. So if the present of an event or enduring object a consists in all those events or enduring objects compresent with it, we arrive at the fourth theory of the present described in the introduction, the *interactive present*. That is, if we define all and only those extended events or enduring objects to be compresent with a section of an object's worldline a which are capable of mutual physical connection with it during an interval of its proper time π then:

> (iv) the present of an object during an interval of its proper time π (e.g. that during which conscious experience is laid down) is that region of spacetime comprised within the absolute future of the beginning of this (usually short) interval and within the absolute past of the end of that interval.[31]

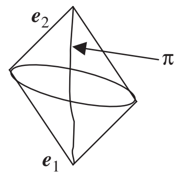
In terms of Minkowski spacetime, the absolute future is the forward light cone, and the absolute past the backward light cone. The result is that the present of an object during an interval of its proper time is a region of spacetime finite in extent, the intersection of two "cones", as in the figure below.

[29]There is a fascinating remark of Leibniz's in one of his papers of 1676 which seems to convey a similar idea: "Every mind is organic and learns something, but with difficulty and over a very long time, in proportion to the periods [of repetition] of the things it senses". "Notes on Science and Metaphysics", in Arthur (Ed.) (2001, p. 59). See also the note on *periodus* in p. 459.

[30]I am here excluding the events actually on the past null cone as having become. For an interesting discussion of this point, see Clifton and Hogarth (1995, pp. 364–365). In their terms the becoming I have described is "chronological becoming", as opposed to "causal becoming".

[31]This is indebted to Stein's (1968) formulation in his work. See footnote 28 above.

The interactive present



Here, e_1 and e_2 are the point-events marking the beginning and end of the worldline of the object in question during the interval of its proper time π. Thus, the events in this present are all the events chronologically between e_1 and e_2. Technically, this is known as the Alexandroff interval between e_1 and e_2[32]. The figure, of course, contains two distortions. One is that the units are represented as if they are equal, i.e. as if $c = 1$ in everyday units, whereas for a lapse of proper time of 1 s the spatial extent of the present is of the order of 1 light second, or 300,000 km or 3×10^{10} cm. The other distortion is that in our Minkowski diagrams one spatial dimension is suppressed: the three-dimensional "cones" we represent in two dimensions are in fact four-dimensional objects.

The present so construed is objective, in that although it can accommodate what may be present to an observer's conscious experience — and thus preserve our intuitions about the great extent of the present at any moment of consciousness — it does not depend on it. *Any segment of a worldline will have a region of spacetime that is present to it* according to this definition. In particular, this construal accommodates the kind of extended conception of "now" mentioned by Aristotle (1996): "it is also used when the time of what is called 'now' is close: 'He will come now', because he will come today" (*Physics* IV.13 222a21–222a22, p. 113). One can even use it in a cosmological context: when a cosmologist refers to "now", he/she means "the present era" — perhaps the 21st century, perhaps the whole of recorded history — as opposed to some earlier or later epoch. This present would be the region of spacetime referred to the Earth's worldline between either 5 or about 6000 years ago and today, and would comprise all those events happening in the absolute future of the beginning of that world-line segment and the absolute past of its end here today.

Although I have defined the present as relative to a segment of a worldline bounded by e_1 and e_2, one could conceivably have defined a present for any two

[32]The *Alexandroff interval* is discussed by John Winnie (1977, pp. 156–157), with a diagram depicting this interval for two chronologically connectible events. (Thanks to Steve Savitt for this reference.) As Winnie explains, Alexandroff intervals have a profound foundational significance, since a topology for Minkowski spacetime may be defined taking these intervals as basis. This is discussed in detail in Hawking and Ellis (1973, 196ff.), who show that they are also a sufficient basis for defining topologies of spacetimes in general relativity, provided the strong causality condition is met.

point-events e_1 and e_2 as the Alexandroff interval between them. For that interval is still well-defined even for two events that are not chronologically connectible, for instance the events in Davies' example mentioned above, that of my beginning to walk across the room (e_1), and an event e_2 somewhere in the Andromeda galaxy which is simultaneous with e_1 in my rest frame. Of course, in such a case the Alexandroff interval is null, so that there is no present relative to such a pair. This neatly underscores the point made by Čapek and Stein, that in relativistic physics simultaneity of distant events precisely entails their non-presence to one another.

But as explained above, the motivation for the above construal of the present based on the possibility of interaction is that it reconstitutes what we intuitively mean when we think of present objects or events. In particular, if we consider the event of one's having a conscious experience during a brief (perceptually subliminal) interval of proper time, *what is present will be all those enduring objects compresent with oneself* during this time, i.e. all those enduring objects with which one could mutually interact *during a specious present*[33].

That this construal of the present in terms of interaction corresponds fairly well with our own intuitions of the robustness of present objects can be seen by reference to a numerical example. Although the notion of the specious present is not without its difficulties — apparently varying in length depending on the context chosen — we may for the sake of definiteness take the minimum perceived time lapse to be the time between successive frames in a standard movie. Since this runs at 25 frames a second, all those objects are visually compresent with us during this time to which light could travel in 1/50 of a second, returning to us in an equal time. Since the speed of light is $3 \times 10^5\,\mathrm{km\,s^{-1}}$, if we ignore any mutual motion between perceiver and perceived, this means any object within 3000 km is visually present to us. Given this, of course, it is really not surprising that most thinkers have considered the speed of light to be practically infinite. (But it is worth noting that even the Epicureans, whom Newton studied assiduously, considered the speed of light finite.) Of course, the speed of sound is considerably slower; we are all familiar with the discordant phenomenon of a distant hammer blow (or bat hitting ball) being "present" visually before it is heard. Thus, I believe it can fairly be concluded that consideration of the extended present is sufficient to reconcile the Robbian position with everyday intuitions. This gives a serviceable notion of what is present to a given event of short duration, as well as saving our intuition of the "reality" or robustness of events that are present in the sense of "at hand".

[33]Note that if the present includes only objects that could mutually interact, and hence only those existing for a finite proper duration, then this would automatically exclude point-events on the cones' surfaces from the present.

This interactive present is not the same, however, as the *passive* or *subjective present*, the set of all those events of which we are consciously aware at the moment of considering them. For on the one hand, which particular events one is aware of will depend on where one's attention is directed. On the other, there will be events among those one perceives that occurred possibly in the very distant past: the present experienced by two lovers gazing at the stars will include events that actually happened many eons earlier (light from very distant stars may take billions of years to reach us). Some might think that this argues for regarding all events within (and even on) the past light cone as present, and that this definition captures better our normal intuition of what is happening now[34]. But this is to eliminate any distinction between past and present. On the account offered here, one can still say that the two lovers are presently perceiving events that took place in the distant past. For each can be perceiving the same long past events during intervals of their proper times in such a way that each is compresent with the other while having these perceptions.

6. Conclusion

In closing, though, it will be worth stressing which of our intuitions concerning this present notion of the interactive present does *not* preserve. First, it is at variance with the idea of a "moving present" discussed in Section 2. At least, it is when this notion is conceived as by McTaggart or in the passages from Wells and Weyl cited earlier, where the present is depicted as a "now" or consciousness moving along a worldline. For that would entail superadding time to a representation that is already four-dimensional. That is, we may think of a worldline as having been traced by some stationary or moving worldpoint. But we cannot superpose such a motion onto a spacetime diagram without paralogism. For in constructing a spacetime diagram we represent processes and events, that is, things that are supposed to have occurred. Becoming — or at least, having become — is already included in the diagram.

Second, this conception of the extended present is not an absolute one: *the interactive present is meaningful only relative to a segment of a worldline*, usually of short duration. This does not, however, make it subjective or somehow dispensable. Indeed, it is false to say that physics does not take the "now" into account. Of course, it is not to be expected that its laws or theories will refer to the "now", any more than they would refer to "here"[35]. As many authors have pointed out, these are indexicals, specific to particular places and times, and as

[34]If I understood him correctly, Robert Rynasciewicz suggested such a construal of the present to me in Montreal in a conversation after my talk.

[35]Dennis Dieks (1988) makes a similar point (pp. 459–460).

such have no place in laws. But application is a different matter. To see this, consider the cosmological now noted above. This still involves an indexical sense of "now". But it makes a great deal of difference with respect to available observational evidence whether it is supposed that the Big Bang occurred 14 billion years ago or 26 bya (a billion years ago — meaning a billion years before *now* — is an accepted unit used by astronomers, abbreviated "bya")[36]. For the superclusters we can see (or infer) to have existed earlier than now ("now" in this cosmic sense) may have taken longer than 14 billion years to have evolved, as has been charged by some critics of the Big Bang Theory. Thus the relativity of the "now" to certain events, such as humans having theories, does not detract from its objectivity.

Third, on this view events come to be in the present in a quite specific sense: if one extended event *b* lies in the present of another *a*, then *b* comes about during the proper time of the event *a*. Such a notion is neither symmetric (even though a part of *a* will lie in *b*'s present) nor transitive. So there is no question of this construal supporting the notion of the present as an equivalent class of events separating the past from the future.

Finally, I have said nothing above about one of the crucial issues that has motivated all recent debates about the reality of becoming in the Special Theory of Relativity: namely, its compatibility with the essential indeterminism of Quantum Theory. The particular form of incompatibility alleged by Nicholas Maxwell (1985) and criticized by Dieks (1988) and Stein (1991), depends on the relative present view I have criticized above. However, Mauro Dorato (1996) has argued that even the type of worldline-dependent becoming I have defended here is incompatible with a realistic picture of the collapse of the wavefunction on a space-like hyperplane. Echoing the closing remarks of Clifton and Hogarth (1995), who elaborate in great technical detail an account of becoming along worldlines based on Stein (1968) (cf. also Arthur, 1982; Dieks, 1988, 2006), Dorato suggests this may be too high a price to pay for the reality of becoming. Wayne Myrvold (2003) has recently argued that this allegation of incompatibility is misplaced, and has suggested that the Steinian notion can be extended to space-like slices of extended objects. Should his defense be rejected, however, I still see two possibilities for upholding the reality of becoming in quantum theory. One is to deny that wave-function collapse is an event or process, and there are perhaps several ways of doing this; the other is that of Kent Peacock, who accepts that collapse is a real causal process because information

[36] Paul Davies (1995, pp. 71–77, 283) subscribes (with some misgivings) to the "block universe view", claiming (p. 258) that "physicists can find nothing of this [i.e. no 'now', "no privileged present"] in the objective world". Ironically, each of his diagrams of expanding universes on pp. 133 and 154 has an ineliminable "now" clearly marked on it.

is exchanged, but abandons the idea that it must occur on a hyperplane, and proposes instead that it occurs on a hypersurface of equal phase.

To conclude: I have argued that the block universe view founders on a kind of equivocation about the "reality" of events: although we represent events and their spatiotemporal relations as real, this does not license an inference to their "already" existing, or indeed to the existence of the spacetime manifold of events at any time. I argued that the relativized present view, like Gödel's denial of objective time lapse, is vitiated by a misconception of the status of the time co-ordinate function in relativistic physics, and that becoming in Minkowski spacetime must be construed as taking place along worldlines and at a rate measured by the proper time of the object traversing the worldline. I examined the punctual present view, which results from insisting that only point-events that have become for each other are real, and found that taken literally it is susceptible to paradox, and in any case runs counter to our normal intuitions of the present. Finally, I elaborated a view of the present that avoids these problems, construing it as relative to an extended event or segment of a worldline, usually of short duration. The present in Minkowski spacetime is neither null (0-D) nor punctual (1-D) nor hyperplanar (3-D), but is a finite four-dimensional region contained within the two hypercones centered on that segment.

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Chapter 8

Becoming, Relativity and Locality

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Abstract

It is a central aspect of our ordinary concept of time that history unfolds and events come into being. It is only natural to take this seriously. However, it is notoriously difficult to explain further what this 'becoming' consists in, or even to show that the notion is consistent at all. In this article, I first argue that the idea of a *global* temporal ordering, involving a succession of cosmic nows, is not indispensable for our concept of time. Our experience does not support the existence of global simultaneity and arguments from modern physics further support the conclusion that time should not be seen as a succession of cosmic nows. Accordingly, I propose that if we want to make sense of becoming we should attempt to interpret it as something purely local. Second, I address the question of what this local becoming consists in. I maintain that processes of becoming are nothing but the successive happening of events, and that this happening of events consists entirely in the occurring of these events at their own spacetime locations. This leads to a consistent view of becoming, which is applicable even to rather pathological spacetimes.

1. Simultaneity and the now

Untutored intuition sees an inextricable bond between time and global simultaneity: time is a succession of cosmic nows. Each such 'now' extends over the whole universe, connecting simultaneous events. Part of this intuition is the supposed self-evidence of the meaning of statements about distant simultaneity.

However, in 1905 Einstein famously subjected this intuitive picture to a drastic epistemological critique. He started by conceding (Einstein, 1905) that there cannot be any dispute about whether *coinciding* events are simultaneous. But, Einstein pointed out, for events that do not spatiotemporally coincide the meaning of simultaneity is not so obvious. The reason is that we do not have immediate empirical access to the temporal relations between events that take place at a distance from each other — at least, not in the cases in which these events are outside each other's sphere of causal influence. We ourselves are more or less spatially localized and this, together with the fact that information cannot travel faster than light, implies that at any instant in our lives there are events that can be influenced by us (in the future lightcone), events that can influence us (in the past lightcone), but many more events that are not within causal reach at all. Events in the future and past lightcones are unambiguously temporally ordered with respect to the event at their apex (indeed, we could have veridical memories of all past lightcone events, and there could be memories of the apex event everywhere in the future lightcone); but what about all the other events, outside the two cones? Notoriously, Einstein concluded that in the case of such distant events their temporal order with respect to us, in particular simultaneity, must be established *by definition*. His concrete proposal for establishing simultaneity was that two clocks that rest with respect to each other can be taken to be in synchrony if a light signal that leaves clock A at time t_0 (as indicated on A) and is reflected at clock B when B's hands indicate t_1, arrives back at A at local A time $2t_1 - t_0$. In other words, the event at A halfway between the emission of the signal and its return is taken to be simultaneous with the reflection of the light at B. The arbitrary aspect typical of definitions, according to Einstein, is that it has to be *stipulated* that light going from A to B and back again needs equal amounts of time in the two directions (in other words, the speed of light is direction independent). This definition is equivalent to taking $\varepsilon = 1/2$ in Reichenbach's famous formula $t_1 = t_0 + \varepsilon(t_2 - t_1)$ (Reichenbach, 1957).

In the spirit of Einstein's 1905 discussion, Reichenbach and many others after him have argued that this value of ε, and therefore which events are regarded as being simultaneous, is purely a matter of convention. The justification of this view is that the consistent use of any other value of ε (with $0 < \varepsilon < 1$) leads to a description that is empirically equivalent to the standard one ($\varepsilon = 1/2$). Indeed, distant simultaneous events, whatever the value of ε that is taken for the definition of simultaneity (as long as $0 < \varepsilon < 1$), have spacelike separation with respect to us, so that we cannot reach them by signals and cannot be reached by them. In other words, the definition of simultaneity only pertains to what lies outside our past and future lightcones and can therefore have no influence on the content of our observations. Relativistic theories (in which the speed of light is the maximum speed of information transfer) are therefore empirically equivalent to their variants with $\varepsilon \neq 1/2$.

It is important to note that there are *two* ingredients in this epistemological critique of the relevance of simultaneity. First, there is the assumption that there is no action at a distance: signals cannot propagate faster than with the speed of light c. Second, it is assumed that observation is a *local* process. The whole conventionality argument is based on the presumption that the observation event can be represented by the apex of a lightcone, i.e. a spacetime point.

If observations instead are taken to correspond to extended regions in spacetime, it could legitimately be asked whether simultaneity plays a role in determining the outcome of the observation *within* such regions; in which case simultaneity on this local level would not be conventional. It seems more plausible to suppose that an observation is a process of finite spatiotemporal extension that does *not* depend on simultaneity within the region of observation (so that the content of the observation supervenes directly on the collection of events within the spacetime region of the observation). However this is taken to be, the fact remains that the 'observation spacetime region' is of very limited extent — its spatial dimensions should certainly not exceed that of the human body. Our perceptual apparatus, memory, etc., are all more or less localized. So regardless of the status of local simultaneity, in the very small, the way simultaneity is assigned *outside* this limited region of observation plays no role for the content of observation. The representation of an observation by a point-event is therefore a justified approximation, especially in the context of the cosmological considerations we shall be concerned with in this article. In the arguments we shall put forward, this (quasi-) local character of observation will play an important role.

In spite of the argument about the irrelevance of simultaneity for what we observe, the claim that simultaneity in special relativity is merely conventional is controversial. The reason is that the conventionality thesis is epistemologically inspired, and therefore more or less automatically suspicious from a realist point of view. Especially after Malament's proof (Malament, 1977) that the $\varepsilon = 1/2$ relation is the only plausible equivalence relation between events that can be defined from the four-geometry of Minkowski spacetime and a given inertial worldline, the tide seems to have turned against Reichenbach and his followers. I will later come back to Malament's argument, which is ontological rather than epistemological. But whatever one's attitude with respect to the conventionality thesis, it has to be admitted that its two premises, namely that there is a maximum signal speed and that observation is local, lead to the conclusion that choosing $\varepsilon \neq 1/2$ makes no difference for observational results. This conclusion stands, whether or not one accepts it as a good argument for the conventionality thesis. Local observations — the experiences of localized observers — are invariant under different choices of the value of ε in the same way as they are invariant under different choices of coordinate systems. In particular, *it follows that those human experiences that suggest that time flows are invariant under different choices of* ε.

This observation undermines the idea that our direct experiences of time, passage and becoming provide support for the idea that there are cosmic nows, whose succession determines the flow of time. We do not need a succession of a definite set of global-simultaneity hyperplanes in order to accommodate our experience. For it follows from what was just said not only that completely different choices of such hyperplanes lead to the same local experiences[1], but even that we do not have to bother about global simultaneity *at all*. If we decided to scrap the term 'simultaneity' from our theoretical vocabulary, no problem would arise for doing justice to our observations. This ties in with the fact that relativistic theories can be given completely local formulations — simultaneity plays no role in the dynamical laws of relativity theory. Clearly then, our direct time experience does not provide epistemological warrant for the existence of a global now and global becoming. This line of reasoning parallels Einstein's 1905 argument that our local experience does not support the classical notion of absolute simultaneity.

2. Rotating frames

So, if arguments based on our direct awareness of the flow of time were the only ones at our disposal, we might already now deny the relevance of global simultaneity for our conceptions of time and becoming. However, it would be too quick to think that limitations of our means of observation, in this case the fact that we are restricted to the observation of local events, imply strict bounds for our conceptions about the structure of the world. There may be good theoretical reasons for assuming the existence of things or structures we do not have direct observational access to. Indeed, the fact that our observations take place in a restricted spacetime region have not prevented us from theorizing about spacetime as a whole — like Minkowski spacetime in special relativity. Now, in the context of Minkowski spacetime there is a well-known theoretical argument designed to show that there exists exactly *one* global equivalence relation that meets natural requirements to be imposed on the concept of simultaneity relative to an observer, namely the relation of Minkowski orthogonality with respect to the worldline of this observer (Malament, 1977). This simultaneity relation is built into Minkowski spacetime, in the sense that it is completely definable from the Minkowski metric (plus the specification of the worldline in question). If one takes a realist stance with respect to Minkowski spacetime — and we do not want to argue against such a realist position here — this global simultaneity therefore appears to have a clear ontological grounding. Is it not

[1]We could also take ε , position and direction dependent, without observational differences, in which case simultaneity would not correspond to a set of hyper*planes* but to curved hypersurfaces.

natural to assume that this particular simultaneity relation fixes the successive instants in the history of the world, which come into being one after another?

Actually, it is misleading to state that the above argument leads to a simultaneity relation that is built into Minkowski spacetime and therefore must be assumed to exist as soon as the existence of Minkowski spacetime itself is accepted. As already mentioned, the relation in question is defined with respect to worldlines. Now, it may be maintained that as a mathematical fact all possible worldlines (also curved ones) exist in Minkowski spacetime, together with the associated orthogonality hyperplanes at each of their points. This, however, clearly does not lead to one definite notion of simultaneity. Instead it is a vast *collection* of simultaneities whose existence is warranted by the existence of Minkowski spacetime, and this collection does not yield one sensible notion of global temporal succession. We must apparently specify which worldlines are privileged and relevant for simultaneity. This is tantamount to augmenting the structure of Minkowski spacetime.

Our own worldlines seem prime candidates for the required additional structure. After all, we are the ones who come up with these intuitions about global becoming and successive cosmic nows, so it appears reasonable to suppose that the simultaneity that is involved is simultaneity relative to us. However, our worldlines are complicated: we take part in the annual and daily motion of the Earth and are therefore not moving inertially. Our situation is very nearly that of inhabitants of a rotating system in Minkowski spacetime. The study of the properties of time in rotating systems is therefore relevant for the question of whether the simultaneity related to actual observers leads to a global now.

The study of rotating frames of reference played an important role in Einstein's discovery of general relativity (Stachel, 1989). Time in these frames exhibits a structure that is also important from a modern foundational point of view (Dieks, 2004; Dieks & Nienhuis, 1990). The most significant point for our present discussion is that local Einstein synchrony ($\varepsilon = 1/2$) in a rotating system *does not extend to a consistent global definition of simultaneity*. Each observer on a rotating disc can locally apply the Einstein definition, but the so-defined local nows do not combine into one hypersurface. Therefore, orthogonality with respect to rotating worldlines cannot serve the purpose of defining a succession of global nows.

This can be seen easily by considering observers who are positioned along the edge of a rotating disc (and who are at rest with respect to the disc). Synchronizing along the edge with $\varepsilon = 1/2$ leads to a discrepancy, a time gap, upon returning to the initial position. Imagine the circle that forms the edge to be folded out into a straight line. The spacetime diagram of Fig. 1 represents the uniformly moving observers sitting along this line, together with their local $\varepsilon = 1/2$ synchrony hyperplanes.

It is evident that the initial and final events cannot coincide when the line is folded back into a circle: there is a time gap. More generally, local Einstein

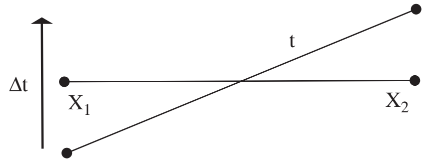

Fig. 1. Standard synchrony along a rotating circle ($x_1 = x_2$), folded out into a line.

simultaneity with respect to worldlines with accelerations that involve rotations cannot lead to a global equal time hypersurface (this is a consequence of Frobenius's theorem Wald, 1984).

So, if we accept that Einstein simultaneity with respect to worldlines enjoys a special status and is the candidate *par excellence* for grounding an objective now, we face the disappointing result that this notion cannot define a global now in the case of our own worldlines of rotating earthlings, or the worldlines of other arbitrary rotating systems. However, in view of the omnipresence of forces and fields, we can only expect that actual observers and other actually existing physical systems are in a state of acceleration that involves rotation. That means that Einstein simultaneity with respect to actually materialized worldlines will quite generally not lead to a global definition of simultaneity.

Therefore, nows of global becoming cannot be fixed by Einstein simultaneity with respect to worldlines in Minkowski spacetime that are realistic representations of actual material worldlines[2]. Special relativistic cosmic nows must clearly be related to a particular choice of *non-materialized* parallel timelike geodesics (actually, a continuous set of them that completely fills up spacetime, i.e. a congruence). Such a congruence defines a frame of reference and the unique Einstein simultaneity associated with it. But which congruence of inertial worldlines should be chosen? The spatiotemporal structure of Minkowski spacetime does not single out any set of parallel geodesics from the infinitely many defined in it — this is one way of formulating the relativity postulate, which says that all frames are equivalent. So if we are not going to refer to the actual material worldlines in the universe, but only to the spacetime structure itself, we have insufficient resources to fix a unique set of global nows. If we attempt to rely on the actual material worldlines, however, we will not succeed in defining global nows at all.

In the context of Minkowski spacetime, the project of defining a global notion of becoming is therefore hopeless. We could of course just *choose* some foliation

[2]One may object that it does not make sense at all to represent the actual universe by means of special relativity. However, Minkowski spacetime provides an approximation to general relativistic spacetimes that is quite good even for large spatiotemporal regions. But see the next section for an assessment of the situation in general relativity.

of Minkowski spacetime and declare it to realize universal nows. But these nows would not play any role in our time experience, since our experience is local and does not depend on stipulations about the time coordinates to be assigned to space-like separated events. Moreover, such a global now would not play any role in the formulation of physical theory. Finally, it would not be definable from Minkowski spacetime structure without the addition of arbitrary elements. It would be bad metaphysics to opt for something as gratuitous as that.

But there may be a way out. The best available theory of our actual universe is not special relativity with its highly symmetrical flat Minkowski spacetime but *general* relativity. Perhaps this theory offers better prospects for global becoming.

3. Non-rotating universes

In completely generic general-relativistic spacetimes the situation is worse rather than better. There are solutions of the Einstein field equations that cannot be sliced up at all by means of spacelike hypersurfaces. This feature of general relativity, and its possible consequences for the theory of time, have become notorious since Gödel's seminal work (Gödel, 1949a, 1949b). Gödel found solutions of the field equations in which there are closed timelike curves (it is characteristic of these Gödel spacetimes that the matter in them possesses a net rotation). It is clear that there can be no linear ordering of global nows and therefore no global linear flow in universes in which worldlines bend back into their past. So if we take the view that the essential features of time are those that are solely determined by the Einstein equations — in other words, that the essential features of time are those that are present in all models of the theory — it follows that global linear flow cannot be such a feature: there are solutions of the Einstein equations without it[3].

In his 'Reply to Criticisms' Einstein remarked about the Gödel universes: "It will be interesting to weigh whether these are not to be excluded on physical grounds." (Schilp, 1949, p. 688) In other words, Einstein suggested that not all mathematically correct solutions of the general relativistic field equations may represent physically possible worlds. If the class of possible worlds is indeed taken to be smaller than the full set of mathematical models satisfying the general relativistic field equations, then in this smaller set of 'physical solutions'

[3]I take it that Gödel's argumentation is directed against the idea that it is an essential characteristic of time that it *flows linearly*; that becoming in this sense exists. Although Gödel's formulation is not quite unambiguous, I think that this is the only way his argument makes sense (cf. Earman, 1995). The form of Gödel's argument as I understand it then is: time is usually said to be different from space because it *flows* from the distant past to the distant future; but in some solutions there is time without such flow being possible; flow can therefore not be an essential, defining characteristic of time.

the shared properties of time might include the total ordering that is needed for Gödel's global becoming[4].

The proposal to not take into account Gödel-type solutions of the Einstein equations may seem *ad hoc*. However, on second thought it is perhaps not implausible. First of all, observational evidence indicates that our own universe is not rotating (Scherfner, 1998). Other possible general relativistic worlds, in which strange Gödelian things happen, exist as far as we know only on paper. That by itself, however, is no obstacle for considering them relevant to an analysis of the concept of time based on our best physical theory. But it should be noted that general relativity with its usual scope may not be the only contender here. Already in the case of classical particle mechanics there is a serious rival for Newtonian mechanics in the case of non-rotating universes, and the situation seems similar in relativity theory. For those solutions of the classical Newtonian equations of particle motion in which there is no net particle rotation, it is possible to formulate a completely relational, Leibnizean particle mechanics that is empirically equivalent (for these cases with no net rotation) to Newtonian classical mechanics (Lynden-Bell, 1995). In this relational classical theory only mutual distances and relative orientations of the particles occur — there is no need for absolute space. As just mentioned, our universe actually appears to be non-rotating. So, as a piece of counterfactual history, we could speculate about what the history of mechanics would have been if Newton had proposed this relational theory instead of his actual theory involving absolute space. In the relational version of particle mechanics it is a built-in and law-like feature that there is no net rotation (there is no background with respect to which such a global rotation could even be defined). Only non-rotating universes are therefore possible according to this theory. In other words, the lack of rotation is essential and necessary within this theoretical framework. In our counterfactual history, this feature could then have been carried over to the conceptual framework of an alternative version of general relativity theory. Indeed, it can be shown that general relativity accommodates Leibnizean and

[4]This suggestion could alternatively be couched in terms of essential versus contingent properties of time. As just mentioned, Gödel's argument for the 'ideality' of time, as he puts it, relies on the idea that if time 'objectively lapses' (if there is objective becoming), this should be an *essential* property of time, instantiated in all possible worlds. The Gödel universes are then relevant as counterexamples. If the set of possible worlds is restricted so as to exclude Gödel universes, objective passage may regain its status as an essential attribute of time. As a limiting situation we could consider taking only our own universe as possible: then everything existing in our world would exist necessarily. The actual characteristics of time in our world would thus by definition also be essential. This seems too drastic a curtailment of the scope of physical theory and a trivialization of the distinction between the essential and the contingent, however. Even if we are convinced that there is actually only one universe and if we are strict empiricists, it makes sense to conceptually distinguish between the merely contingent and the essential, on the basis of the properties of (a set of) models of our theories.

Machian desiderata if one restricts the set of allowed solutions to non-rotating closed universes (Lynden-Bell, Katz, & Bicák, 1995). So one can imagine an alternative course of history in which the notion of a net rotation of the matter in the universe would never have made sense as a physical possibility. Such an absence of rotation is conducive to the existence of global nows, as we already saw, and it excludes Gödel universes. If we go on to exclude exotic possibilities like wormholes in spacetime that give access to the past, this could lead to spacetimes that allow global foliations as the only physical possibilities.

Let us go along with this line of reasoning, and assume that physically possible universes (of which our universe is one) do not rotate on an astronomical scale and do not contain closed timelike worldlines. This allows (Malament, 1995) the introduction of a foliation of spacetime into a linearly-ordered set of three-dimensional spaces, each space being orthogonal to the worldlines representing the mean motion of matter[5]. At first sight this possibility seems to decide the issue: in all physically possible universes it could be said "that reality consists of an infinity of layers of 'now' which come into existence successively" (Gödel, 1949a).

However, Gödel himself already expressed reservations about this way of constructing a now (without pressing the point). He observed "that the procedure described above gives only an approximate definition of an absolute time. No doubt it is possible to refine the procedure so as to obtain a precise definition, but perhaps only by introducing more or less arbitrary elements (such as, e.g. the size of the regions or the weight function to be used in the computation of the mean motion of matter). It is doubtful whether there exists a precise definition which has so great merits, that there would be sufficient reason to consider exactly the time thus obtained as the true one."

Consider, to make Gödel's worry clear, the Robertson–Walker solutions of the field equations. These are the solutions that are found if spatial homogeneity and isotropy are imposed. It is possible to define a global time t in them (t is the argument of the scale factor occurring in the standard way of writing the solutions). The equal-t hypersurfaces are orthogonal to the worldlines of matter — matter is at rest in these hypersurfaces (in which the matter density is constant). The total spacetime can thus be represented as a stack of equal-time

[5]There may also exist other ways of defining a global time. In particular, in spatially homogeneous cosmologies three-dimensional spaces of constant mass density may foliate the spacetime. Often this does not yield something new, because these homogeneity spaces are in many models orthogonal to the worldlines as well; but there also exist cosmological models in which the homogeneity condition and the orthogonality condition lead to different foliations (Belot, 2005, Section 3.3). We focus on the orthogonality criterion because it matches the special relativistic notion of simultaneity, which appears as a natural requirement in view of the indistinguishability between special and general relativity on the local scale. But the arguments against global becoming to be put forward below will also work against the homogeneity definition.

hypersurfaces, a succession of three-dimensional spaces each of which belongs to one value of t. This cosmic time t thus seems very well suited to make the notion of global becoming more precise.

Though the Robertson–Walker metric is often used as a representation of our own universe, our universe is obviously not homogeneous and isotropic. It is only when we average over very large spatial regions that the distribution of matter in the actual universe appears to approximate homogeneity and isotropy. That means that only if we leave small-scale details out of consideration, our universe can be approximated by a model of the Robertson–Walker type. Now, we could define equal-t hypersurfaces in our actual universe as surfaces that are orthogonal to the average mass distribution that we can calculate by coarse graining over large volumes. But the result of this procedure depends on the details of the averaging process and the size of the regions considered. One would expect that the conformity to a Robertson–Walker spacetime becomes better when the sizes of the regions over which the averaging takes place become bigger (though it is not really certain that the homogeneity and isotropy assumption will be satisfied in a limiting situation, or even that there is a well-defined limiting situation), but as long as the averages are taken over finite regions homogeneity will not be complete and will vary with the sizes of the volumes. Accordingly, the equal-t hypersurface that is found will be different depending on the choices we make for the averaging procedure. So there is arbitrariness in the definition of the global time t, comparable to the arbitrariness in choosing one set of parallel inertial worldlines over another in Minkowski spacetime. However, if we concentrate not on the imaginary worldlines of smeared out matter but go to the detailed scale of real, actually existing worldlines, we encounter the same problems as when we attempted to do this in Minkowski spacetime: in general these actual worldlines will be rotating and there will be no global simultaneity hyperplane orthogonal to even a small subset of them (like our own worldlines on Earth). It is obvious that the above-mentioned empirical fact of a vanishing rotation in our universe can only refer to the net rotation, found by averaging on a cosmic scale: on a small scale, rotation is present everywhere around us.

As Gödel stated, in order to arrive at a notion that has a chance of representing *objective* global-time flow one should first of all provide an unambiguous definition of global time. What we have just seen is that it is impossible to arrive at such a definition if we attempt to extend special relativistic local simultaneity defined with respect to actual worldlines in our universe. Only in very special highly symmetrical cosmologies do hypersurfaces exist that can plausibly be considered to realize such uniquely determined cosmic instants. As soon as we turn to realistic, asymmetrical, cosmological models the definition of such hypersurfaces comes to depend on statistical considerations and is no longer unique.

More generally, even if we forget about the orthogonality condition, in asymmetrical spacetimes[6] that admit foliation at all no unique foliations can be singled out on the basis of the spacetime geometry (Belot, 2005). Many slicings of spacetime are generally possible, none of them deserving the label 'fundamental'.

However, what we would like, in Gödel's words, is a definition that "has so great merits, that there would be sufficient reason to consider exactly the time thus obtained as the true one". It will not do to just stipulate that one or another way of cutting up spacetime in a series of non-overlapping three-dimensional spaces furnishes a succession of nows. In particular, what we would like to have is a foliation of spacetime that does explanatory work with respect to our experience of time and our intuition of time flow. That, however, appears an unattainable goal. The arbitrariness of foliations just discussed, basically derives from the fact that the physical laws have a local character and do not need a notion of simultaneity for their formulation at all. That is the reason that we were driven to consider contingent, fact-like circumstances as a basis for possible definitions. But such contingent circumstances, pertaining as they do to far-away conditions in the universe at large, are completely irrelevant to our local experience. We can conclude that global time plays no role at all in our time experience.

This general diagnosis is not changed by the various proposals that have been made to use foliations that lead to simplifications of the equations in the constrained Hamiltonian formalism of general relativity theory (GRT), like those that take the mean extrinsic curvature of hyperplanes as the time parameter. The constrained Hamiltonian formalism itself characterizes these choices as choices of a particular gauge (Wald, 1984), which is tantamount to saying that nothing observable depends on the selection of one possibility over another.

The bottom line is that cosmic time on any proposal is defined via a global description that has no bearing on what happens on a small scale. But it is exactly the processes on the small scale (like the time experiences of human observers and the evolution of localized systems) that lie at the basis of the idea that there *is* objective becoming. The rate of these local processes is determined by the amount of *proper time* between events, and not by differences in cosmic time. Consider local observers in arbitrary motion with respect to each other and starting from one spacetime point: proper time differences along their worldlines will not conform to contour levels of any cosmic time function, due to the non-integrability of proper time. As a consequence, discrepancies will generally occur in the time lapses recorded by observers that meet again after having traversed different paths between two events, as illustrated by the twin effect. However, during their respective journeys such twins will be able to use the same physics; one twin ages as fast as the other, as judged by his own clocks.

[6]Spacetimes without symmetry actually lie dense in the total space of solutions.

They have the same time experiences. This empirically verified democracy would be broken once we started measuring the rate of processes by some ‘true’ global time. Accordingly, global time — if it can be defined at all — is unrelated to our experience of becoming. Proper times are the quantities we use in daily life in our local environment. Cosmic time plays no role on a mundane level.

In sum, what follows from these considerations is that we do not really need to engage in meditations about other universes. Both according to special and general relativity, applied to our *actual* universe, a plausible global time cannot be defined by reference to what happens on the small scale of human experience and local physical experiments. Such a global time *can* probably be defined through theoretical considerations on the cosmic scale, but such definitions involve an unavoidable element of arbitrariness, and the resulting t is irrelevant to our time experience and the description of local processes.

4. The block universe and becoming

A global time function, if it exists at all, thus appears to be a theoretical expedient. It is a helpful tool in the theoretical treatment of spacetimes with a certain amount of symmetry and is a useful concept in, e.g. the constrained Hamiltonian formulation of GRT. In the latter context it is comparable to the choice of a particular gauge in electrodynamics. It does not have consequences on the level of observation (which is local) and *a fortiori* is not relevant for our time experience.

However, according to traditional doctrine the existence of a unique series of global nows is indispensable for what this doctrine considers the essential difference between space and time, namely that time is ‘dynamic’ whereas space is ‘static’. The basic idea behind this is that time is objectively *progressing* from the past to the future. The history of the universe is unfolding itself, and this process consists in the successive coming into being of global nows. This was exactly the notion of time targeted in Gödel’s attack. Accordingly, after Gödel had argued that time *cannot* be flowing this way, he concluded that it must be ‘ideal’, by which he meant that our feeling of becoming does not reflect an objective process of becoming that exists in physical reality itself, independently of us. Time flow and the associated difference between space and time must be mind-dependent if there are no global nows, according to this argument.

This way of reasoning is not at all peculiar to Gödel’s analysis. That the absence of a unique succession of universal nows entails that there is no essential difference between space and time is in fact the basis of a notorious argument within special relativity. The core of this argument is that without a unique series of nows all events must have their places in spacetime in the same way as the objects on my desk possess their spatial positions. All events in the history of the universe should be there 'together', 'at once'. Put differently, we live in a 'block universe' in which all events — past, present and future — 'exist jointly'. Allegedly, this block view would imply that the universe is 'static', without change and becoming and without fundamental differences between past, present and future. It is sometimes added that this blatantly conflicts with our direct experience of temporal change, and that this experience must therefore be an illusion. Several versions of this argument exist in the context of special relativity (cf. Maxwell, 1985; Maxwell, this volume; Petkov, this volume; Putnam, 1967; Rietdijk, 1966), but as we have seen it can be adapted to the situation in general relativity as well.

There is something deeply puzzling about this argumentation, especially about any possible 'illusion part' of it. As emphasized in the preceding sections, our time experience — local as it is — does not depend on the concept of global time. So how then could the denial of the objective existence of global time lead to a picture that is in conflict with our direct experience? If there indeed is a mismatch between the block universe and our experience it must surely come from some other source, not from the absence of global simultaneity. So let us try to find out whether there actually is something in the block universe that is at odds with our time experience and whether it is true that our intuitive notion of time is in conflict with what the block picture tells us.

This project is hopeless from the outset. It is the purpose of the four-dimensional spacetime picture, which the block universe is, to represent *all* events that actually take place in the universe, complete with *all their properties and mutual* relations. An adequate block universe representation therefore also contains all events in the lives of individual human beings, with all the impressions and experiences that (partly) constitute these events. For example, that I now remember past events and do not yet know much about what is to come is part of my experience at this instant of my life and should be part of the four-dimensional picture; the same applies to my conviction that exactly *now* it is now. All actual events, experiences and intuitions must be there in the block representation, exactly at the spacetime position where they actually occur. So there cannot be any conflict between experience and the block universe. More generally, since all actual events in the history of the universe are faithfully represented, with all their characteristics and mutual relations, there cannot be anything missing in the four-dimensional picture at all.

This latter conclusion is, of course, independent of whether or not global simultaneity exists. If objective global time does exist, this can and should be represented in the block representation. If it does not exist, it is not represented in the block. In both cases, the block representation does not need to leave anything out of consideration. But the question of course remains whether the absence of global simultaneity implies anything for the difference between space and time, and for the viability of the notion of becoming.

Since everything that we experienced, are experiencing, and will experience is represented in the four-dimensional block, quite independent of whether or not there is global simultaneity, all experiential differences between space and time are also there. Is there any reason to maintain that in the case of lacking global simultaneity these experienced differences must have the status of illusions whereas they may refer to something real if there is global time? I can see no justification at all for this position. As argued above, our experiences are local in character and independent of global simultaneity — they do not therefore lend support to the hypothesis that global temporal distinctions exist in reality. A theory about the nature of reality according to which there is global becoming transcends direct experience much more than any interpretation that stays on the local level. There is consequently no reason to think that the temporal differences we experience can only refer to something global. Consequently, if it turns out to be possible to develop a view of reality in which there is becoming and a difference between space and time in a local way, the resulting conception will have every chance of being better supported than rivals postulating global becoming.

To start with, let us have a closer look at what the doctrine of global becoming precisely consists in. The global aspect is that the supposed temporal ordering extends over the whole universe. But becoming itself is not implied by the existence of an ordering, whether it is global or not — a stack of papers is linearly ordered but surely the papers do not come into successive existence by virtue of this. So independent of the question of temporal ordering, an analysis of becoming *tout court* has to be supplied. As I have argued, any such analysis will apply *a fortiori*, with better support, to a doctrine of local becoming. Sense must be made of the notion of the becoming of events in any case, both in order to get the global and the local doctrines off the ground.

Now, the four-dimensional spacetime diagram *records* events with their qualities and relations. But in order to be recordable at all, the events in question must *occur*. They must *happen*. It is exactly here that there is room for 'coming into being' in the block universe. Events come into being by occurring, by happening; what other coming into being could there be? Since non-occurring events are evidently not represented in the four-dimensional picture, events can only be part of the block universe if they in fact come into being at their own spacetime location. Their coming into being is a *precondition* for their being part of the block universe. In the block picture it is recorded for each actual event *that*, and where/when it occurs. The specification of the coordinates of an event document first of all *that* it happens; all represented events actually happen. Thus, our proposal is that 'coming into being' means the same thing as 'happening'. Since everything that happens is recorded in the block universe diagram, 'coming into being' is also fully represented. There is no need to augment the block universe in any way.

This proposal boils down to a deflationary analysis of becoming: becoming is nothing but the happening of events, in their temporal order. This obviously requires some ordering structure in the space of events. However, there is no need that this is a total linear ordering. In fact, relativity theory tells us that there is a different temporal ordering in reality, namely, the partial ordering induced by the lightcones. Each event is later than the events in its past lightcone, earlier than the events in its future lightcone, and not temporally ordered with respect to events outside these two lightcones. This ordering structure (a partial ordering) can without difficulty be applied to define becoming. The total pattern of relativistic temporal ordering relations in the block universe accordingly represents how events come into being with respect to each other. Given any event, some other events come into being later or earlier, and still other events — those at spacelike separation — come into being without being earlier or later than the given event. In particular, the successive happening of events along a worldline implements the notion of 'becoming' with respect to an object or causal process.

One may object that the mere ordering with respect to each other of localized events is not sufficient to justify a notion of becoming, though. Events can be spatially ordered as well, and this does not lead to spatial becoming (from left to right, for example). So we still have to assume that there is a difference between space and time that makes it possible to reserve the label 'becoming' to temporal succession. We do not need to come up with something new here, however: spacetime physics indeed makes such a distinction. There is an objective difference between spacelike and timelike vectors; this relates to the fact that space and time are treated differently in the expression for the metric (in local Lorentz coordinates the metric tensor has one -1, for the temporal dimension, and three times $+1$ for the spatial ones). Given the objective distinction between spatial and temporal ordering, that events *happen* or *occur* and are not just spatially juxtaposed can be seen as a *sui generis* attribute of events. The block picture is complete in its representation of this becoming: it contains all information about exactly which events occur, where and when this happens, and in which temporal order.

Still, one may feel the need for a deeper explanation of what 'temporality' and 'coming into being' exactly consist in. Indeed, the four-dimensional picture only tells us *that* events occur and that they have certain spatiotemporal relations between them. It only gives us a structural description of the web of events; does this exhaust the essence of becoming? To counter this request for explanation, it should be noted that the same thing may be asked with respect to spatiality. 'Being something spatial' is a quality whose content is not fixed by saying that it belongs to elements possessing the interrelations of the points of the Euclidean plane. A picture of a plane only represents structural properties, in the same way as the four-dimensional block universe picture; and it can be applied to very different entities that happen to exemplify the same structure. To fix the reference to spatial things something additional must be invoked. A natural move to make is to embed ourselves in the network of relations, and to identify some of the experiential relations between ourselves and the world around us as spatial. The same manoeuver can be carried out in the spatiotemporal context: then the relevant experiences will partly refer to 'becoming'. If we do not want to invoke experience in this way, both 'spatial position' and 'occurrence' must be regarded as *sui generis* attributes — of objects and events, respectively.

So according to this proposal, 'coming into being at (x,t)' is what *it means to be an event at* (x,t). The four-dimensional picture represents the relations between events, but does not explain further what events are. In order that a spacetime diagram is acceptable to us as a representation of the universe, we *already* have to know what events are, by acquaintance with them via other means than the contemplation of such representations. That events happen is something we should already know. We should not become confused, of course, by the fact that a concrete representation before our eyes is itself very different from what it represents, namely the events in the history of the universe. If a spacetime diagram is on a sheet of paper, it is itself part of the events in the life of the paper, and happening in that sense. But this is different from the happening of the events represented *in* the diagram. The fact that the block diagram itself at any instant is perceived as purely spatial and does not 'flow' is irrelevant for the status of what is being depicted.

So 'coming into being', 'happening', 'taking place', 'occurring', are what it is for an event to be an event — it is a primitive concept that cannot be defined by means of more basic notions. This suggestion seems to be close to the analysis of 'becoming' put forward by (Savitt, 2002 and Dorato, 2002).

5. Conclusion: local becoming

Becoming thus consists in the successive coming into being of events. This does not require a global notion of time as in Gödel's "infinity of layers of 'now' which come into existence successively". Our direct time experience does not impose such a total ordering on becoming, and the special theory of relativity has made us already accustomed to the idea that events possess only a partial temporal ordering. Since our experience does not tell us anything about temporal ordering that goes beyond this special relativistic ordering (induced by the lightcone structure), it is natural to be led by the characteristics of this partial ordering structure in our theorizing about the characteristics of objective becoming. So the natural view is that the history of our universe is realized by events that come into being; and that they come into being after and before each other as dictated by the partial ordering relation induced by the spacetime structure (Dieks, 1988).

According to this proposal the life of the universe is not one linear series of events, but a partially ordered set of events. The process of becoming is *local* in two respects: first of all and most importantly, the focus of becoming are the local events that come into being; and, second, the ordering relations that govern the temporal relations in this network of happenings are not global in character. The resulting picture is in accordance with what relativity theory tells us about the structure of spacetime and the role of time in it: it captures the 'many-fingered' aspect of time. It accords with our direct time experience as well. It thus provides us with a scientifically informed notion of becoming.

What has just been said presupposed that an unambiguous temporal ordering indeed exists. But this condition is not fulfilled in all solutions of the Einstein equations: in Gödel-like universes ambiguities arise about the temporal order of events. This may be countered by declaring such models unphysical — we have encountered this move before and argued that it may possess a certain plausibility. But another and I think better possible response is to say that 'happening' or 'occurring' of events is the essential thing, and that whether or not a consistent large-scale ordering is possible between these local happenings is a secondary question. If we take this line, local becoming can be accommodated in all models of general relativity, even in universes with a complicated Gödel-like temporal ordering structure.

To see what this may result in, and how this contrasts with other analyses of 'becoming', consider the following example from Reichenbach's *Philosophy of Space and Time* (Reichenbach, 1957; see Fig. 2).

Worldlines I and II in the figure represent human beings; worldline II returns to the neighborhood of one of its earlier points, Gödel-style. Reichenbach describes the experiences of the individual associated with worldline II as follows: "Some day you meet a man who claims that you are his earlier self … Years

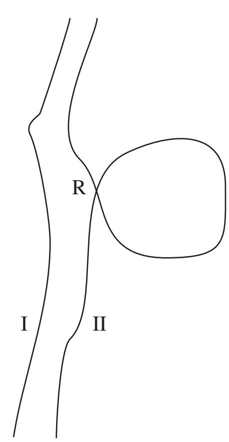

Fig. 2. Becoming along an almost closed worldline.

later you meet a younger man whom you suddenly recognize as your earlier self … You also see your former companion again, exactly as old as he was when you last saw him … He denies any acquaintance with you and agrees with your younger self that you must be insane. After this encounter, however, you walk along with him. Your younger self disappears from sight and from then on you lead a normal life." Reichenbach goes on to conclude that the following must be true in universes with almost closed worldlines: "On the same worldline there would be periodic now-points one after the other. In region R we would find two now-points of the same worldline in causal interaction; and under these circumstances we would lose the possibility of conceiving of the self as one identical individual in the course of time. There would be on this worldline a succession of new individuals who would travel the worldline at certain intervals. On worldline I we must also mark off such periods …."

Reichenbach is obviously thinking here in terms of a process of objective becoming that is progressing along the two worldlines. The way he represents this may at first sight seem plausible: he assumes that becoming consists in the motion of a now-point along the worldlines. This same idea can be found in the work of many authors[7]. This conception is completely different from the one put forward in this paper and it is important to be clear about the difference. The 'moving now' approach requires the *addition* of something to the four-dimensional continuum, namely a moving very narrow 'window' through which a small portion of the continuum is made visible (or 'real'). By contrast, what we have proposed here is a conception according to which nothing has to be added to the spacetime diagram: the four-dimensional picture *already contains* becoming. In Reichenbach's example the relevant processes of becoming are the successive happening of events along the two worldlines.

The 'moving now conception' leads to the well-known conundrum of how fast, and as a function of what, the 'now' changes its position. Motion, in the ordinary sense of the term, means different positions at different times and this kind of motion is already fully represented in the block picture as it is. The motion of the added 'now' is apparently a completely new concept, and we are at a loss to explain what it is. But as we will see, in the example at hand the implausibility of the whole approach becomes even clearer, *pace* Reichenbach. This observation will lend further support to the view that becoming does not reside in something to be added to the block universe — it is already there.

[7]The famous words of Hermann Weyl, "The objective world simply is, it does not happen. Only to the gaze of my consciousness, crawling upward along the life line of my body, does a certain section of this world come to life as a fleeting image in space which continuously changes in time" (Weyl, 1963), expresses the same intuition: the four-dimensional continuum needs the *addition* of a *moving* focus, this time that of consciousness, in order to accommodate the notion of becoming.

When the individual of worldline II talks to his younger (or older) self, the 'now' conception employed by Reichenbach says that both persons actually exist and must therefore be 'touched' by a now-point (because the 'now' identifies the points on the worldlines that are actual). So there must be *two* now-points in region R, which both are travelling up the worldline. But when the younger person now reaches R for the second time, the story repeats itself, so that a third now-point becomes necessary, and so on. Because actualized points on worldline I are in contact with actualized points on worldline II, this multiplicity of now-points carries over to worldline I. So an unending sequence of now-points travel up the two worldlines, repeating the same history over and over again; the same events keep on happening and there no longer is a unique connection between a worldline and an object or individual. This appears a *reductio ad absurdum* of the doctrine of the shifting now. Indeed, the very idea of an event is that it occurs exactly once, namely at its own spacetime position; and the idea of the four-dimensional spacetime picture is that it fully contains the history of the whole universe, not an infinity of indistinguishable repeated histories. At the very least one should say that an infinite multiplication of entities as necessitated by the moving now doctrine is a highly undesirable piece of metaphysics.

On our construal of becoming no such absurdities arise. Each event comes into being only once, at its spacetime position in the four-dimensional world. *Along the two worldlines* there is a linear temporal ordering, and therefore ordinary becoming. When the stroller converses with his younger self, he is in causal contact with an event that happened long ago in his own life, i.e. if measured along worldline II, but that is recent if measured along a different path. This is a direct consequence of the absence of a unique temporal ordering in the network of occurrences (as is to be expected in Gödel-type universes), but entails nothing about a periodicity in the process of becoming, let alone about a multiplicity of personalities. It seems clear that this sober account is to be preferred over an account according to which a mysterious 'now' travels through spacetime in an incomprehensible way while doing something unintelligible over and over again to events on its way.

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Chapter 9

How to Square A Non-localized Present with Special Relativity

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1.

It is often alleged that relativity theory has revolutionized our ontology, that, in particular, it has done away with the distinction between past, present and future. There is now solid empirical evidence, it is claimed, in favor of the age-old tenseless theory of time, which denies the reality of this distinction, and for holding that time's passage — the becoming of future events present and then past — is an illusion. I shall argue against this contention. The appeal to relativity is made with the intention of making a physical theory into a metaphysical one, but, as I hope to show, it already relies on weighty and unacceptable metaphysical assumptions. In the first part of the paper, I wish to uncover these hidden assumptions and highlight their role in the argument from relativity theory to the tenseless view. In the second part, I will show how transcending them paves the way for squaring our understanding of tense with relativity theory. The third part consists of some general remarks concerning physics and ontology.

Philosophers writing on relativity theory and time have been engaged in two separate tasks. One is a destructive, negative task, consisting of refuting, on the basis of special relativity (henceforth – SR), the tensed theory of time. For the purposes of the present paper, this theory will be represented, somewhat simplistically, by the assertion that (1) "All (and only) things that exist now are real" (Putnam, 1975, p. 198). The other, constructive task is to provide grounds, scientific grounds, for espousing the rival, tenseless view of time, which can (likewise simplistically) be represented by the contention that (2) "All future things are real, and likewise all past things are real, even though they do not now exist" (Putnam, 1975, p. 204)[1]. However, little attention, if any, is paid to the fact that two distinguishable issues are involved. In fact, the two tasks are conceived as one — it is assumed that refuting (1) is tantamount to endorsing (2). In other words, it is taken for granted by those assessing the philosophical implications of SR that we are facing a forced choice between the tensed and tenseless views, and that, therefore, it is enough to undermine one of them — the correctness of the other is thereby established.

Now, though this may not be immediately apparent, behind the idea that there are these two possibilities concerning tense — either only present events are real, or else, all events, past, present and future, are equally real — lies a metaphysical assumption. The assumption is that the difference between past, present and future, concerns the *ontological status* of events, and that it is to be analyzed in terms of *reality claims*, claims to the effect that events are or are not *real*. I shall call this assumption, the *ontological assumption*. And I shall argue that this assumption, far from being self-evident or self-explanatory, is in fact unintelligible. However, before discussing it, I wish to underscore its role in the argument from SR to the tenseless view of time.

The argument is quite straightforward[2]. Let us assume, first, that what is real for me is real for you and vice versa, at least when you and I are in the same place at the same time. (Here "real for x" seems to mean what x can truly *say* is real, and the idea is that if one person can truly say that something is real, so can any other person who is in the same place at the same time). This supposition seems indisputable, certainly in light of SR, which bans the idea of privileged observers. In particular, the theory emphasizes that neither of us enjoys privileged access to ontology, to "what there is". Thus, if the statue of liberty is part of my physical reality, then it seems natural to require that it be part of your physical reality as well, at least while you and I happen to be in the same place.

Next, we bring in the central consequence of SR, namely, that simultaneity is a frame-dependent relationship: two events that are simultaneous according to the clock of one observer may be measured to be temporally separated by other observers. To take an example, let us assume that three observers, α, β and γ,

[1]The tensed and tenseless views are sometimes also referred to as the presentist and eternalist views, respectively, or the A- and the B-theories or the dynamic and static views (though the different names do indicate some differences in substance).

[2]I am using Putnam's version of the argument (Putnam, 1975). Though the argument has been insightfully articulated by several other writers, Putnam's version continues to stand out in its clarity and conciseness.

intersect at a given moment. Let us call this event e_1. Let us also assume that another event, e_2, is measured by α to be simultaneous with e_1, and to be one billion kilometers apart from e_1.

Now, if β and γ are moving along the line connecting e_1 and e_2, β moving toward e_2 and γ away from it, each of them moving at roughly 50% of the speed of light with respect to α, then the time interval separating e_1 and e_2 according to β's and γ's clocks will be 32 min — in β's frame of reference e_1 succeeds e_2 by 32 min, and it precedes it by 32 min in γ's frame of reference.

Putnam's reasoning proceeds as follows. At the moment the three observers intersect, α determines e_2 to be a present event, and therefore a real event, for it is simultaneous with their intersection. But according to the "no privileged observers" assumption, at that moment, whatever is real for α is also real for β and γ. Hence, e_2 is real for β and γ even though it is past for β and future for γ. Thus, a fairly simple train of thought seems to compel us to renounce postulate (1), "All (and only) things that exist now are real" and to accept instead (2), "All future things are real, and likewise all past things are real, even though they do not now exist". In other words, we seem to have *empirical grounds* for concluding that the present is not "more real" than the past and future. Rather, all events, past, present and future, are "equally real".

Note that a disagreement between the three observers α, β and γ about the *time order* of the events is inconsequential. They can agree to disagree on this matter. That is, they can agree that according to α's watch e_2 is simultaneous with e_1, while on β's watch it precedes it and on γ's watch it occurs later than it. There is nothing to prevent such an accord, for these differences have no *further* implications. In particular, they do not imply any ontological disagreements, they say nothing about whether or not an event "really exists". Matters are different when it comes to tense. For tense, it is being assumed, has to do with an event's ontological status. Imagine a dispute between a tensed theorist and a tenseless theorist, as to whether or not e_2 is part of physical reality. Here, as Putnam puts it, they "cannot both be right" (p. 202) — the event is either real or not. So we are left with no other option but to forsake one of these claims; and relativity tells us that it is the tensed position that must give in. And, as explained above, forsaking (1) is taken to be tantamount to endorsing (2), the tenseless view.

But is it? We can now come to appreciate the pivotal role of the ontological assumption. The assumption, recall, is that the difference between the past, present and future concerns the ontological status of events, or, in other words that the issue concerning tense is whether past and future events are or are not "just as real" as present ones. It is this assumption that yields the forced choice: either (1) "All (and only) things that exist now are real" or else (2) "All future things are real, and likewise all past things are real, even though they do not now exist". Evidently, without this assumption, a rejection of (1) does not entail an acceptance of (2). Outside the framework of the ontological assumption, SR does not provide underpinnings for the tenseless view of time.

Let us, therefore, shift our attention to this framework. There are three claims that I wish to make about the ontological assumption. All three require elaborate defenses. In the context of the present paper, however, I will merely state two, and briefly outline an argument for the third.

1. The ontological assumption is the product of a philosophical investigation. Our pre-philosophical understanding of the distinction between the past, present and future does not involve ontological distinctions. The tensed language that serves us both in our ordinary transactions and in our theoretical and experimental scientific endeavors does not express, not even tacitly, any claims about the ontological status of events.
2. However, once we turn our philosophical curiosity toward time and tense, then claims concerning the ontological status of events will come up *inevitably*. Hence, we find them figuring in the works of almost all philosophers who have investigated time, from Aristotle onward.
3. Yet the ontological assumption cannot be sustained, and must be transcended. I say transcended because, being a vital and inescapable component of the philosophical inquiry, the ontological assumption cannot simply be rejected, circumvented or ignored. We must work our way through it. The result of this effort, however, is the realization that we do not really understand the ontological assumption, we do not know what sense to attach to the claims that past and future events are (or are not) "just as real" as present ones. Here is a brief summary of parts of the reasoning.

In general, assertions that something is (or is not) real are meaningful only when they can be used to rule out concrete ways in which the thing spoken of could be not real (or real)[3]. Accordingly, the question "Real or not?" can be meaningfully raised on a given occasion only if, on that occasion, a definite and relevant way in which the thing in question can be real, and a definite and relevant way in which it can be not real, are specifiable. Think of Jones telling you, as he points to a wrapped box: "you know, the thing inside *is real*".

[3]The observations I am relying on here are Austin's (1962, cf. his *Sense and Sensabilia*, esp. ch. VII).

Plainly, it is impossible to attach a definite sense to this utterance. The thing in the box could be a phone in the shape of a "Corvette", so it is a real phone (rather than, say, a toy phone) but a not real corvette (in contrast with the car many youngsters dream of driving). That one and the same thing can be a real *x* and a not real *y* means that assertions of the form "*x* is real" are meaningful only if on the occasion of their uttering it is clear what forms of being not real are being excluded (contrast this with "*x* is pink"). Smith points at a dog in the yard stating that that thing is real. Well, the thing in the yard could be a real dog rather than a perfect robot, or a real robot rather than just a dummy, in which case it is not a real dog. If on that particular occasion it is not clear what Smith has in mind to exclude, the listener will not be able to make out Jones's assertion. To put it in stronger terms, under such circumstances, appearances to the contrary, what Jones is uttering cannot even count as a proposition of language.

This is just as true of scientific reality claims. When it is asserted that, say, neutrinos "are real", or that they "really exist", what is meant, possibly, is that they are not like the ether, or like phlogiston, which were thought for a time to be real but lost this status as the theories they belong to became obsolete. Or, alternatively, it might be meant that they are not theoretical entities, of the sort that the electromagnetic potential was thought to be (prior to the discovery of the Bohm–Aharonov effect). It is *only* against such ways of being *not real* that assertions that something is real make sense. The converse also holds. To say that something is not real (as Bohr said of the neutrino) is to say nothing, unless it is clear what mode of being real is being excluded.

If these observations are valid, then it is not hard to grasp the gravity of the difficulties afflicting the ontological assumption. To so much as make intelligible the question "Are past and future events just as real as present ones?", we need to understand the assertion that present events are real. But what form of being *not real* is excluded by such an assertion? Needless to say, no one thinks that present events are real in that they are not toys, dummies, holograms or fictions. And to say that they are real in the way that past and future events are not begs the question twice — first, it already supposes that past and future events are not real, when the question is precisely *whether* or not they are; second, it assumes we understand the assertion that past events are *not real*, when the difficulty is that we do not really understand such reality claims. So, again, what specification could we have of how a present event can be *not real*? Plainly, none. But it is only against such a specification that a definite sense can be attached to the assertion that it is real. And, with the demise of the intelligibility of the claim that present events are real, the two theses at issue, viz., the tensed contention that *only* present events are "real", and the tenseless claim that past and future events are "just as real" as present ones, fall as well.

Some dismiss considerations of this type as unimportant, as pertaining to "ordinary language" rather than to scientific inquiry. Be that as it may, it remains pointless to parade arguments, and invoke scientific theories, in support of views that cannot even be intelligibly stated, or for settling a matter that has not been given a meaningful formulation. Tense poses a formidable philosophical challenge, which is bound to lead to the question of the reality of past and future events. But further analysis, of the kind just presented, shows that the challenge cannot be conclusively met by theories that answer the question "Real or not?", for neither the question, nor the theories, can be given sense.

The argument against the ontological assumption must be further elaborated, because adherents of either the tensed or the tenseless theories might claim that rather than assume the intelligibility of the ontological assumption, their theories endow it with meaning. We cannot, within the scope of this paper, consider this rejoinder in connection with every theory — scientific or metaphysical — in which the ontological assumption figures. Let us limit ourselves to our subject, SR. The rejoinder is that, just as SR gives the notion of "simultaneity" a new meaning, so it could be used to equip the "real"/"not real" distinction with a meaning and facilitate the articulation of the tenseless view, in addition to establishing its correctness. But, first this line entails that, indeed, without SR the theses of the tenseless view are not merely unproved, but are devoid of meaning, something none of the view's adherents has ever admitted. Second, it is not at all clear what *novel* interpretation of the reality claims of the tenseless view could arise out of SR. And finally, adherents of the tenseless view do not usually support it on account of its own merits, but rather because they find the alternatives indefensible. But then, if, as I shall claim in the next section, SR *can* be squared with our understanding of the difference between the past, present and future, then the impetus for conjuring up a tenseless view on the basis of SR vanishes.

2.

In this section I wish to suggest that, having gone beyond the tensed and tenseless theories, and beyond the ontological framework they belong to, we can smoothly import the understanding we *already* have of the difference between past, present and future from non-relativistic to relativistic situations. Needless to say, doing so requires that we spell out our understanding of tense. And this, as it turns out, is no small feat.

Before turning to it, there is another conclusion to draw from the transcendence of the ontological assumption, which concerns the "no privileged observer" assumption. I wish to assert that outside the ontological framework, the notion that co-presentness has to be a transitive relation is indefensible. Granted, it cannot be allowed that different observers will disagree as to what physical reality consists of, at least not at the moment they intersect: when α and β are next to each other, if event e is part of α's world, then it is part of β's world as well. So, as long as it is held that all and only present events are real, it must be acknowledged that if event e is real and present for α, and if α and β are present to each other, then e must be real and therefore present for β. Hence the transitivity of co-presentness. But, if "being present" is no longer identified with "being real", this argument for the transitivity of co-presentness no longer holds.

On the other hand, SR gives us a decisive reason to reject the transitivity of co-presentness. For, it teaches us that simultaneity is a frame-dependent relationship. And, plausibly, if α and β are simultaneous and α is occurring now then so is β; and, conversely, if both α and β are occurring now, then they are simultaneous. It follows that co-presentness is a frame-dependent, and therefore a non-transitive, relationship as well.

Let us return now to the difference between the past, present and future, and note a few things about what we take this difference to consist of, regardless of SR. As already stated above, this difference is not reducible to ontological categories, in the manner that both tensed and tenseless theorists would have it[4]. Nor is it reducible to epistemic differences, differences between what we know and what we do not know; or between what we can know or cannot know or between sentences to which we can ascribe a definite truth value and those to which we cannot, etc. In general, the difference between the past, present and future cannot be fleshed out in terms of some other differences. Rather, we must study it by describing how it operates in our experience, language and thought: our access to, grasp on and understanding of the difference between the past, present and future relies entirely on the manner in which this difference figures phenomenologically, though it cannot be reduced to phenomenology. Here is a preliminary and partial list of some salient features of this phenomenology:

(a) Events are always experienced, thought of and spoken of as possessing a tensed location. We do not always know whether a given event is past, present or future, but we cannot help thinking and speaking of it as being either past, present or future.
(b) Our experiences are typically accompanied by sentiments and modified by attitudes that are tense-based: we dread future painful experiences, and feel relief once they are past and over. Hope with respect to certain future

[4]Former adherents of the tenseless view, such as Russell, Quine and Goodman thought that tensed language could be "translated" to tenseless language, in principle at least. This reductive aspiration has been given up. Nowadays, tenseless theorists such as Mellor (1998) put forth arguments to the effect that such reductions cannot be carried out. Nevertheless, they defend the ontologically eliminative claim that there are no tensed facts, and explain the difference between the past, present and future in terms of an ontology in which all events are "equally real".

occurrences is replaced by satisfaction or disappointment once the event in question transpires and becomes past; and so on.

(c) Among the tense-based sentiments that are part of the phenomenology of tense, those that give us the contrast between the future's openness and the past's fixity need special mention. You are over the Atlantic. Imagine that you have flown from New York to London numerous times, and yet you are apprehensive. You remember the relief you felt after previous landings, but cannot rid yourself from the nervousness you are experiencing now. In addition, you are aware of the following contrasts: you know that the previous landings were successful, but do not know that the upcoming one will be as well; you take the specific features of the approaching landing to be undetermined, unlike those of previous landings; you have no doubts that the previous landings actually took place, but can easily imagine scenarios in which the upcoming one will not. You have records of past landings, e.g. memories and photos, but none of future experiences and events.

There are many other interesting and subtle ways in which the difference between the past, present and future manifests itself in experience, language and thought. And it is a major philosophical task to map out these manifestations, for it is from them alone that our conception of the difference between the past, present and future is derived. For our present purposes, however, the points just listed will do.

Let us remark the weightiness of the first observation, which entails that (phenomenologically) some distant events are present (they cannot all be either past or future), that is, simultaneous with events occurring here at present. In other words, (a) entails that a notion of distant simultaneity figures in our tense experience. Now, it may be objected that the notion of distant simultaneity is not an essential element of our experience; moreover, this notion rests on uneducated intuitions that relativity theory, with its relativization of simultaneity, renders questionable. But to reject this notion as an element of experience amounts to denying that in our experience, thought and language every event is tensely located, i.e. it is either past, present or future. This denial, I contend, is incoherent, though I cannot within the scope of this paper argue for this contention. Suffice it to note that, following the demise of the program to reduce tensed language to tenseless language, not even the staunchest tenseless theorists deny that our language, thought and experience are ubiquitously and unavoidably tensed. On the contrary, tenseless theorists agree that it is unclear what removing tense (and with it the notion of distant simultaneity) from our language, thought and experience would amount to.

Now, a theory that brings profound conceptual novelties may force us to eschew some of our conceptions, even those that are most deeply entrenched. But if it does not *force* us to do so, then the appropriate interpretative task is to show how the theory *can* be squared with those conceptions. To be sure, I am not claiming that the theory *must* be squared with pre-theoretical conceptions — we can always reject even deeply grounded conceptions. But such a rejection will be unmotivated, and in many cases even unintelligible, unless an accepted theory *necessitates* it.

Squaring a novel theory with existing conceptions may, of course, involve modifying some aspects of our conceptions while retaining their essentials. Specifically to our case, if we accept that tense, far from being a naïve and obsolete intuition, is indeed an indispensable element of our language, thought and experience then, unless we are forced to do otherwise, we should seek an interpretation of relativity theory that accords with this element rather than conflicts with it. In the previous section I demonstrated the failure of the main argument that purports to show that relativity theory forces us to abandon our conception of tense. Thus, our task is to accommodate tense within the framework of relativity theory, that is, to establish that the phenomenological manifestations of tense remain unaltered when we move to relativistic situations.

To discuss this, let us add some detail to the story presented above. Let us assume that event e_2 is the closing of the ballots in some inter-galactic elections. Event e_1 continues to be the intersection of α, β and γ. Recall that e_1 and e_2 are co-temporal according to α, but that at the moment of the intersection, e_2 is already past for β and yet future for γ. This means that at the moment of their intersection, the elections are over for α and β, and their results fixed, while for γ the race is still open, with 32 min remaining before the outcome is decided. A peculiar state of affairs indeed, which, however, does not undermine the acquaintance α, β and γ already have with tense from non-relativistic situations. The key to seeing that it does not lies in the fact that, even though the closing of the ballots is present, past and future for α, β and γ, respectively, no disagreements arise between them.

First, let us note that there is no dispute concerning the elections' results. This is a consequence of the same fundamental stipulation of SR that yields such unusual scenarios, namely, that there is an upper bound on the velocity of light and of the transmission of information. Thus, since in α'*s* frame of reference the elections are taking place one billion kilometers from where she momentarily crosses paths with β and γ, she can receive the radio announcement of the results no less than 55 min after the intersection. If α then decides to radio the results to β and γ, her transmission will not reach them before the original transmission from which she herself learned the results reaches them. The same is true of β and γ: they cannot inform their fellow observers of the results prior to the arrival of the announcement transmitted from the elections. So it cannot happen that, when the three observers are together, one of them will know something the others do not. Equipped with this fact let us examine the phenomenology of tense in the context of the relativistic scenario α, β and γ are in.

To begin with point 'a' of the above list, the three observers think and speak of the closing of the ballots as a tensely located event. They do not know any better than we do what to make of the notion that an event is neither present, nor past nor future. To repeat, few, if any, tenseless theorists deny that tense is an indispensable and irremovable feature of our experience, thought and language. It continues to be indispensable and irremovable also in relativistic situations.

Moreover, the experiences of the three relativistic observers continue to be accompanied by the very same tensed-based sentiments and attitudes that are so central to the ordinary phenomenology of tense (point 'b' above). For α and β the elections are over, but they do not yet feel the joy of victory or the disappointment of failure. Together with γ, for whom the elections are still in progress and undecided, they anxiously await the results. Indeed, it would have been disastrous for the observers' conception of tense if, in relativistic situations, their sentiments and attitudes would have been disrupted. If, for example, β could cause γ to experience joy or disappointment about a race that for γ is still open; or if γ could raise in β's heart hope for a victory in a race that β knows to have lost, both would lose whatever grasp they have of the difference between past, present and future. But, since tense-based sentiments depend on what one knows, and since, as pointed out, none of the observers knows something the others do not, such inversions do not occur in relativistic situations. Rather, β's condition is, in all relevant aspects, just like that of someone who voted in some ordinary, earthly elections but could not receive word of their conclusion (was on an airplane, or without electricity at home, etc.) until several hours after they were over.

And the contrast between the past's fixity and the future's openness continues to be part of the three observers' experience of their relativistic world as well. γ is troubled by the possibility that the elections will be interrupted before the ballots are closed. α and β think and speak of the closing of the ballots in the past tense, as an event the occurring and outcome of which are no longer in question, though, given their particular situation, they do not yet know that the elections terminated smoothly. Needless to say, γ cannot induce in α and β a future-tense worry that the elections will not end as planned, and α and β cannot instill in γ a past-tense certitude that the elections were successful.

Admittedly, the scenario described harbors confusions of a kind we are not familiar with. Imagine that Wolf, an acquaintance of α, β and γ, is one of the candidates in the elections, and that at the moment the three intersect, β muses out loud "I wonder how Wolf is feeling now". What would happen if the three were to share their thoughts on the matter? α might think that Wolf was "probably very tense, now that the ballots are closing", while γ would guess that "knowing Wolf, she's still trying to persuade hesitant voters, and will continue doing so in the half hour left until the ballots close"; β tries to imagine how Wolf is coping with the result, which he believes has been known to her for the past half hour. This is unquestionably a curious state of affairs. But, here too there will be no disagreements between α, β and γ. Each will know the others' temporal relation to the closing of the ballots, and will understand why the question "I wonder how Wolf is feeling now", prompted the different reactions that it did. Like with other frame-dependent magnitudes, such as mass, or spatial and temporal length, the agreement that marks objectivity will be, not about the magnitudes themselves, but about how these are measured by each of the observers[5].

If the above provides a plausible account of how the difference between the past, present and future can be accommodated within relativistic situations, then it exposes the weakness of a different approach, several variations of which appear in contemporary literature. According to this proposal the present is spatially restricted. There are both tensed and tenseless versions of this idea. The best known tensed construal is Stein's, who derives as a theorem the conclusion that the only relationship of temporal "becoming" that satisfies certain constraints (among them a transitivity requirement) is one in which "becoming" is relative to a point in spacetime: given an event e — a point in spacetime — all and only events that are in e's past light-cone have "already become" and are "ontologically fixed and definite[6]" with respect to it[7]. In essence, then, the boundaries of an event's past consist of its past light-cone; its future lies within its future light-cone and the present is conceived as that which is both *now* and *here*[8]. Others defend the notion of a spatially localized notion of "becoming" within the well-known "Block Universe" picture, which is often, though not always, taken to constitute a brand of the tenseless view (cf. Dieks (1988) and Savitt (2000)).

However, the spatially localized present does not cohere with the first, and perhaps most undeniable feature we can read off from the phenomenology of tense, namely, that every event is tensely located. For according to this proposal, events that are spatially separated from a given point in spacetime are not past, nor present nor future with respect to that point. Think of the following

[5]For some, such agreement is not enough. Saunders (2002), for example, seems to insist that only invariant magnitudes are "physically real" (whatever "real" means here). Obviously, those who deny that frame-dependent masses and lengths are part of physical reality will not accept that events have frame-dependent tensed locations.

[6]Stein (1991), p. 148. These formulations are taken from Maxwell's (1985) paper.

[7]More technically, with "*Rab* signifying that the state at b is definite as of a" then, "if R is a reflexive, transitive relation on a Minkowski space, invariant under automorphisms that preserve the time-orientation, and if *Rab* holds for some pair of points (a, b) such that ab is a past-pointing (time-like or null) non-zero vector, then for any pair of points (x, y), Rxy holds if and only if xy is a past-pointing vector" [Stein, (1991), p. 149].

[8]Stein's proposal is further developed by Clifton and Hogarth (1995) in their "The Definability of Objective Becoming in Minkowski Spacetime".

scenario. You are at the control center in Houston, where the monitors are showing pictures of an astronaut inside a spacecraft, preparing for a telescope-reparation space-walk. She is some 10 light-hours away, and so the pictures you see are 10 h old. You glance at the large clock ticking on the main screen. It indicates that the reparation has just begun. You pray everything is going well. Of course, it will be almost 10 h before the first report about the reparation will reach Earth. Still, you know that, unless something unexpected happened, the reparation is taking place *now*. But if the present is spatially localized, such a thought is misguided — the reparation is too distant to count as present. And, of course, there is no sense in which you can think of it as already past or yet future. This is in plain contradiction to the claim that events are inevitably thought of and spoken of in a tensed manner.

Moreover, distant events that are future with respect to a given point, become past without ever being present! To return to our story, 2 h before the closing of the ballots, this event lies within *a*'s future light-cone, and is therefore future for her. She may even participate in the elections, e.g. by radioing her vote. Three hours later, she receives the results, at which time the closing of the ballots is inside her past light-cone. But being a distant event, it is never present for *a*: there is no moment when she can say or think truthfully: "the ballots are closing *now*". Rather, after conceiving the event as future, she apprehends it as neither past, nor present nor future, and after a little while longer it suddenly becomes past. I do not believe we can make sense of such ideas. To the contrary, no matter when *a* thinks or speaks about the closing of the ballots, she inescapably thinks of it as either past, or present or future. If this is true (as most tenseless theorists would grant), then the localized-present view, in either its "Steinean" tensed version or in its "block universe" versions, is untenable.

The impasse reached with proposals grounded in the ontological assumption, such as those discussed in the last paragraphs, leads back to the alternative I have been defending: shunning reality claims, which purport to capture the difference between the past, present and future; accepting the non-transitivity of co-presentness; and working out a detailed description of the manifestations in our experience, language and thought of the difference between the past, present and future. I have offered beginnings of such a description a few pages back. To repeat, it is via such descriptions of the phenomenology of tense that a sound conception of tense can be obtained. This conception, I claim, holds good in relativistic situations as well.

3.

The impact of science cannot be overestimated. Science has shaped the manner in which we set out to study our world, and our understanding of almost every aspect of it. It has also brought about deep changes to our world. However, certain undesirable dogmas have emerged alongside science's successes. One is that whatever is not banned by science is actually possible. Time travel is a famous time-related example of an idea that seems to be compatible with our best scientific theories but which, nevertheless, many believe should be ruled out as impossible, if not unintelligible, on other, extra-scientific, grounds. Another dogma is that if something is not part of the ontology of physics, then it is not part of the world. Let us call this "the exclusivity dogma". Now, it is easy to see this dogma prescribing the thought that if the difference between the past, present and future does not show up in Minkowsky spacetime diagrams, then it is not part of reality. I wish to suggest that the conviction that physics has done away with tense and with time's passage is indeed driven, in part, by this dogma.

This conjecture, however, can be disputed on the following grounds. First, tense does not show up in Newtonian phase-space diagrams either. Looking at the trajectory of a system, what one sees is the state of the system at any given moment of the time interval represented in the diagram, not the state of the system *now*. In this respect, tense was *never* part of the ontology that can be read off from physics[9]. Yet no scientifically based arguments against the reality of tense were put forth prior to SR, a fact that suggests that these arguments stem from SR, and not from "the exclusivity dogma". Second, the argument from relativity theory seems to say something much stronger than that tense is not part of the ontology of physics. It seems to say that tense cannot, without contradiction, be incorporated into the ontology of physics. If so, then relativity establishes the unreality of time irrespectively of "the exclusivity dogma".

Still, despite these rejoinders, I believe "the exclusivity dogma" plays a pivotal role in the argument against the reality of the difference between the past, present and future. Consider the first. Newtonian physics was not invoked for the sake of arguing against the reality of tense for two reasons. First, it is the unprecedented stature that physics has attained in the 20th century, to a large extent due to relativity theory, which made it, in the eyes of many, the sole authority on ontology. Since "the exclusivity dogma" itself is a creation of 20th century culture, it was not part of the era of Newtonian physics and so was not used in connection with it. Second, modern philosophers were not really pre-occupied with the reality of tense prior to the appearance of McTaggart's *The Nature of Experience*, which was published in 1921, when SR has already re-placed Newtonian physics as the scientific reference for such queries.

As for the second rejoinder, once it is noted that there are ways of squaring tense with relativity — the spatially restricted present and the approach offered

[9]That is not to say, of course, that Newton was a tenseless theorist. The theory did not exist at the time and Newton never questioned that time flows. Still, though the notion of time's passage can be combined with Newton's physics, it is not part of it.

in this present paper are examples of such ways — the supposition that in the context of relativity tense terms are contradictory and that, therefore, physics forces us to exclude tense from our ontology, loses its strength.

The aforementioned dogmas are not the product of physics, but of philosophy, or of a certain brand of philosophy. In what was one of the manifestos of Logical Positivism, *Empiricism and Sociology*, Neurath wrote: "this much is certain: *there is no such thing as philosophy as a basic or universal science alongside or above the various fields of the one empirical science*". Philosophy, according to Neurath's vision, is to blend into the existing empirical sciences, where the questions it can meaningfully pose, find their answers. In particular, questions such as whether a given x is real or not (where x could be the difference between the past, present and future, a moral or aesthetic value, free will, etc.) were deemed either meaningless and not worthy of discussion, or scientific and capable of being decided empirically. Philosophical texts such as Neurath's thus became the birthplace of dogmas, which, as they became entrenched, brought about the marginalization of philosophy, and the shifting of much of the clout it enjoyed to the sciences. Physics, above all other sciences, was crowned as an exclusive authority on ontological matters.

But it is not. Assessing the philosophical, and in particular, the ontological significance and implications of the theories of physics, continues to be a philosophical task, in which considerations that are beyond those of physics, non-scientific considerations, such as phenomenological ones, are vital for the task's success.

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Chapter 10

Philosophical Consequences of the Twins Paradox

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Abstract

Under suitable circumstances, Jill may travel to a nearby star and back while her twin Jack remains at home, and when they reunite he will be 10 years older then she. A diagram which explains the age discrepancy shows that in Minkowski spacetime the law of triangle inequality holds in reverse: $dt_1 > dt_2 + dt_3$. But neither this nor a proper understanding of the train/tunnel paradox implies that 4D explanations are always superior to 3D explanations. It is argued that to bestow a metric on 4D spacetime requires 3D rods and clocks, which endure through time rather than perduring. This line of thought, which holds that length depends on congruence, and that congruence depends on measurement, is in accordance with that of Riemann and Poincaré rather than Russell, who maintained that measurement is successful if and only if it yields a quantity possessed by an object before it is measured. The notion that spacetime has an "intrinsic metric" is rejected. In reference to the question, does the world *really* consist of 4D objects, or does it consist of enduring 3D objects, the answer is that 3D and 4D descriptions are intertranslatable, and that *both* are needed for an adequate understanding of physical reality. Finally, time flow, measured by 3D clocks such as Jack's and Jill's heartbeats, is (i) objective, but (ii) particular to different frames of reference, and does not take place in a single preferred frame.

1. The paradox

The twins paradox runs as follows. Jack stays on earth while his twin Jill steps into her spaceship, rounds Alpha Centauri at 3/5 the speed of light, and returns. Since at this speed the time dilation factor is 4/5, when she gets back Jack has aged 50 years while she is only 40 years older (Darwin, 1957; Resnick, 1968, pp. 201–209). In the special theory of relativity, the difference in ages is explained by the fact that when Jill changes direction and starts to return to earth, her "simultaneity classes" — the sets of events which partition spacetime in the different inertial frames she inhabits — undergo a sudden change (see Fig. 1).

Jill's journey outward from A to B, and homeward from B to C, each takes 20 years as registered by her clock. The events on earth which are Jill-simultaneous with events on her voyage are marked by the intersection of her different "now" lines with Jack's spacetime trajectory. Jack's age increases along his lifeline, going straight from A to C. When Jill changes her inertial frame at B and heads back to earth, her "now" lines move abruptly upward on Jack's lifeline, leaving a gap between X and Y. Suppose that in her absence, in the space of 50 years, Jack reads *War and Peace* three times. Then Jill can truthfully say, as she journeys outward, "He is now reading *War and Peace* for the first time", and coming home she can say "He is now reading *War and Peace* for the third time". But on the assumption that Jill's turnabout is instantaneous, there is no time at which Jill can say that Jack is reading *War and Peace* for the second time. If Jack gets married during the interval XY, there will be no period on Jill's clock which corresponds to the wedding ceremony. For her, the middle section of Jack's life goes by in a flash, and this explains why there is the difference in their ages. It does not explain the *quantitative* difference, since the gap XY is 18 years and when they reunite Jack is only 10 years older. But it does explain why, in Jill's reference frame, there are "missing" events in Jack's life.

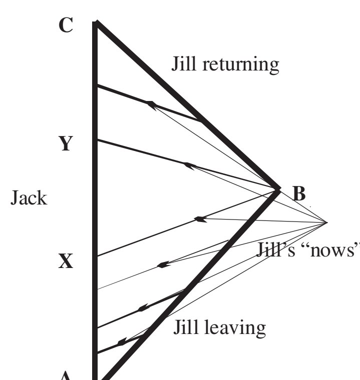

Fig. 1. The Twins Paradox.

Since Jack inhabits only one inertial frame[1] in contrast to Jill's two, their situations are asymmetric. On Jack's clock, there are no missing events in Jill's life.

Figure 1 provides an intuitive explanation why, in 4-dimensional (4D) relativistic geometry, the sum of the lengths of two sides of a triangle composed of time-like inertial lines is always less than the third side. (An inertial line is the path of a body at rest in an inertial frame.) Since for any inertial line $dx = dy = dz = 0$, and since $ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$, the length ds of a line segment is equal to the elapsed time cdt. Dividing by the constant c, let the lengths of the segments AC, AB, and BC be dt_1, dt_2, and dt_3 respectively. Then Fig. 1 explains why, in Minkowski geometry, triangle inequality operates in reverse of Euclidean geometry.

$dt_1 > dt_2 + dt_3$

In Fig. 1, $dt_1 = 50$ years, $dt_2 = dt_3 = 20$ years, and $50 > 20 + 20$. To be sure, in real life Jill's turnaround at point B is not instantaneous, and the triangle ABC will have a curved apex at B. Only in the "three clock paradox" (Bondi, 1964, pp. 80–87; Marder, 1971, pp. 73–78, 112–113; McCall & Lowe, 2003, pp. 119–120) will ABC be a perfect triangle. In the three clock paradox clocks 1 and 2, each travelling in its own inertial frame, are synchronized at A, and clocks 2 and 3 are synchronized at B. When 1 and 3 are compared at C, they are found to disagree. But although in real life Jill's turnaround at B is smooth rather than abrupt, it occupies only a tiny fraction of her overall voyage. Consequently, during the turnaround, there may be a period of only a few hours during which she can truthfully assert that Jack is making a second reading of *War and Peace*. During that period years of Jack's life are, for her, condensed into a matter of minutes. Their loss explains why, in relativistic spacetime, triangle inequality holds in reverse.

2. Three dimensions or four?

Since the appearance of Quine's 1950 paper "Identity, ostension, and hypostasis", a protracted, lively debate has taken place between contemporary followers of Heraclitus, and contemporary followers of Parmenides. Heracliteans believe that the world is made up of 3D objects, which endure and change in time, while retaining their identity from one moment to the next. Parmenideans, on the other hand, believe that the world is a changeless 4D spacetime continuum, containing material objects that are 4D worm-like volumes extended along the time dimension. Viewed along the time axis, these 4D worms twist,

[1]If Jack is on earth, he is being continuously accelerated by the pressure on the soles of his feet. A "pure" version of the twins paradox would have Jack floating freely in an inertial frame in space.

enlarge, shrink, and touch each other so as to perfectly mimic the motions and changes of 3D objects. The ontological question for metaphysicians and philosophers of science is this: is the physical world *really* 3D or 4D?

Philosophers who argue for a 4D ontology include Quine (1950/1953, 1960, 1981); Smart (1972); Perry (1972, pp. 466–469); Armstrong (1980); Lewis (1983, pp. 76–77, 1986, pp. 202–204, 2002); Heller (1984, 1990); Sider (1997, 2001); Le Poidevin (2000). Some 4D supporters prefer a ''worm ontology'', according to which ordinary objects such as teacups and butterflies are entire elongated 4D volumes. Others consider the basic ontological building blocks to be ''temporal parts'', instantaneous or thin temporal slices of 4D volumes. For Quine, a purportedly enduring object such as a rabbit is in reality composed of ''rabbit stages'', short segments of the history of a rabbit. (An instantaneous rabbit slice, though 3D, must plainly be distinguished from a 3D rabbit that endures and changes through time.)

Opposed to the 4D school are those who believe that the physical world is made up of 3D objects which move and interact, are created and destroyed, and retain their identity throughout the time they exist. These are the things Aristotle calls ''individual substances'' (*Categories*, Chapters 2–5). Philosophers who favour a 3D ontology include Geach (1965/1972); Chisholm (1976, Appendix A); van Inwagen (1981, 1990); Mellor (1981, p. 104); Thomson (1983); Lowe (1987, 1998, pp. 114–125); Simons (1987, 2000); Haslanger (1989, 1994).

The choice between 3D and 4D is sometimes presented as a choice between common sense and science. We can explain the workings of a steam engine in terms of the translations and rotations of 3D pieces of steel, driven by the expansive force of steam. But how are we to explain the famous train/tunnel paradox without recourse to 4D ontology? A train, stationary in a tunnel, fits exactly inside it. But if the train is backed up and run through the tunnel at speed, observers on the ground will record the ends of the train fitting comfortably inside the tunnel at the instant when the centre of the train coincides with the centre of the tunnel. If the ends of the tunnel have glass tops, a helicopter stationed above the tunnel's mid-point will take a photograph showing the entire train inside the tunnel with room to spare. The photo shows the train to be shorter than the tunnel. But at the same instant an airplane, flying above the tunnel with the same velocity as the train, takes a photo showing the two ends of the train protruding from the tunnel. How can there be two photographs, shot from above, one showing the train to be shorter than the tunnel and the other showing it to be longer?

The photograph-version of the train/tunnel paradox presented in the previous paragraph needs fuller discussion, given that the photons travelling upwards to the cameras take time to complete their journey. Imagine that the helicopter contains a movie camera, which is positioned above the midpoint of the tunnel, and which takes numerous shots of the train as it first enters and then exits the tunnel. Let time (*a*) be the time it takes a photon to travel from the front end of the train to the camera, time (*b*) the time from the rear end to the camera, time (*c*) from the tunnel entrance to the camera, and time (*d*) from the tunnel exit to the camera. Since the tunnel is stationary and the camera is centered, we have, in the tunnel's rest frame, time (*c*) = time (*d*) always. There will, however, be only one instant at which time (*a*) = time (*b*). That instant, *t*, will be when the train is positioned symmetrically under the camera, with its midpoint immediately underneath. Before *t*, time (*a*) < time (*b*), and after *t*, time (*a*) > time (*b*).

When the two light rays, or light packets, emitted at *t* from the train's back and front, converge on the camera accompanied by the "constant" light rays from the two ends of the tunnel, the resulting photo will show the train entirely within the tunnel, with something to spare at each end (as revealed by the glass roof).

Consider now the situation in the rest-frame of the train, where the tunnel is in motion. Assume that the camera in the airplane remains centred above the midpoint of the train, looking down. In the train's rest-frame, we have time (*a*) = time (*b*) always, since the time taken for a photon to travel from the front end of the train to the camera in the airplane always equals the time taken for photon to travel from the rear end of the train to the camera. But there will be one instant only at which time (*c*) = time (*d*), and when the photons emitted at that instant arrive at the camera they will show the two ends of the train sticking out from the tunnel. The two photos, from two different cameras, show different relative lengths of train and tunnel.

The most obvious and most elegant resolution of the paradox comes by treating the train and the tunnel as 4D objects. In the tunnel's inertial frame, the train is shorter; in the train's frame, the tunnel is shorter. 4D diagrams, which make everything clear, are found in Maudlin (1994, p. 54) and Balashov (2000, p. 336). For many philosophers, the train/tunnel paradox demonstrates that while a 3D ontology suffices for ordinary purposes, true scientific understanding of the world requires four dimensions.

In Section 5 it will be argued that, rightly seen, the choice between 3D and 4D is a matter of "both/and" rather than "either/or". In the next section I shall argue that full and adequate foundations of a theoretical framework in which to situate the twins paradox can be achieved only by recognizing the existence of both 3D and 4D objects. Explanation using 3D elements complements explanation using 4D elements, and vice versa. Neither alone covers every situation: both are needed.

3. The metrization of spacetime using 3D elements

When Jack and Jill meet after Jill's journey, she has aged 40 years and he has aged 50. What testifies to this? Their clocks, and the wrinkles on Jack's face. In

Minkowski spacetime, the length of Jack's world-line, measured by the difference of his time coordinate at the start and end of Jill's journey, is 50 units. To give the answer "50 years" to the question "How long is Jack's world-line between A and C?" presupposes that the region of spacetime that encloses the twins is *metrized*, that it has a metric. If it did not, spacetime would support only an affine geometry, and there would be no answer to the question about Jack's world-line in the last sentence. But, in the metric space enclosing the twins, what philosophical meaning is to be attached to a statement like "Jack wiped his eyes 5 minutes after Jill left"? Does spacetime come equipped with some intrinsic metric, a little pointer that indicates "5 minutes" as the temporal length of that interval? No. The only conceivable entity that can bestow a metric on the time coordinate of Jack's frame is a clock. And a clock is a 3D object. In the same way, the only conceivable entity that can metrize spatial dimensions is a rigid measuring rod, a 3D object that can be transported and applied repeatedly to spatial intervals, giving them a length. Without 3D objects, 4D space would lack a metric.

I can sense criticism building in the face of what many will consider an unacceptably operationalist approach. An obvious rejoinder would be: "The clock does not *give* the temporal interval a length, it merely measures the length that the interval *already has*". Thus Russell, in his debate with Poincaré in the years 1897–1900, rejects Poincaré's basing of the equality of spatial and temporal intervals on an external (and therefore conventional) definition of "congruence". Russell appeals to the idea of an intrinsic spatial metric.

> Whatever one can discover by means of an operation must exist independently of the operation: America existed before Christopher Columbus, and two quantities of the same kind must *be* equal *or* unequal before being measured. Any method of measurement is good or bad according as it yields a result which is true or false. M. Poincaré, on the other hand, holds that measurement creates equality and inequality. (Russell, 1899, pp. 687–688, translated in Grünbaum, 1963, pp. 44–45)

One can sympathize with Russell's stout realism, but the question of what makes two intervals objectively or intrinsically equal remains unanswered. Riemann, in his inaugural lecture of 1854, had pointed out that if space were discrete or granular, one could determine the equality or inequality of two intervals by counting. (See Grünbaum, 1963, Chapter 1 for a detailed discussion of these issues.) Such a method would yield an objective, intrinsic result. But since physical space as far as we can determine is continuous, not discrete, the method of determining equality of intervals cannot proceed by counting, but must be by way of measurement. For Riemann, "Measuring consists in superposition of the magnitudes to be compared; for measurement there is requisite some means of carrying forward one magnitude as a measure for the other" (Riemann, 1854/1959, p. 413). Riemann's words "superposition" and "carrying forward" clearly imply the use of a ruler, i.e. a rigid body which establishes the congruence of two intervals by (i) occupying the first, then (ii) being carried forward, and finally (iii) occupying the second. Without the availability of a 3D transportable measuring device, 4D spacetime intervals (which are not transportable) cannot be said to be equal, i.e. will not *be* equal. For this reason a purely 4D ontology is ultimately untenable. Without 3D measuring rods and clocks, no adequate philosophical account of the notion of spatial or temporal congruence, and consequently of spatial or temporal length, is possible.

To this it might be objected, and indeed *has* been objected by at least one colleague, that I have no warrant for assuming that clocks and rods must be 3D objects. Why could they not be 4D? In fact my colleague thinks they *are* 4D. He asks, how could they be used to measure 4D intervals if they were not? This objection goes to the heart of what I am saying about the necessity of complementing a 4D description of the world with 3D elements. What I am saying is that it is impossible to give a clear philosophical account of *measuring* intervals, or of two intervals being *congruent*, or for that matter being of *different lengths*, without the concept of a 3D rod or a 3D clock. The essential thing about a rod, or a clock, is that it must be the *same* rod or clock from one moment to the next, i.e. when we apply it first to one interval, and then to another. In addition rods must remain the same length, and clocks must tick at the same rate, under conditions of slow transport. That is what measuring is all about. Riemann had it right here. E.g. if it were not the *same* (rigid) rod when we apply it to interval Y as it was when we applied it to interval X, we would not have the slightest reason for judging the two intervals to be same length, or different lengths. Now, what sorts of things are (identically) the same from one moment to the next? Answer: 3D things. Using what is now accepted terminology: 3D things *endure*, while 4D things *perdure*. (For further discussion of this distinction, a clear definition of "endurance", and the philosophical desirability of retaining and making use of *both* the concepts of endurance and perdurance, see McCall & Lowe, forthcoming.) Something perdures in virtue of having different temporal parts at different times. It extends temporally. In the same way, for example, a road extends spatially in virtue of having different spatial parts. But how do we know whether two different spatial parts of the same road are of the same length? Only by taking a 3D ruler and transporting it from one region to another. The only criterion for saying two intervals are congruent is to apply a measuring device (rod or clock) to them and see if they agree. And this measuring device cannot be a 4D object, it must be a transportable, enduring 3D object. Otherwise you cannot measure with it.

To sum up the results of this section, it might be thought that our ordinary 3D notions of physical objects moving, changing, and existing through time must give way to more sophisticated 4D conceptions if we are ever to understand the sometimes astonishing effects of special relativity. But in fact the notions of *length* and *duration* rest upon *congruence* and *measurement*, and the latter are inexplicable without 3D measuring devices. In the world of modern science, the 3D and the 4D ontologies are inextricably interlocked, and one cannot be privileged to the exclusion of the other. Instead, both are needed.

4. 3D/4D equivalence

In this section it is argued that the 3D and the 4D ways of looking at the world are even more closely linked. Not only are both needed in science, but they are in fact *equivalent* in the sense that, given a 3D description of something, it can be translated without remainder into a 4D description and vice versa. A 3D description of a tadpole changing into a frog over a period of 3 weeks can be translated into a 4D description involving an elongated tubular volume with tail-like and leg-like protuberances, immersed in its early stages in 4D water and in its later stages in 4D air. Conversely, the 4D description is translated by taking 3D cross-sections of the 4D volume at different levels, revealing a creature with a tail and gills lower down, and a tail-less air-breathing animal higher up. These 3D sections are "snapshots" of a 3D continuant that endures through time while moving and changing every moment.

Figure 2 is a 4D picture of a yardstick measuring a bolt of cloth. Without the equivalent 3D description, which shows the ruler establishing congruence, no sense can be attached to the assertion that the 4D intervals 1–3 are of equal length.

True equivalences of the 3D/4D kind, based on intertranslatability, are rare in philosophy. A different example derives from A.N. Whitehead's method of extensive abstraction. In geometry, lines or volumes can be regarded as sets of

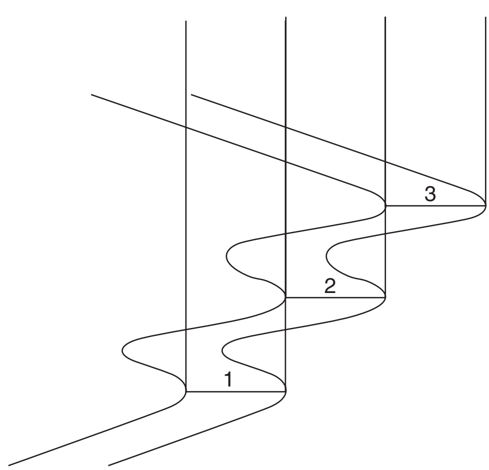

Fig. 2. 4D picture of a 3D ruler.

points, and consequently a philosopher studying the foundations of geometry might come to the conclusion that his ontological primitives were points, and that other geometrical notions could be defined in terms of them. What Whitehead demonstrated, however, was that this definition could be reversed, and that a "point" could be defined as an infinite descending nested set of volumes (Whitehead, 1920, Chapter 4). Given the interdefinability of the two notions, any description of a geometrical figure in terms of "points" can be translated into a description in terms of "volumes", and vice versa.

Before Whitehead's discovery, a philosopher who asked whether physical space was "really" made up of points, or "really" made up of tiny volumes, could perhaps be taken as raising a genuine foundational question. But in the light of point/volume equivalence, the ontological issue disappears. In the same way, given the intertranslatability of 3D and 4D descriptions of the world, the ontological question of whether the world is "really" 3D or 4D also disappears. In order to understand physical reality, in particular some of the more bizarre phenomena of the STR, 4D descriptions are necessary. But to understand the concept of 4D length, and its relation to measurement, 3D descriptions are equally necessary. Since the two are equivalent, the ontological question of whether the world is "really" 3D or 4D makes no more sense than to ask whether physical space is "really" composed of points, or "really" composed of tiny volumes.

5. The ontology of spacetime

We come now to the central issue of the volume: the ontology of spacetime. Consider the thesis of 3D/4D equivalence put forward in the last section. Vesselin Petkov has objected that although 3D and 4D *descriptions* of the world are equivalent, 3D and 4D *ontologies* are not. Petkov argues that since a 3D space and the objects it encloses is a subspace of 4D spacetime, physical reality must be one or the other, it cannot be both. If we assume that the physical world consists of the totality of presently existing 3D objects, this totality plus the space in which it is embedded constitutes a 3D "simultaneity slice" of 4D spacetime. To assert that this slice constitutes physical reality is inconsistent with relativity theory, for which there is no unique set of events simultaneous with "now". The same goes for objects: the set of objects which exist "now" is observer-dependent, and cannot be taken as constituting the physical world in any objective sense. Petkov's conclusion is that physical reality cannot be 3D, but must consist of the whole of 4D spacetime. There is therefore no "equivalence" between 3D and 4D ontologies.

Petkov's conclusion would be correct if "3D object" meant "instantaneous state of a 3D object". Thus a given observer's simultaneity class is a global 3D space which includes innumerable "objects-at-an-instant", and it might seem that the choice between a 3D and a 4D ontology was the choice between this simultaneity slice and the whole of 4D spacetime. But "3D object" can also mean something quite different, namely a 3D object that endures and exists *through* time as opposed to *at a time*. An object's existing *through* time does not make it into a 4D object. A rabbit that lives for 8 years is not a 4D rabbit, but a 3D rabbit that exists continuously over a period of 8 years. If the central ontological question is rephrased so as to pose a choice between 4D spacetime, and a universe of 3D objects that exist through time, then the 3D/4D question is put in quite a different light. Since the 3D objects which are proposed as making up the world are not merely objects which exist at *some specified moment*, but instead include all objects which exist *at any time*, relativity theory has nothing to say about whether the ultimate choice of ontologies must be 3D or 4D. There need be no suggestion that 3D existence must be "relativized to an observer", and a 3D ontology can include past individuals such as Julius Caesar, present ones such as Nelson Mandela, and future ones such as the 50th prime minister of Canada.

Concerning the central question which this book addresses, the question of the dimensionality of reality and the ontological status of 4D spacetime, the present paper takes the position that no choice between 3D and 4D ontologies is forced upon us. That is to say, there is no "fact of the matter" as to whether the world is 3D or 4D. For certain purposes and in certain contexts it is enlightening and revealing to regard it as 4D, as for example, when we are trying to understand how a train can be photographed as being both longer and shorter than a tunnel, or how two twins can be different ages when they are reunited after a long journey. For other purposes, we are forced to recognize the continued existence and self-identity of 3D objects in time, as when we use a clock to record the length of a journey or a ruler to measure a piece of wood. Not only are the 3D and the 4D descriptions of the world indispensable, they are equivalent, and it is not a question of one being true and the other false. All of which is to say that there is no answer to the question, is the world *really* 3D or 4D? It is *both*, or *either*, depending on the type and degree of understanding that we seek.

6. The nature of time

There is one more important topic to be dealt with. According to the thesis of 3D/4D equivalence Jack and Jill can be regarded as 4D objects, or they can be regarded as 3D objects existing through time. But if the latter, what time do they exist in? Since when they reunite Jack is older, it would seem that Jack has lived more than Jill. What if anything does this tell us about the nature of time?

A frequently encountered reaction to the twins paradox is that elapsed time, or proper time, is "path-dependent". Jack and Jill follow different paths in spacetime, Jill's being broken and Jack's straight, and consequently their total elapsed times differ. This is correct as far as it goes, but ignores the fact that *any* inertial path in frame f_2, followed by an inertial path in frame f_3, will be shorter than a single inertial path in frame f_1 if the three paths form a triangle. Imagine for example, an infinity of distinct triangles of the same size and shape as triangle ABC of Fig. 1, located in different parts of spacetime. These triangles are made up of infinitely many line segments A′B′, parallel to and congruent to the inertial line AB in frame f_2, infinitely many segments B′C′ parallel to and congruent to BC in frame f_3, … etc. Yet they all share the characteristic that in each case the sum of the temporal lengths, or proper times, of the segments A′B′ and B′C′ will be less than the lengths A′C′ by exactly the deficit in Jill's age as compared to Jack's. What this shows is that quantity of elapsed time is common to all congruent segments of inertial lines in a given frame, and therefore that time flow, and elapsed time, are in the most general sense *frame-dependent* rather than *path-dependent* concepts.

What is a spacetime coordinate frame? Ignoring for the moment the metric aspect, i.e. the calibration of the *x*-, *y*-, *z*- and *t*- axis, a frame is essentially a partition of spacetime by parallel hypersurfaces, each of which is orthogonal to the time axis of the frame. Every distinct inertial frame partitions spacetime differently. Our image of spacetime is comparable to the surface of a vast ocean, agitated by parallel wavetrains moving in every direction. The difference between the cosmic ocean and a real ocean is that the cosmic wavetrains do not exhibit interference, but pass harmlessly through each other. At a purely affine level, this is part of the structure of Minkowski spacetime.

When we come to assign a metric to spacetime, a clock is needed to define the relationship of temporal equality of intervals. As discussed earlier, there are no 4D clocks. A 4D volume with regular markings along the time axis provides no guarantee that the markings are equally spaced. There is therefore no substitute for a 3D pendulum clock, or a 3D cesium ion that emits radiation in periodic energy-level transitions, or for that matter a living, breathing person like Jill who keeps time with her heartbeats. Timekeeping is essentially a 3D process, and this fact has implications for the proper understanding of what time is.

There have been in the philosophical literature since the days of McTaggart two very different ways of conceiving time: as an A-series in which different moments possess the changing attributes of "past", "present", and "future", and as a B-series in which moments stand only in the permanent relationship of "earlier" or "later" (McTaggart, 1927). A necessary feature of the A-series is the notion of temporal becoming: a future event *becomes* present, and a present event *becomes* past. Focussing on the A-series creates the impression that time is flowing, although no such impression is created by the B-series. A nice question, connected with but distinct from the problem of the ontology of spacetime, is the question of whether temporal flow is real. This is the question of whether temporal becoming is an objective property of the world, or whether it is a subjective illusion, an idea which conscious beings have but which corresponds to nothing in physical reality. I shall argue that one of the consequences of the twins paradox is that it lends credibility to the thesis that temporal becoming is real, not illusory.

As mentioned above, Jill in her spacecraft, and Jack at home base, act as clocks, keeping time with their heartbeats. At the end of the voyage, it turns out that Jack has experienced many more heartbeats than Jill. In relativistic geometry his 4D inertial path is longer than the sum of Jill's two inertial paths, and the increased length serves as the 4D explanation of why Jack is older: his timeline is longer. But as was stated above, to determine *how much* Jack is older requires a metrization of spacetime, and this in turn requires a clock, human, or otherwise. Clocks do two things. Firstly, they measure *temporal length* by (i) establishing the temporal congruence of spacetime intervals and (ii) counting. But secondly, because clocks are 3D objects they undergo a cyclical *temporal process*, the regular periodicity of which qualifies them as measuring instruments. Furthermore, it seems correct to say that it is precisely in virtue of the fact that a clock undergoes this cyclical process that it is able to measure temporal length. If this is so, then, for a clock, *process* is the primary consideration, and measurement of *length* is a by-product, the use to which the process is put. Now, finally, what is process? Here we find the link to temporal becoming.

In the 4D world there are volumes of all shapes and sizes, cut many ways into temporal parts by the partitioning of different frames, but there is no movement and there are no processes. A process is a dynamic thing, and the 4D world is static. Process, like temporal becoming or temporal flow, is an A-concept rather than a B-concept, and is found in the domain of 3D things but not in the 4D world[2]. All of this is to say that if 3D objects evolve by undergoing temporal processes, as they do, and if the cyclical temporal processes of a clock are essential for the definition of temporal length, as they are, then temporal processes must be an objective characteristic of the physical world. They cannot be a subjective illusion, any more than the 4D world can be a subjective illusion. As was said before, both 3D and 4D descriptions are needed if we are to understand physical reality. Finally, a necessary condition of there being temporal processes is that there be temporal flow or becoming. No temporal becoming,

[2]In this paper, I am ignoring the dynamic 4D model of time flow found in McCall (1994). The argument for temporal becoming in the domain of 3D objects of the present paper in independent of the "argument to the best explanation" found in (1994).

no temporal processes. The upshot is that, with care, a complex many-step inference from

(1) 3D clocks measure time
to: (2) The universe manifests objective time flow

can be constructed.

A final note. If indeed there is such a thing as temporal becoming, the twins paradox demonstrates that it cannot be universal or global, but must take place within coordinate frames. The temporal passage or "ageing" undergone by Jack in his frame is not the same as the temporal passage undergone by Jill in her frames. Contrary to what Newton says, it is not the case that "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably, without reference to anything external". There is no "universal tide of becoming", in which events across the entire cosmos move in step from "future" to "present" to "past". Instead, each and every inertial frame exhibits its own temporal becoming, and the transition of an event E from "present in frame f_i" to "past in frame f_i" is not the same as the transition of E from "present in frame f_j" to "past in frame f_j". Because of the huge number of frames partitioning spacetime, the surge of temporal passage particular to each and every one of these frames is difficult to picture. But it, rather than the absolute or global time flow which a preferred frame of reference would imply, must be what spacetime undergoes if temporal becoming is a feature of the physical world.

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PART III: TIME, BECOMING AND RELATIVITY: INCOMPATIBILIST VOICES

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Chapter 11

Is There an Alternative to the Block Universe View?

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Abstract

This paper pursues two aims. First, to show that the block universe view, regarding the universe as a timelessly existing four-dimensional world, is the only one that is consistent with special relativity. Second, to argue that special relativity alone can resolve the debate on whether the world is three-dimensional or four-dimensional. The argument advanced in the paper is that if the world were three-dimensional the kinematic consequences of special relativity and more importantly the experiments confirming them would be impossible.

1. Introduction

If one can talk about a widely (explicitly or implicitly) accepted view on reality it is presentism — the view that it is only the present (the three-dimensional world at the moment "now") that exists. This common-sense view, which reflects the way we perceive the world, has two defining features: (i) the world exists only at the constantly changing present moment (past and future do not exist) and (ii) the world is three-dimensional.

Our immediate perception of the external world reveals it as being in a constant change. The concept of time and its three components — past, present, and future — are deduced from what we directly perceive. And indeed, in ancient Greece Heraclitus argued that the world is perpetually changing, but did not explicitly discuss the relationship between change and time (as the excerpts from his writings that reached us appear to show). According to him everything flows (*panta rhei*), everything moves (*panta chorei*) (Barnes, 1982, p. 65). Later, Aristotle effectively arrived at the conclusion that everything exists only at the moment ''now'' since it is this moment that ''connects past and future time'', (Aristotle, 1993, p. 301) which themselves do not exist: ''one part of (time) has been and is not, while the other is going to be and is not yet''. (Aristotle, 1993, p. 297) Aristotle made another contribution to the presentist view by arguing that the world is three-dimensional: ''A magnitude if divisible one way is a line, if two ways a surface, and if three a body. Beyond these there is no other magnitude, because the three dimensions are all that there are''. (Aristotle, 1993; see also Galileo, 1967)

The two defining features of presentism — the world exists only at the present moment and the world is three-dimensional — are intrinsically linked: if the world is three-dimensional it exists only at one moment of time and vice versa. Saint Augustine made the first step toward the realization of that link by trying to determine the duration of the moment ''now''. He concluded that the present moment cannot have any duration: ''In fact the only time that can be called present is an instant … . For if its duration were prolonged, it could be divided into past and future. When it is present it has no duration'' (Augustine, 1993, p. 119). In order to see the link between the three-dimensionality of the world and its existence only at the moment ''now'', assume that the present moment has a finite duration. For the sake of the argument let that duration be 10 s. As these 10 s are not further divisible into past, present, and future they are all present. Therefore, every object and the whole world would exist *at once*[1] *at all seconds* of the finite moment ''now''. This means that all objects would be extended in time. For instance, a moving object would exist at once at all points of a distance it travels for 10 s. However, objects that are extended in time are four-dimensional, not three-dimensional. The presentist view is based on the fact that we seem to perceive three-dimensional objects, i.e. objects that do not appear to exist at more than one instant of time. So, on the presentist view the fact that the world is regarded as three-dimensional implies that the present moment must be an instant with no duration.

Saint Augustine could not have possibly realized that the duration of the moment ''now'' must be zero (as he concluded) in order that the world be three-dimensional. But presentists should see this clearly. The realization of the link between the three-dimensionality of the world and its existence *only* at the present moment (whose duration is zero) shows that the past and the future do

[1]Obviously, here ''at once'' does not mean ''simultaneously''. Throughout the paper ''at once'' will be used timelessly to mean ''given as a whole'' or ''given in its entirety''.

not exist in any sense in the framework of the presentist view. The past and the future are merely sets of previous and forthcoming *states* of the three-dimensional world, which exists *solely* at the present moment. But states do not exist on their own without the entity they are states of.

Another view on reality that is *ontologically* different from presentism and for this reason is completely counter-intuitive is the block universe view. It can be traced back to the eternal and unchanging being of the Eleatic school of philosophy (Barnes, 1982, Chapter X). Saint Augustine also believed in an ever-present eternity which, however, was not accessible to humans (Augustine, 1993). In 1884, Hinton wrote about a four-dimensional world in which the ordinary particles are regarded as threads (Hinton, 1884, 1980. The scientific birth of the block universe view, however, was in 1908 when Minkowski proposed that space and time should be united into an inseparable four-dimensional entity — spacetime — which he called *the world*. He began his talk at the 80th Assembly of German Natural Scientists and Physicians with the now famous introduction: "The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality"(Minkowski, 1952; Lorentz, Einstein, Minkowski, & Weyl, 1952, p. 75).

It should be pointed out that Minkowski viewed the idea of the world as being not objectively split into space and time as deduced from the experimental evidence and not just as an alternative representation of special relativity. That is why a genuine understanding of special relativity could not be achieved without regarding spacetime as a four-dimensional space whose four dimensions are *entirely given*[2] (like the two dimensions of a plane). Minkowski left no doubt that the idea of spacetime should be understood in this way by pointing out one immediate consequence of that idea, namely that one could not talk about *one* space any more. He noticed that "neither Einstein nor Lorentz made any attack on the concept of space" (Minkowski, 1952, p. 83) and stressed that the idea of many spaces is inevitable in special relativity: "We should then have in the world no longer *space*, but an infinite number of spaces, analogously as there are in three-dimensional space an infinite number of planes.

[2]It might appear tempting to regard the temporal dimension as not entirely given, but if this were the case spacetime would not be four-dimensional–one cannot talk about a four-dimensional entity if all dimensions are not equally existent. Spacetime is not like space since the nature of the temporal dimension is different from the nature of the spatial dimensions, but this has nothing to do with the equal existence of all dimensions of spacetime (like the different nature of physical objects and phenomena has nothing to do with their existence). In this respect I completely share the position of Taylor and Wheeler regarding the temporal and spatial dimensions of spacetime: "Equal footing, yes; same nature, no" (Taylor & Wheeler, 1992).

Three-dimensional geometry becomes a chapter in four-dimensional physics. Now you know why I said at the outset that space and time are to fade away into shadows, and only a world in itself will subsist''. (Minkowski, pp. 79–80) But although Minkowski demonstrated that the consequences of special relativity (length contraction, for instance) found a natural explanation in the four-dimensional spacetime, he did not find it necessary to argue that these consequences were possible only in a four-dimensional world.

Unfortunately, the depth of Minkowski's idea does not seem to have been immediately and fully appreciated as evident from Sommerfeld's notes on Minkowski's paper: ''What will be the epistemological attitude towards Minkowski's conception of the time–space problem is another question, but, as it seems to me, a question which does not essentially touch his physics''. (Sommerfeld, 1952)

About two decades after Minkowski's four-dimensional formulation of special relativity Weyl appeared to have realized that Minkowski spacetime is not merely a mathematical space but represents a four-dimensional external world which is not directly reflected in our perceptions: ''The objective world simply is, it does not *happen*'' (Weyl, 1949). In 1952, Einstein added the fifth appendix ''Relativity and the problem of space'' to the 15th edition of his book ''Relativity: The Special and General Theory'' in which he seemed to have arrived at the same conclusion: ''It appears … more natural to think of physical reality as a four-dimensional existence, instead of, as hitherto, the *evolution* of a three-dimensional existence'' (Einstein, 1961). However, neither Weyl nor Einstein showed that the four-dimensionality of the world unavoidably follows from the consequences of special relativity.

The first argument designed to demonstrate that one of the basic consequences of special relativity — relativity of simultaneity — inescapably implies a four-dimensional world was advanced by Rietdijk (1966) and Putnam (1967). Later, the same argument was rediscovered by Maxwell (1985). However, it was criticized twice by Stein, (1968, 1991) — in 1968 after Rietdijk and Putnam published their papers and in 1991 after the appearance of Maxwell's paper. This double criticism appears to have created the impression that Stein ''has settled the issue'' (Clifton & Hogarth, 1995).

Stein's criticism of the Rietdijk–Putnam argument is revisited in Section 2. A closer examination of this argument shows that Stein's objections not only does not disprove it but also, in fact, further reinforce it. Section 3 develops a more general argument, which demonstrates that the consequences of special relativity and the experiments, which confirm them, would be impossible if the world were three-dimensional and if the existence of the objects involved in these experiments is absolute. This shows that only the block universe view does not contradict the experimental evidence, which supports special relativity. The issue of whether or not an equivalence of three- and four-dimensional presentations of special relativity implies an equivalence of three- and four-dimensional ontologies is discussed in Section 4.

2. Has Stein disproved the Rietdijk–Putnam argument?

To analyze Stein's objections let us briefly describe a version of the argument he criticized. Consider three inertial observers A–C in relative motion whose worldlines are shown in Fig. 1. Observers A and B meet at event M. The third observer C is represented by a vertical worldline in the figure, which means that A is approaching C, whereas B is receding from C.

Two events P and Q happen with C at different moments of his proper time. Since an event in relativity is defined as an object, a field point, or a space point at a given moment of time, the events P and Q are simply the observer C existing at the moments t_P^C and t_Q^C of his proper time, respectively. As event P is simultaneous with event M according to B and therefore lies in observer B's present, both events M and P are equally real for B (according to Putnam) or equally determinate for B (according to Rietdijk). Event Q is simultaneous with event M in A's reference frame; that is, it belongs to observer A's present. This means that both events M and Q are equally real and determinate for A. Since Putnam and Rietdijk assumed that the reality and determinateness of an event are *absolute* (observer-independent) they arrived at the conclusion that if event Q is real (determinate) for observer A, it should be as real (determinate) for observer B and for observer C as well. Therefore, observer C should exist *at once* at both moments t_P^C and t_Q^C of his proper time since events P and Q (corresponding to the two moments) are equally real. But such a situation is not possible in the common-sense (pre-relativistic) view according to which it is only the present — the three-dimensional world at the moment "now" — which exists. This led Rietdijk and Putnam to conclude that relativity of simultaneity,

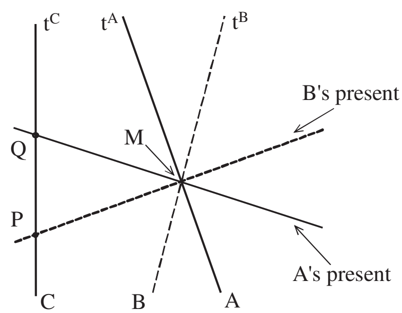

Fig. 1. Three inertial observers A–C are in relative motion. Events M and Q belong to A's present and are therefore real and determinate for A, whereas for B real and determinate are events M and P, since they lie in B's present.

when applied to what exists, contradicts the presentist view and is possible only in a four-dimensional world, where the histories of the physical objects are entirely realized in their four-dimensional worldtubes. In such a view the presents of observers A and B are equally real because they are merely three-dimensional cross-sections of the four-dimensional world.

Stein criticized the Rietdijk–Putnam argument since it incorrectly used the concept of *distant present events* (i.e. the concept of the present), which is based on the pre-relativistic division of events into past, present, and future. He pointed out that "in the theory of relativity the only reasonable notion of 'present to a space–time point' is that of the mere identity relation: present to a given point is that point alone — literally 'here-now'". (Stein, 1991, p. 159). This is a valid objection but it does not affect the ultimate conclusion of the Rietdijk–Putnam argument — that the world is four-dimensional. The reason is the following.

In fact, Stein's criticism of the Rietdijk–Putnam argument supports the first part of the argument — that presentism contradicts special relativity and is therefore wrong. And indeed the present, i.e. the three-dimensional world at the moment "now", can be defined only in terms of the pre-relativistic division of events into past, present, and future. More specifically, the present is defined in terms of *simultaneity* — as everything that exists *simultaneously* at the present moment. Therefore, Stein's argument that one cannot talk about distant present events in the framework of special relativity is an argument against presentism. So, Stein's criticism is effectively directed against the three-dimensionality of the world since a three-dimensional world consists of distant present events (everything that exists simultaneously at the moment "now"). But, unfortunately, he did not address the most fundamental question Rietdijk and Putnam had raised — what is the dimensionality of the world according to special relativity? Had he done that he would have had two options:

- accept the conclusion of Rietdijk and Putnam that we live in a four-dimensional block universe,
- regard the event "here-now" as the only real one.

The latter option, however, does not appear realistic since such a view clearly amounts to event solipsism — for every observer the world would be reduced to a single event (the event "here-now"). Once the question "What is the dimensionality of the world"? is asked, one could not hold the view that only the event "here-now" is real because that would mean that for every observer the world would be zero-dimensional (just one event). It should be stressed that it amounts to a contradiction in terms to say that the world is four-dimensional, but for every observer only the event "here-now" is real. If the world is four-dimensional all its events are equally real; otherwise it would not be four-dimensional[3]. This shows that in spacetime it is impossible to have an event, representing the event "here-now", which is "more real" than the other events. Therefore, objective flow of time and objective becoming are impossible in a four-dimensional world, if they imply that there are events which are "more real" than the other spacetime events. For this reason, the question of the dimensionality of the world clearly precedes, in my view, the questions of time flow and becoming and should be resolved first.

Stein could not argue that existence should be relative (frame- or observer-dependent), which would preserve the three-dimensionality of the world and would allow two observers in relative motion to have different presents, i.e. different three-dimensional worlds, because this would mean that he would be again using the concept of distant present events applied to each observer. In such a way Stein's criticism of the Rietdijk–Putnam argument not only does not disprove it but also effectively constitutes another argument for the block universe view: the world cannot be three-dimensional since a three-dimensional world is defined in terms of the pre-relativistic division of events and therefore the only option that remains is a four-dimensional world. This argument appears to be even more rigorous than the Rietdijk–Putnam argument because both Rietdijk and Putnam used the pre-relativistic concept of distant present events to arrive at the conclusion that the world is four-dimensional, whereas by pointing out the meaninglessness of that concept in special relativity Stein effectively demonstrated the contradiction between the presentist (three-dimensionalist) view and relativity which meant that it is the four-dimensionalist view that is in agreement with relativity.

In terms of its real value, Stein's criticism is similar to Weingard's criticism of the Rietdijk–Putnam argument. Weingard (1972) wrote:

> In his 1967 [paper] Hilary Putnam concludes that all events in special relativistic spacetime, whether past, present, or future, are equally real, i.e. that a tenseless concept of existence is the appropriate concept of existence in a special relativistic world. Although I believe this conclusion is correct, I think Putnam's argument is not.

Weingard, like Stein, pointed out that Putnam's argument is wrong because it is based on the pre-relativistic concept of the distant present events[4]. Despite being formulated in terms of pre-relativistic concepts I think, the Rietdijk–Putnam argument is perfectly valid for the reason given in the next section.

[3]Similarly, one could not say that only one point of a line is real because that would mean that the line would be reduced to a point and there would be a zero-dimensional, not a one-dimensional space.

[4]Formally, Stein's and Weingard's objections are different but they boil down to the same point — that the pre-relativistic division of events makes no sense in special relativity.

3. Only the four-dimensionalist view is compatible with special relativity

The Rietdijk–Putnam argument can be easily generalized if the question of the *dimensionality* of the world according to special relativity is explicitly addressed. One can start to discuss that question by pointing out that on the pre-relativistic (presentist) view the world is three-dimensional — it is the present (Fig. 2). Then there are two ways to demonstrate the impact of special relativity on this view. First, one can point out that the world cannot be three-dimensional since such a world is defined in terms of the pre-relativistic division of events into past, present, and future as seen in Fig. 2. Therefore, the debate over the dimensionality of the world is resolved in favor of the four-dimensionalist view. This is the conclusion that follows from Stein's argument against the Rietdijk–Putnam argument.

The second approach to determining the dimensionality of the world according to relativity is precisely the generalization of the Rietdijk–Putnam argument. One starts with the pre-relativistic view of the world. Then it inescapably follows that having different sets of simultaneous events two observers in relative motion have different presents, i.e. different three-dimensional worlds. If existence is absolute, it follows that the world must be four-dimensional in order that the relativity of simultaneity be possible: the two observers will have different three-dimensional cross-sections of the four-dimensional world, which they will regard as their presents. If we assume that the world were three-dimensional, two observers in relative motion would have a common three-dimensional world and therefore a common set of simultaneous events, which means that simultaneity would be absolute in contradiction with special relativity.

So, the generalized version of the Rietdijk–Putnam argument does make use of the pre-relativistic concept of present events but that is a completely

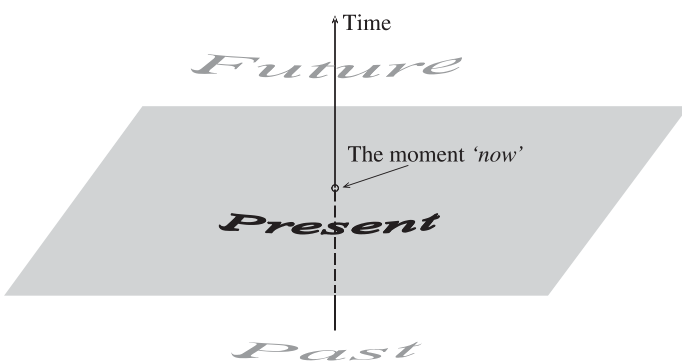

Fig. 2. On the presentist view it is only the present — the three-dimensional world at the moment "now" — that exists.

legitimate and natural approach — one starts with the pre-relativistic (three-dimensionalist) view of the world (defined in terms of that concept) and by taking into account relativity of simultaneity wants to see how special relativity affects this view. Moreover, the kinematic relativistic effects (with the exception of the twin paradox) can be formulated only in terms of the pre-relativistic division of events if the *existence* of the objects involved in these effects is explicitly taken into account. And indeed as we have seen relativity of simultaneity makes sense only in terms of the pre-relativistic concept of present events when we ask what *exists* simultaneously. If one objects that the question ''What exists simultaneously?'' does not appear to be well defined, it will be shown below that the length-contraction effect makes sense only in terms of the pre-relativistic concept of present events.

When the issue of the dimensionality of the world according to relativity is explicitly addressed, it does appear that there is no alternative to the four-dimensionalist view. This is best seen if one assumed that the world were three-dimensional. Then not only relativity of simultaneity but all kinematic relativistic effects would be impossible (Petkov, 2005, 1986, 1988). This is immediately evident for the cases of length contraction and time dilation since these effects are merely manifestations of relativity of simultaneity.

To demonstrate the impossibility of the kinematic relativistic effects in the framework of the presentist (three-dimensionalist) view consider, for example, the length-contraction effect. Two observers A and B in relative motion meet at event M. The observers are represented by their worldlines as shown in Fig. 3. A rod at rest in A's reference frame is represented by its worldtube.

At event M the two observers determine the length of the rod in their reference frames. For B, the rod is of shorter length $L_B < L_A$. As seen in Fig. 3 the contraction of the rod is only possible if the worldtube of the rod is a real four-dimensional object, which means that the rod exists equally at all moments of its history. The instantaneous three-dimensional spaces of A and B intersect the

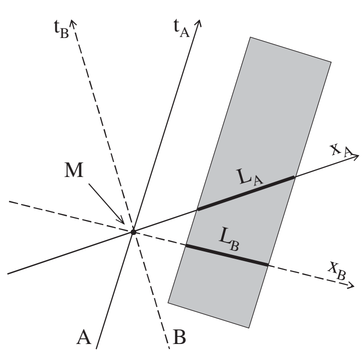

Fig. 3. A rod represented by its worldtube is at rest in observer A's reference frame.

worldtube of the rod at two different places and B's cross-section is smaller than A's cross-section. If the rod's worldtube were not a real four-dimensional object, i.e. if the rod existed only at its present moment and therefore were a three-dimensional object (say, A's rod which is represented by the cross-section L_A), no length contraction would be possible — A's rod of length L_A would exist for B as well[5] and B would measure the same rod with the same length L_A.

It seems little attention has been paid to the fact that A and B do not measure the *same* three-dimensional rod; the rod which B measures is a *different* three-dimensional object. This is clearly seen in Fig. 3 — at event M both A and B know that the rod exists for each of them, but this is only possible if there are two different three-dimensional cross-sections of the rod's worldtube, i.e. *two different* three-dimensional rods. If one decides not to trust spacetime diagrams too much, it is easily demonstrated that the same conclusion follows directly from relativity of simultaneity. The different parts of the spatially *extended* three-dimensional rod constitute a set of events that exist *simultaneously* for A. As B has a different set of simultaneous events (the events constituting the cross-section L_B) it unavoidably follows that B measures a different three-dimensional rod. In order that this be possible, the rod's worldtube must be a real four-dimensional object. So, when we say that A and B measure the *same* rod we refer to the worldtube of the rod, but the observers regard different three-dimensional cross-section of the rod's worldtube as their rod, which means that they do measure *different* three-dimensional rods.

The fact that B measures a different three-dimensional rod appears to rule out any explanation of the length-contraction effect that involves a deformation of the rod caused by forces acting on the rod's atoms along the lines of the original Lorentz–FitzGerald proposal and what Bell (1987) called "Lorentzian pedagogy" (see also Brown & Pooley, 2001). The reason is that the deformation (or dynamical) explanation of the length contraction implies that A and B measure the *same* three-dimensional rod, whereas relativity of simultaneity requires that A and B measure *different* three-dimensional rods. Perhaps, the most convincing argument that the deformation explanation of the length contraction is wrong, however, is that this explanation cannot account for the contraction of *space* itself where there are no atoms and no forces that can cause its deformation. For instance, the muon experiment (Rossi & Hall, 1941) cannot be explained if it is assumed that space does not contract (Ellis & Williams, 1988).

Let us now see why the length contraction can be formulated only in terms of the concept of distant present events, which demonstrates that this concept is

[5] If the rod existed only at its present moment, which would mean that it is *ontologically* a three-dimensional object (retaining its identity as a three-dimensional object in time), it would not exist in its past and future. Therefore, B's cross-section of length L_B would lie in the rod's past and would not exist.

still used in special relativity when the *existence* of the physical objects involved in this relativistic effect is described in three-dimensional language. When A and B meet at M what everyone of them measures is what *exists* for him — his *present* rod, that is, all parts of the spatially extended three-dimensional rod which exist simultaneously at the moment "now" of the observer. Therefore the three-dimensional rod constitutes (is defined as) a set of *distant present events* and both observers must use this pre-relativistic concept in order to talk about a three-dimensional rod. The same situation occurs in the time dilation effect — it too can be formulated only in terms of distant present events when one considers the existence of the physical objects that take part in this effect (Petkov, 2005, Chapter 5). But the very fact that this concept has no meaning in special relativity implies that there is nothing three-dimensional in the objective world. In the case of length contraction each of the observers A and B in Fig. 3 measures a three-dimensional rod, but it is not a real three-dimensional object in the sense that it is not an object, which retains its identity through time as the *same* three-dimensional object. What is real is the rod's worldtube. Its existence is deduced from the existence of length contraction — if the worldtube did not exist no length contraction would be possible (below I will provide further arguments for this strong claim).

A's and B's rods are not real three-dimensional objects because the rod's worldtube is an indivisible four-dimensional entity which is not objectively divided into three-dimensional cross-sections[6]. Therefore, the three-dimensional rod every observer measures is just a *description* of the rod's worldtube in terms of the ordinary three-dimensional language. This situation is analogous to the one that arises when the x–y planes of different coordinate systems "cut" different two-dimensional cross-sections of a cylinder — those sections are not real two-dimensional objects since the cylinder itself is not objectively divided into different two-dimensional cross-sections.

Our commonsense belief in the existence of three-dimensional objects and a three-dimensional world originates from the way we interpret what we perceive. For instance, we believe that we see three-dimensional objects and a three-dimensional world. However, this is clearly not the case as seen in Fig. 4. Observers A and B, who are in relative motion, have different sets of simultaneous events and therefore different three-dimensional worlds, but at event M they both see the *same* thing — the past light cone. They interpret all images contained in the light signals, which constitute the past light cone in a sense that at event M they perceive a three-dimensional world. This is an obvious misconception since the past light cone does not form a three-dimensional space or a three-dimensional world, which is defined in terms of simultaneity — a

[6]This is a direct consequence of the fact that spacetime is not objectively divided into different spaces, i.e. different three-dimensional cross-sections.

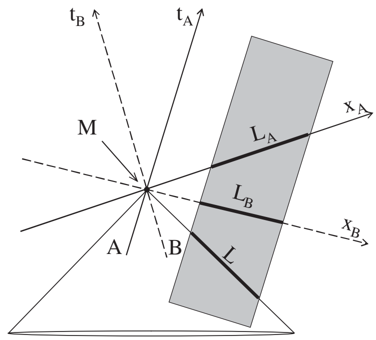

Fig. 4. What observers A and B see is the same cross-section L of the rod's worldtube. In general, when two observers A and B in relative motion meet at event M they see the past light cone.

three-dimensional world is defined as all space points and all three-dimensional objects that correspond to the *same* moment of time. It is obvious that the points of the past light cone do not correspond to the same moment of the time of each of the observers. In particular, A and B have different three-dimensional rods, but they see the *same* three-dimensional cross-section L which, however, cannot be regarded as a three-dimensional rod since all parts of a three-dimensional object exist *simultaneously* at one moment (the moment "now"). By contrast, the parts of the three-dimensional cross-section L correspond to different moments of the time of each observer[7]. It follows from here that it is not possible to interpret the length contraction in a sense that it is the *same* three-dimensional rod that exists for A and B, but they see it differently.

The fact that A and B have different three-dimensional rods means that the two rods of lengths L_A and L_B, respectively, belong to the presents of A and B that correspond to event M. However, it is obvious that the observers do not usually measure the length of their rods at M since in most cases a measurement takes some time and each of the observers sees his rod a little later, not at the moment when light signals left simultaneously the end points of the rod. But when the observers take into account that delay, they arrive at the conclusion that at the event M they had different sets of simultaneous events and therefore *different* three-dimensional rods. So, the fact that observers are not usually in an immediate contact with what they measure does not affect the conclusion that A and B have different three-dimensional rods — a conclusion which demonstrates that on the presentist view the length-contraction effect is impossible since on that view the rod exists only at its present moment as a *single*

[7]The fact that what we see are images, which cannot be interpreted to represent three-dimensional objects is itself another indication that our senses cannot be fully trusted especially when it comes to such fundamental questions as the dimensionality of the world.

three-dimensional object, which means that A and B cannot have different three-dimensional rods as relativity of simultaneity requires.

Although the realization of the physical meaning of length contraction — that A and B have different three-dimensional rods — is a direct consequence of relativity of simultaneity, it is so counter-intuitive that it is worth to consider a thought experiment (Petkov, 2005, p. 137) in which the measurement of the rod's length is instantaneous in A's and B's reference frames. This thought experiment will also provide additional arguments supporting the claim that the three-dimensionalist view contradicts the experiments which confirmed the kinematic relativistic effects.

Let the rod again be at rest in A's reference frame (Fig. 5). There are lights mounted on the end and the middle points of the rod. At every instant the color of the lights changes simultaneously in A's reference frame: an instant before the meeting of A and B all three lights are green at the moment t_A^g, at the moment of the meeting $t_A^M = t_A^r$ the lights are red, and an instant after the meeting they are blue at t_A^b. As seen in Fig. 5, A and B move along their x axes and the rod is positioned parallel to A's x axis. Both A and B place cameras at different points of their x axes. All cameras have clocks that have been synchronized in advance in each frame by using the Einstein rule (assuming that the back and forth velocity of light in A's and B's frame is the same). The cameras have been

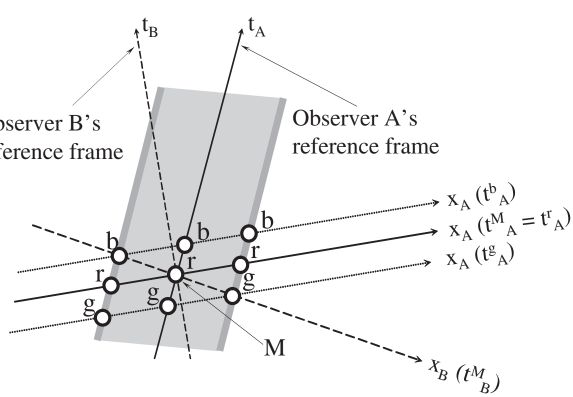

Fig. 5. Observers A and B, who are in relative motion, meet at event M. A rod at rest in A's reference frame has lights mounted on its two end points and on its middle point. In A's frame all lights of the rod were simultaneously green an instant before the meeting with B; they are all red at the moment of the meeting, and their color changes simultaneously to blue, for A an instant after the meeting. Each of A and B determines the rod's length instantaneously in his frame by taking snapshots of the rod's end and middle points with cameras placed at different points on A's x-axis and on B's x-axis along which the rod moves. The rod, which B measures, consists of parts of A's past rod (with the green light), present rod (with the red light), and future rod (with the blue light).

synchronized in such a way that all clocks in each frame show zero at the event of the meeting M.

When A and B meet at M at the moment $t_A^M = 0$ of A's time and at $t_B^M = 0$ of B's time they determine the length of the rod instantaneously in their reference frames by taking snapshots of its end and middle points. Some time after the meeting A and B collect all pictures from their sets of cameras to see the results of their experiments. Observer A sees that the three pictures (showing the middle and the two end points of the rod) display the same time $t_A^M = 0$ and the same color — red, red, and red. Observer B also sees that the three pictures show the same time $t_B^M = 0$, but the colors in the three pictures are green, red, and blue.

Let us now ask what exists for A and B at M. As at the instant of the meeting all three red lights of the rod are simultaneous for A, at his present moment $t_A^M = t_A^r$ what exists for him at M is the red rod which lies in A's present. The green rod existed for A one instant *before* the meeting and is in his past while the blue rod will exist one instant *after* the meeting and is in his future. According to the presentist view the green and blue rods do not exist for A at $t_A^M = t_A^r$ since they belong to A's past and future, respectively.

As observer B has a different class of simultaneous events at M, it does follow that at the moment t_B^M the lights of the rod will not all be red for B. The fact that at M in B's present lies a three-dimensional rod whose front end point, middle point, and rear end point are green, red, and blue, respectively (B is moving to the left in Fig. 5) means that the green–red–blue rod, which is present for B, consists of part of A's past rod (the front end point with green light), part of A's present rod (the middle part of the rod, which is also present and therefore exists for A at the moment of the meeting), and part of A's future rod (the rear end point with blue light). As all parts of a spatially extended three-dimensional object exist *simultaneously* at the present moment of an observer, the three-dimensional rod that exists for B at his present moment t_B^M is *different* from the three-dimensional rod of A existing at his present moment $t_A^M = t_A^r$. (The event of the meeting M in Fig. 5 is the only common present event for both observers.) The rod of each observer is composed of a mixture of parts of the past, present, and future rods of the other observer. Therefore, the conclusion that each of the observers A and B measures a *different* three-dimensional rod is indeed inevitable.

Imagine now that this experiment has been performed and, as expected, confirmed both the length contraction and the relativity of simultaneity. What conclusions can be drawn from it? The observers A and B will be convinced that the only way to explain their pictures is to assume that the rod they measured exists equally (at once) at all moments of its history in time. Their reason is that the experiment directly confirmed this conclusion: parts of the rod's past, present, and future (which are also A's past, present, and future since the rod is at rest in A's frame) exist *simultaneously* as B's present rod. A's present rod also contains parts of B's past, present, and future rod[8]. This would not be possible if the rod did not exist equally in its past, present, and future[9]. Therefore, A and B conclude that their experiment has a profound physical meaning — it proves that all physical objects are extended in time, which means that they are four-dimensional.

A and B believe they can claim that a single experiment, which allowed a single interpretation, proved the four-dimensionality of the world. However, a philosopher of science would immediately disagree. He will point out that the claim is based on an implicit ontological assumption — that the existence of the physical objects is *absolute* (observer- or frame-independent). Since this claim is deduced from an experiment no other ontological assumptions seem to be needed. For instance, it does not appear necessary to assume (i) that A's and B's sets of simultaneous events are ontologically equivalent since both A and B used the same rule to synchronize the clocks of their cameras, and (ii) that A and B are ontologically equivalent since they carried out identical experiments[10].

The philosopher of science will explain that the experiment performed by A and B allows two interpretations:

(i) if existence is absolute, the simultaneous existence of parts of A's past, present, and future rod as B's present rod (and vice versa) does lead to the conclusion that the rod must exist equally at all moments of its history;
(ii) if existence is relative (observer- or frame-dependent), each observer will claim that it is only his three-dimensional rod that exists.

A and B admit that their experiment allows a second interpretation, but since the experiment is, in their view, the ultimate judge they are convinced that it is only the experiment that can decide whether the world is three- or

[8]This specific experiment would allow A and B to arrive at the idea of the rod's worldtube even if they never heard of Minkowski.

[9]The experiment depicted in Fig. 5 deals only with the immediate past and future of the rod, but one can add other observers that also meet A at M but their velocities relative to A are greater than B's velocity. The present rods of these observers will contain parts of more distant past and future of A's rod.

[10]Even if A and B are not equivalent (inertial) observers the same conclusion will be drawn. Imagine that two inertial observers A and B and an accelerated observer C meet at M (but A's frame is not C's comoving inertial reference frame at M). C's present rod will again be a mixture of A's past, present, and future rod and the conclusion that the rod's worldtube must exist follows. In this case, C will use (before the meeting) the same synchronization procedure but with a small correction to the velocity of light (proportional to C^{-2}) (Petkov, 2005) which, however, does not affect the final conclusion. This is immediately seen if B's frame is C's comoving inertial reference frame at M which means that B and C have a common set of simultaneous events at M. Therefore, B and C will have the same contracted rod that consists of parts of A's past, present, and future rod.

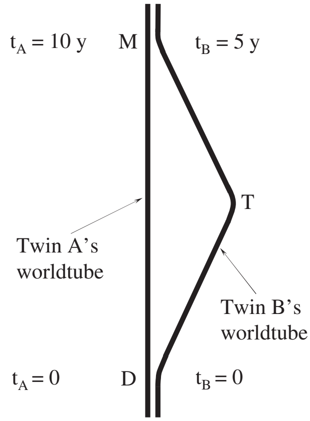

Fig. 6. Twins A and B are represented by their worldlines. At the event of departure D twin B starts a journey at a speed that is close to the speed of light. At event T he turns back and meets his brother at event M.

four-dimensional. They agree that, formally, existence can be regarded as relativized. A and B realize that such an assumption preserves the three-dimensionality of the world, but it is an alternative option to the conclusion of a four-dimensional world only in the case of the *reciprocal* length contraction and time dilation which are based on relativity of simultaneity. That is why A and B concentrate their attention on the twin paradox since it is an absolute, not a reciprocal effect, which means that no relativity of simultaneity is involved in its explanation and therefore the relativization of existence should not be an alternative explanation.

And indeed the derivation and the explanation of the twin paradox (Fig. 6) are based on the triangle inequality in the pseudo-Euclidean geometry of spacetime, which *presupposes* the existence of the twins' worldlines (in order to be able to talk about a triangle in spacetime). In other words, the explanation of the twin paradox is in the framework of the four-dimensionalist view: the length of twin B's worldline between the event of the departure D and the event of the meeting M is shorter than the length of twin A's worldline between the same events (in Fig. 6 twin B's worldline is longer but this is caused by the representation of a pseudo-Euclidean relation on the Euclidean surface of the page). This means that B measures less time between D and M than his brother.

Let us now see, how the view of relativized existence contradicts the experiments that confirm the twin paradox[11]. Assume that the world is objectively three-dimensional as this view states. This is an ontological assumption; the *description* of the world in a three-dimensional language is a completely different issue. Obviously, in such a world the twins exist as three-dimensional bodies

[11]This is a summary of an argument which is given in Petkov (2005).

at their moments 'now' only. When A and B meet at event M they both will exist at this event and nowhere else — neither in their pasts not in their futures. As seen in Fig. 6 at M twin A's clock shows that 10 years have passed between events D and M, whereas according to twin B's clock only 5 years have elapsed between the same events. Both twins agree that B is younger. As on both the pre-relativistic and the relativized three-dimensionalist view time objectively flows, the only way for the twins to explain the 5-year difference of their clocks' readings at M is to assume that twin B's time has slowed down. The acceleration to which B is subjected appears to be the only cause for the slowing down of B's time. However, that cause has been ruled out by (i) the so-called "clock hypothesis" according to which the rate of an ideal clock is not affected by its acceleration (Misner, Thorne, & Wheeler, 1973; d'Inverno, 1992; Naber, 1992) (and the experiments which confirm it, Mould, 1994), and (ii) the three-clock version of the twin paradox (see, for instance, Kroes, 1983). Hence the three-dimensionalist view cannot explain why twin B is younger which means that this view cannot explain the twin paradox[12].

Another argument, which, in my view, even more clearly shows that the three-dimensionalist view contradicts the twin paradox, is the following. What A's and B's clocks show is their *proper times*. So at M the twins compare their proper times. Given the fact that on the three-dimensionalist view time objectively flows, the twin paradox and the time dilation make sense only in terms of a *change of the rate of the time flow*. But this is precisely the problem for the three-dimensionalists — the rate of the proper time does not change[13] according to special relativity (proper time is an invariant), which means that when A and B meet at M their clocks should show the *same* time.

I believe this argument convincingly shows that the three-dimensionalist view contradicts not only the twin paradox as a theoretical result, but more importantly all experiments that confirmed it. These experiments also rule out the ontological assumption that existence should be relativized since this assumption requires that the world be three-dimensional[14].

I think nature has given us the twin paradox as a valuable gift — the interpretation of the experiments, which confirm it, does not appear to need any ontological assumptions and for this reason these experiments allow a single interpretation and *alone* resolve the debate over the dimensionality of the world.

[12]It may appear inviting to "explain" the different readings of the twins' clocks by saying that time is frame-dependent in relativity. However, this is not an explanation at all since the very question is: Why is time frame-dependent in relativity?

[13]What is relativistically dilated is not the proper time, but the time of a clock, which is determined by a second clock with respect to which the first clock moves uniformly.

[14]This means that the length contraction experiment depicted in Fig. 5 has just one interpretation — the rod's worldtube must be a real four-dimensional object in order that the observers A and B have different three-dimensional rods.

As we have seen, the analysis of relativity of simultaneity, length contraction, and the twin paradox leaves no doubt that we live in a four-dimensional block universe in which the whole histories of all objects are realized in their worldtubes[15]. The same conclusion is reached when time dilation is analyzed (Petkov, 2005). What indicates that special relativity *alone* resolves the issue of the dimensionality of the world at the macroscopic[16] level is the fact that not only would the kinematic relativistic effects be impossible if the world were three-dimensional, but also the experimental evidence which confirms them would not be possible either. And indeed any experiments designed to test the three relativistic effects we discussed — relativity of simultaneity, length contraction, and the twin paradox — would detect absolute simultaneity, no length contraction, and no time difference in the twins' clocks' readings if the world were three-dimensional. For instance, the muon experiment (Rossi & Hall, 1941) which proves both length contraction and time dilation would be impossible if the world were three-dimensional.

It is a widely accepted view "that relativistic mechanics does not carry a particular ontological interpretation upon its sleeve" (Balashov, 2000), but the conclusion that the relativistic effects are possible only in a four-dimensional world demonstrates that special relativity does contain just one ontology — the four-dimensional ontology — which is deducible from those effects. In light of the arguments presented here, I believe this widely accepted view should be made more explicit. Here is how Balashov (2000) presents it:

> It is a well-known fact that one could accept all the empirical consequences of SR (including length contraction, time dilation, and so on) and yet insist that there is a privileged inertial reference frame, in which meter sticks really have the length they have and time intervals between events refer to the real time.

What should be made more explicit is the physical meaning of such a privileged inertial frame. In my view, this can be best achieved by asking what is the *dimensionality* of the world in which such a frame can exist. Then, as a privileged inertial frame means a privileged three-dimensional space, it becomes evident that there are two options: (i) a three-dimensional world, and (ii) a four-dimensional world in which "associated with this reference frame would be a set of hyperplanes of simultaneity uniquely slicing space–time into equivalence classes of absolutely simultaneous events". (Balashov, 2000)

I think it is obvious that option (i) contradicts special relativity and in this sense is empirically distinguishable from it. Option (ii) is, in fact, a block universe in which the privileged three-dimensional cross-sections (i.e. the privileged

[15] An independent argument for the four-dimensionality of the world comes from the conventionality of simultaneity (Petkov, 1989).

[16] The macroscopic level of the world is specified here in order to distinguish the issues of dimensionality of the world in relativity and in string theory, for example.

hyperplanes of simultaneity) should be objectively distinguishable from the three-dimensional cross-sections of the other reference frames. That this does not appear to be the case is demonstrated in Fig. 5 where both observers measure directly and instantaneously the length of the rod without the need of any assumptions or calculations. Assume that A's rod lies on such a privileged three-dimensional cross-section, whereas B's rod lies on an "ordinary" three-dimensional cross-section. How can the privileged rod of observer A be objectively distinguishable from the "ordinary" rod of B if that privileged state cannot be discovered experimentally? Note that due to the direct measurement of the rod's length the following explanation would not work[17]: "A suggested privileged reference frame would not be distinguished in any empirical sense and would not be identifiable in any real experience. Thus the speed of light measured in any inertial frame would still be exactly *C*, the number obtained by dividing the apparent distance covered by light by the apparent time spent". (Balashov, 2000)

4. Different descriptions versus different ontologies

The arguments advanced in this paper were concerned with the question of what ontology — three- or four-dimensional — is compatible with special relativity. The reason for placing the emphasis on this question is that it is this question, in my view, which is most fundamental in the interpretation of special relativity.

However, McCall and Lowe have recently argued that if the world can be equivalently described in a three- and four-dimensional language, the debate over the three-dimensional versus four-dimensional ontologies should not reflect a real problem: "the three-dimensional and the four-dimensional descriptions of the world are equivalent" and therefore "it is not a question of one being true and the other false" (McCall & Lowe, 2003). There are two objections to this claim. First, it is not completely clear in what sense one can talk about a three-dimensional description of the world. At first sight it appears that the 1905 Einstein paper is an example of how relativity can be described in a three-dimensional language. However, upon a closer examination it turns out that this description presupposes a four-dimensional ontology. To see that assume the opposite — that the original Einstein presentation of special relativity implies a three-dimensional ontology. But simultaneity is absolute in a three-dimensional world which means that it is impossible to regard the times t and t' of two observers in relative motion on equal footing. Hence, special relativity does not work in a three-dimensional world. It can be argued that it is Lorentz's description of moving bodies, not Einstein's theory, that implies a

[17]It should be noted that the constancy of the velocity of light is not determined as stated in the quote. Every inertial observer measures the velocity of light in his reference frame; so no apparent distance and no apparent time are involved in his calculations.

three-dimensional ontology since it regards only one of the times t and t' as the true time. Then due to the different ontologies (involving different dimensions of the world) behind Lorentz's and Einstein's theories a rigorous and consistent application of Lorentz's ideas would lead to predictions which differ from the predictions of special relativity[18]. Lorentz himself admitted the failure of his approach (Lorentz, 2003):

> The chief cause of my failure was my clinging to the idea that the variable t only can be considered as the true time and that my local time t' must be regarded as no more than an auxiliary mathematical quantity. In Einstein's theory, on the contrary, t' plays the same part as t; if we want to describe phenomena in terms of x',y',z',t' we must work with these variables exactly as we could do with x,y,z,t.

The second objection to McCall's and Lowe's claim is based on the superiority of an ontology over a description. It is a fact that the kinematic consequences of special relativity can be expressed in three-dimensional language, but this does not mean that for special relativity a three-dimensional ontology is as good as the four-dimensional ontology. If a three-dimensional ontology is consistently presupposed, no three-dimensional description of the kinematic relativistic effects would be possible since the effects themselves would be impossible. This situation can easily be visualized in a two-dimensional space. Consider a strip on a plane. The x axis of a coordinate system "cuts" the strip at a given location. One can describe the whole strip by taking into account the one-dimensional cross-sections that correspond to different values of y. That the strip can be equivalently described in one- and two-dimensional language, does not imply equivalence of the one- and two-dimensional ontologies — the strip is either a strip or a line.

The major objection regarding the three- and four-dimensionalist views as equivalent is that such an equivalence amounts to regarding a three- and a four-dimensional world as equivalent.

5. Conclusions

It has been shown that the three-dimensionalist view contradicts special relativity and more importantly the experiments, which confirm its consequences. To demonstrate this contradiction relativity of simultaneity, length contraction, and the twin paradox were analyzed and it was shown that if one assumed that the world were three-dimensional, neither of these relativistic effects would be possible.

[18]For instance, no reciprocity of the length contraction is possible in a three-dimensional world. Most importantly, however, the experiment shown in Fig. 5 will rule out Lorentz's theory if it does presuppose a three-dimensional world.

In this sense special relativity *alone* appears to provide a definite proof of the block universe view. One may argue that the arguments discussed here are insufficient for rejecting the presentist view since those arguments demonstrated that presentism contradicts only special relativity, not the other established theories (quantum mechanics, for instance). Such a position could hardly be defended because if a view contradicts the experimental evidence it is definitely wrong. There is just one way to prove that the presentist view does not contradict the relativistic effects — to demonstrate that the experiments, which confirm the kinematic consequences of special relativity can be *explained* (not merely described) if it is assumed that the world is three-dimensional.

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Chapter 12

Special Relativity, Time, Probabilism and Ultimate Reality

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Abstract

McTaggart distinguished two conceptions of time: the A-series, according to which events are either past, present or future; and the B-series, according to which events are merely earlier or later than other events. Elsewhere, I have argued that these two views, ostensibly about the nature of time, need to be reinterpreted as two views about the nature of the universe. According to the so-called A-theory, the universe is three-dimensional, with a past and future; according to the B-theory, the universe is four-dimensional. Given special relativity (SR), we are obliged, it seems, to accept (a modified version of) the B-series, four-dimensional view, and reject the A-series, three-dimensional view, because SR denies that there is a privileged, instantaneous cosmic "now" which seems to be required by the A-theory. Whether this is correct or not, it is important to remember that the fundamental problem, here, is not "What does SR imply?", but rather "What is the best guess about the ultimate nature of the universe in the light of current theoretical knowledge in physics?". In order to know how to answer this question, we need to have some inkling as to how the correct theory of quantum gravity incorporates quantum theory, probability and time. This is, at present, an entirely open question. String theory or M-theory, seems to evade the issue, and other approaches to quantum gravity seem equally evasive. However, if probabilism is a fundamental feature of ultimate physical reality, then it may well be that the A-theory or rather a closely related doctrine I call "objectism", is built into the ultimate constitution of things.

1. Eventism versus objectism

McTaggart, famously, distinguished two conceptions of time: the A-series, according to which events are either past, present or future; and the B-series, according to which events are merely earlier or later than other events. Elsewhere (Maxwell, 1968, pp. 5–9, 1985, pp. 29–36, 2001, pp. 249–252) I have argued that these two views, ostensibly about the nature of time, need to be reinterpreted as two views about the nature of the universe — the nature of the entities of which the universe is composed. According to the A-series view (or A-theory), which I have called objectism (and which is sometimes called presentism), the universe is three-dimensional, with a past and future. The entities of which the universe is composed are *objects*, three-dimensional entities that move and change, which can be created and destroyed, and which are spread out in space, but not in space-time. *Objects* in this sense may be very different from familiar stones and tables: the instantaneous state of a field might be an *object*. According to the B-series view (or B-theory), which I have called eventism, the universe is four-dimensional. The basic entities of the universe are *events*, spread out and located in space-time rather than in space.

Objectism and eventism give different interpretations to space-time diagrams. According to eventism, a space-time diagram is a picture of a bit of the world itself, spread out as it is in space and time. According to objectism, a space-time diagram depicts facts about the world, but does not depict the world itself at all, which is three- and not four-dimensional. A four-dimensional worldline of an object is, according to objectism, the history of that object, but not the object itself. Eventism puts spatial and temporal relations on a par; both are relations between the ultimate entities of the universe, *events*. Objectism draws a sharp distinction between spatial and temporal relations: whereas spatial relations are between *objects*, temporal relations are between *facts about objects* or, perhaps, *instantaneous states of objects,* or *histories of objects*, and not between *objects as such*.

In order to make sense of objectism, it is essential not to interpret it as adding what has sometimes been called "objective becoming" to eventism (or to McTaggart's B-series, or to the space-time or "block universe" view)[1]. There are three quite distinct views to consider: (1) eventism — or the block universe view, (2) the block universe view plus "the present", which moves along the time line, thus creating "absolute becoming" and "the flow of time" and (3) objectism. Views (2) and (3) are quite different. These two views find (1), eventism or the block universe view, inadequate in quite different ways, and make quite different modifications to it. Consider a space-time diagram depicting the histories of

[1]This and the next paragraph have been added in response to a request for clarification by a referee.

objects moving through space for some duration of time. According to eventism, this can be taken to represent things as they really are. It is a picture of how things are (with two spatial dimensions missing). The universe really is spread out in space and time, and the space-time diagram depicts straightforwardly the bit of the universe it represents. According to (2), the space-time diagram of eventism leaves out one crucial element, namely "the present", and its motion along time. A spatial line needs to be added to the diagram (in reality a three-dimensional space-like hyperplane), which moves along time from past to future, thus representing "absolute becoming". According to (3), namely objectism, by contrast, the space-time diagram of eventism leaves *everything* out, the entire universe. For the universe is three-, not four-dimensional. The entities of which it is composed — objects — are three-dimensional. They are spread out in space, and have spatial relations between them, but are not spread out in time, and do not have temporal relations between them. Objects persist in time, have pasts and futures, come into existence and cease to exist, but none of this means that they are spread out in time. It is facts about objects, histories of objects — intellectual artefacts — that are "spread out" in time, not objects themselves. The space-time diagram of eventism must, according to objectism, be radically reinterpreted, so that it does not picture or depict anything, and certainly not a bit of the universe: instead it represents *facts about objects* much as a graph of, say, temperature against time might represent facts about objects but would not picture or depict objects themselves. Thus, (2) and (3) make quite different modifications to the space-time picture of eventism. View (2) adds "the present" and "the flow of time" to this picture, whereas (3) reinterprets the diagram as a representation of facts about objects, but is not a picture of objects or a bit of the universe at all. It cannot be because, according to objectism, objects and the universe are three-, not four-dimensional, and are not spread out in time in the way the diagram depicts. (For further clarification see Maxwell, 1968, pp. 5–9, 1985, pp. 29–36, 2001, pp. 249–252.)

This difference between (2), the time flow view, on the one hand, and (3), objectism, on the other, is crucial. For whereas the former view faces intractable problems about the nature of "the present" and "the flow of the present along time", objectism faces no such problems as it rejects, from the outset, the four-dimensional, space-time picture of the block universe (except as a way of representing facts about objects). To repeat, according to objectism, the block universe view is defective, not because it leaves out "the now", and "the movement of the now along time" (or "absolute becoming"), but rather because it leaves out *everything*, *the entire universe* (and only represents facts about objects, histories of objects, facts about the universe). Given objectism, one might try to represent things happening by means of a spatial line, the present, moving along time, but nothing in reality corresponds to the line moving along time because, according to objectism, there is in reality no temporal dimension for the line to move along.

Thus, in order to make sense of objectism, it is essential not to interpret it as adding ‘‘the now’’, ‘‘the flow of time’’ and ‘‘becoming’’ to eventism (or to McTaggart’s B-series or the ‘‘block universe’’ view). It is tempting to do this, because common-sense views about time tend to put eventism and objectism together incoherently to form a picture somewhat similar to ‘‘the flow of time’’ view. Common sense tends to think of the distant past in eventist terms, as ‘‘another place’’, but thinks of current events in objectist terms, the immediate past consisting of past facts about current objects and not being another temporal ‘‘place’’ in any sense at all. Such a common-sense picture of time, incoherently combining eventism and objectism, can lead one to think that the ‘‘now’’, and ‘‘temporal becoming’’ must be added to McTaggart’s B-series, or to the space-time or block universe view, to do justice to the way we experience time, in the present[2]. This incoherent admixture of eventism and objectism is sometimes taken, by proponents of the space-time or block universe view, to be the only potential rival to their view. They have no difficulty in demolishing this rival[3]. But the viable rival to eventism (the B-theory, or the space-time or block universe view) is *objectism*, not some incoherent admixture of eventism and objectism (the AB-theory), which has the objective present moving along spatialized time. The two rival views at issue, eventism and objectism, are best seen as rival views about the dimensionality of the universe, as I have indicated, and not, primarily, as rival views about the nature of time. In particular, objectism must not be identified with the view that there is something called ‘‘the objective now’’, or ‘‘temporal becoming’’, since this tends to appeal to the common-sense ‘‘eventism plus objectism’’ view, just indicated, which is inherently incoherent.

2. Special and general relativity, eventism and objectism

Do special and general relativity demand that one rejects objectism, and adopts eventism instead? It is striking that Einstein formulated special relativity (SR) originally, in 1905, in objectist terms, reference frames being characterized in terms of rods and clocks, persisting objects. It was only with Minkowski’s reformulation of SR, in 1908, that the space-time view came to the fore. ‘‘Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality’’ Minkowski resoundingly declared (Lorentz et al., 1952, p. 75). Einstein initially dismissed Minkowski’s contribution as ‘‘superfluous learnedness’’ (Pais, 1982, p. 152), and remarked that now that the mathematicians had got their hands on his theory, he no longer understood it himself. But subsequently he

[2]On this view, the two views should be known, not as the A- and B-theory, but rather the AB- and B-theory, an observation due to Michael Lockwood (personal communication).

[3]See, for example, Grünbaum (1964, Chapter 10).

adopted Minkowski's space-time view as an essential step towards creating his second great theory — general relativity (GR).

And it seems that SR does indeed imply that we are obliged to reject objectism and accept eventism. For if objectism is true, the universe is made up of three-dimensional objects, persisting and changing. At any instant, here and now, there must be a cosmic-wide state of the universe, indeed *the universe* at that instant. But this clashes with SR. Observers (or objects) in relative motion here and now have associated with them different cosmic-wide presents or "nows". In denying that there is any such thing as a privileged reference frame, SR denies that there is, associated with any space-time point or event, a privileged, cosmic-wide instantaneous "now", which divides all other events into those that are "past" and "future". Any space-like hyperplane that passes through the point or event in question is as good an instantaneous "now" as any other. Thus SR, if true, rules out objectism, and demands that eventism must be accepted — a version of eventism that holds that space-time is Minkowskian[4].

But is SR true? If GR is true, then SR is false (since SR asserts that space-time is flat while GR asserts that, in the presence of energy, it is curved). But appealing to GR instead of SR does not help the case for objectism, since GR would seem to be just as incompatible with objectism as SR.

But is GR true? We seem to have rather good grounds for holding that it is false. Efforts to reconcile GR and quantum theory (QT) have not succeeded. All attempts known to me to unify GR and QT, or GR and the quantum field theories of the "Standard model" (SM), such as string theory (or M theory), and loop quantum gravity, if successful, would imply that GR is false. GR would emerge as an approximation when certain limits are taken, somewhat as Newtonian theory (NT) emerges from GR as an approximation, or Kepler's laws of planetary motion emerge from NT as an approximation. This is a standard state of affairs in theoretical physics. Almost always in the history of physics, when a new theory, T, unifies two predecessor theories, T_1 and T_2, T reveals that T_1 and T_2 are strictly speaking false (even though both T_1 and T_2 make many true, somewhat imprecise empirical predictions).

Granted, then, that we seek to discover which of eventism and objectism is *true*, and granted that both SR and GR are *false*, the important question becomes: Does the true theory of quantum gravity, like SR and GR, imply that objectism is false?

It is possible that the true theory of everything, T, may not, of itself, decide which of eventism and objectism is true. From the standpoint of physics alone,

[4]This conclusion can be avoided if SR is reinterpreted in such a way that it does not deny the existence of a privileged reference frame, but asserts, merely, that it is not discoverable empirically.

eventism must always, it would seem, remain a possibility[5]. It would seem, then, that either T is such that it can be reconciled with either eventism or objectism, or T is such that it implies that objectism is false. Which of these options is true?

3. The true theory of everything and aim-oriented empiricism

This question may seem hopeless. In the absence of the true theory of quantum gravity, or the true theory of everything, it may seem that there is nothing that can be said about their character. Only when a candidate theory of quantum gravity, or of everything, has been formulated, tested and corroborated will we be in a position to assess objectism with respect to these theories[6]. As things are at present, we have no theoretical scientific knowledge about the ultimate nature of the physical universe.

Elsewhere, I have argued at length that the standard empiricist conception of science that is being presupposed here is untenable (Maxwell, 1974, 1984, Chapter 9, 1993, 1998, 1999, 2000, 2001, Chapter 3 and Appendix 3, 2002a, 2002b, 2004b, 2005). Persistent acceptance of unified theories, and persistent rejection (or rather failure even to consider) of empirically more successful but disunified theories, means that science accepts, as a part of theoretical knowledge, a metaphysical thesis about the universe which asserts that the universe has a unified dynamic structure (to some degree at least). In order to do justice to this point, physics needs to be construed as accepting, as a part of scientific knowledge, a hierarchy of metaphysical theses concerning the knowability and physical comprehensibility of the universe, which become increasingly insubstantial, and thus increasingly likely to be true, as one ascends the hierarchy, see Fig. 1. Low down in this hierarchy there is the thesis that the universe has a unified dynamic structure (which I call "physicalism"). Physicalism is thus an integral part of current theoretical scientific knowledge, more secure indeed than any theory however empirically successful, such as SR, GR, QT or SM.

[5]The only argument known to me from physics, or the philosophy of physics, for excluding eventism has to do with the possibility of interpreting physical theories essentialistically, as attributing necessitating properties to physical entities, there thus being something in nature which ensures that the regularities of physical law are obeyed. In Maxwell (1968), I argued that essentialism presupposes objectism. Subsequently, I changed my mind and argued that one can make sense of essentialism given either objectism or eventism (Maxwell, 1998, pp. 141–150; see especially p. 150). It is possible, however, that the earlier argument is the correct one, and the later argument deserves to be rejected.

[6]We can, of course, consider string (or M) theory, and loop quantum gravity, in their present unsatisfactory state, and consider whether these theories are such as to rule out objectism. Insofar as these theories reproduce the way GR declares all space-like hypersurfaces to be equally legitimate instantaneous "nows", these theories rule out objectism for the same reason as GR does. But if a theory of this type picks out a family of cosmic-wide, space-like hypersurfaces as representing uniquely successive cosmic "nows", then the theory fails to exclude objectism (at least for the reasons given in Section 2).

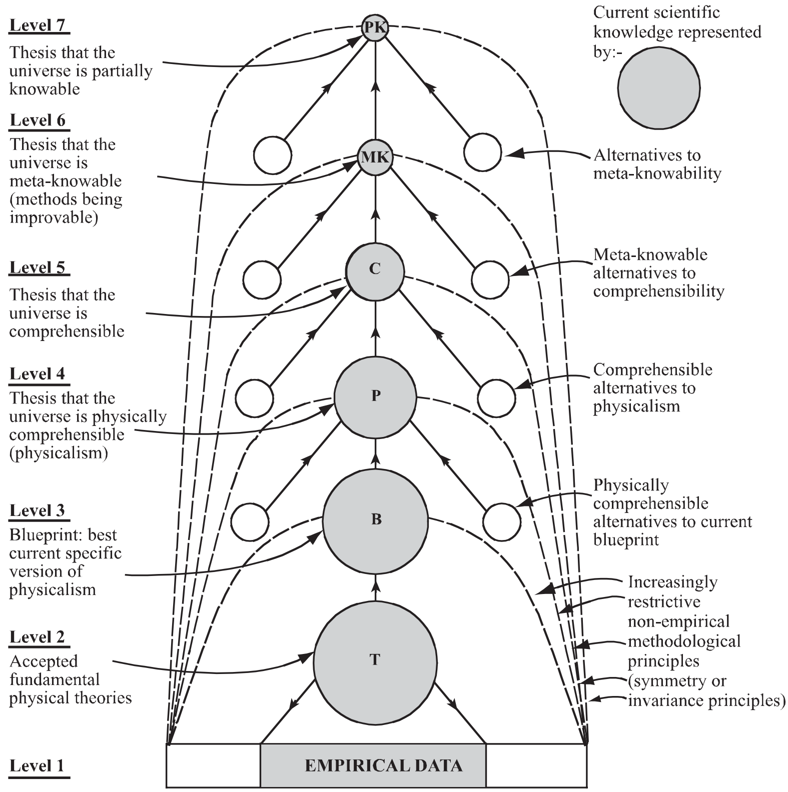

Fig. 1. Aim-oriented empiricism (AOE).

Granted this conception of physics, which I call "aim-oriented empiricism" (AOE), it is to be expected that physics should advance from one false theory to another. If physicalism is true, then no dynamic theory of restricted scope (which cannot immediately be generalized to become an accurate theory of everything) can be precisely true of any restricted range of phenomena. Granted physicalism, if a physical theory is precisely true of anything, it must be precisely true of everything.

The conclusion we should draw from all this is that physics does, now, possess (conjectural) theoretical knowledge about the ultimate nature of reality[7]. A proper, basic task for philosophy of physics, indeed, is to speculate, within the general framework of AOE, about the nature, the general character, of the true

[7]This (conjectural) scientific knowledge about ultimate reality is based on current (and past) research, as a referee has correctly pointed out. But the crucial point is that what we are entitled to take to be our current knowledge about ultimate reality differs dramatically, depending on whether we accept standard empiricism (SE) or AOE. Granted SE, we have no such current knowledge, as we have good grounds for believing all our current fundamental physical theories are false. Granted AOE, we have one highly significant item of knowledge: physicalism.

theory of everything, the ultimate nature of physical reality. (In moving from standard to AOE, the nature of the relationship between science and philosophy of science is transformed: the philosophy of science ceases to be a meta-discipline, and becomes an integral part of the scientific enterprise itself.)

It is thus entirely proper (and not hopeless at all) to consider whether the true theory of quantum gravity, or of everything, will imply that objectism is false.

4. Time and probabilism

SR and GR, we have agreed, rule out objectism. Both these theories will be derivable from the true theory of quantum gravity, or of everything, T, as approximations. Does this not make it likely that T, too, will rule out objectism? What grounds might there be for thinking otherwise? There are two.

The first has to do with time. As Chris Isham has emphasized especially (see Isham, 1993, 1997), time poses an especially severe problem for attempts to develop quantum gravity (and thus the true theory of everything, T). This is partly due to the fact that time figures in quite different ways in GR and QT, even Lorentz invariant QT, or quantum field theory (QFT). As far as GR is concerned, time is a part of space-time, that within which events are, as it were, embedded. As far as QT is concerned, time is something external to the quantum system in question, measured by an external clock.

Whereas GR presupposes eventism, QT is compatible with objectism. (As I pointed out above, no physical theory can presuppose objectism in the sense that it cannot be formulated in such a way as to be compatible with eventism.)

It may be objected that QFT cannot be compatible with objectism, since SR contradicts objectism, and QFT, of course, has SR built into it. But it must be remembered that orthodox QT, whether Lorentz invariant or not, is a theory about the results of performing measurements on quantum systems prepared to be in certain quantum states. The quantum states, and the quantum fields of QFT, cannot be taken seriously as physical entities existing in space and time independently of methods employed to prepare and measure them. QT and QFT have instrumentalism built into them. Severe problems arise when it is demanded that the measurement process itself should be Lorentz invariant. It is by no means clear that this demand can be fulfilled[8].

The only consistent Lorentz invariant treatment of quantum measurement known to me is Gordon Fleming's "hyperplane dependent" theory (see Fleming, 1989). This entails a radical departure from Minkowskian space-time, however, in that it requires that the basic space-time entity is the space-like

[8]For an excellent account of the problems encountered in reconciling QT and special relativity, see Maudlin (2002).

hyperplane rather than the space-time point. According to the theory, what exists in any small space-time region may depend on what hyperplane it is considered to lie on. Reality is, according to the theory, highly non-local in character, a dramatic departure from SR as ordinarily understood.

If Fleming's speculative hyperplane-dependent theory is put on one side, then QFT, including measurement, cannot be held to be fully in accord with SR. QFT, unlike SR and GR, cannot be regarded as presupposing eventism and unambiguously excluding objectism.

Insofar as it is true that the different ways in which time figures in GR and QT amounts to GR presupposing eventism and QT failing unambiguously to exclude objectism, and taking into account that no satisfactory unification of GR and QT has yet been formulated, it must be an open question as to whether the eventism of GR, or the objectism of QT, as a possibility at least, will win out in the unifying theory.

The second, and in my view stronger, ground for holding that T (quantum gravity or the true theory of everything) may not rule out objectism has to do with *probabilism*. Elsewhere I have argued at length that QT needs to be interpreted as a fundamentally probabilistic theory, and I have put forward such a version of QT, testably distinct from orthodox QT (see Maxwell, 1976, 1982, 1988, 1994, 1998, Chapter 7, 2004a). This version of QT is sketched below in the appendix: for other fundamentally probabilistic versions of QT, see Ghirardi and Rimini (1990) and Penrose (1986). By a "fundamentally probabilistic" theory I mean one that postulates real, objective probabilistic transitions in nature, not specifically tied to measurement. If a fundamentally probabilistic version of QT turns out to be "correct", to the extent that it is free of the conceptual defects which plague orthodox QT, and meets with greater empirical success than orthodox QT, then there are strong grounds for holding that nature herself is probabilistic, especially in view of the staggering empirical success of QT.

There are other grounds for taking very seriously the thesis that nature (i.e. the true theory of everything) is fundamentally probabilistic (i.e. probabilism is true). Spontaneous symmetry breaking is an essential feature of the quantum electroweak theory of Weinberg and Salam. Basing their considerations on this feature of the theory, and on the empirical success of the theory, physicists and cosmologists very seriously take the idea that after the big bang, the cosmos has undergone one or more spontaneous symmetry-breaking episodes. It is, for example, a feature of versions of inflationary cosmology. But spontaneous symmetry breaking demands probabilism. Insofar as we take spontaneous symmetry breaking seriously, we take probabilism seriously as well.

The point now is this. If nature is fundamentally probabilistic in character, as well as being quasi quantum mechanical, then it is not unreasonable to suppose that there are cosmic-wide instantaneous "nows" associated with probabilistic transitions that are entirely physical in character. Only very subtle experiments, not yet performed, might be able to detect the existence of these cosmic "nows"[9]. If they do exist, then T (which postulates them) does not exclude objectism. Objectism only appears to be ruled out if we restrict our attention to SR and GR, which fail to do justice to the probabilistic character of nature, and thus fail to do justice to that feature of nature that makes objectism viable.

In creating SR, Einstein took determinism for granted. Nevertheless, SR is not incompatible with probabilism as such. SR could, it seems, accommodate a version of probabilism that is such that all probabilistic events are highly localized throughout. But suppose probabilistic events fail to satisfy this condition. In particular, suppose they take the following quasi-quantum mechanical form. A physical system, S, is spread throughout some spatial region R (as the Ψ-function of QT is spread out spatially); S then interacts with a much more localized system, s, confined to a spatial region, r, somewhere in R. The interaction produces the physical condition for a probabilistic transition to occur, and S is localized, instantaneously and probabilistically, within r. In this case a reference frame, say F_S, which depicts the "collapse of the wave packet" of S, the probabilistic localization of S from R to r, as instantaneous, will make sense of the probabilistic transition. But all other frames, moving with respect to F_S, will fail to do this. For in these other frames, physical parts of S will begin to collapse towards r before the physical condition for this collapse to occur have been met. Physical occurrences will, as it were, anticipate future states of affairs. For such a fundamentally probabilistic theory, then, even though it is Lorentz invariant in other respects, only F_S (and frames stationary with respect to F_S) can make physical sense of the probabilistic transition. The probabilistic transition in effect defines a unique instantaneous "now". It is reasonable to suppose that, for such a Lorentz invariant fundamentally probabilistic theory, all such instantaneous "nows" would add up to a unique family of "nows". The fundamentally probabilistic version of QT that I have sketched in the appendix, and formulated in more detail elsewhere (Maxwell, 1976, 1982, 1988, and especially Maxwell, 1994, 1998, Chapter 7, 2004b) is precisely of this type[10]. So too are other probabilistic versions of QT (see Ghirardi & Rimini, 1990; Penrose, 1986).

[9]The fundamentally probabilistic version of QT that I have put forward elsewhere (Maxwell, 1976, 1982, 1988, 1994, 1998, Chapter 7, 2004a) is in principle experimentally distinct from orthodox QT. The relevant crucial experiments are very difficult to perform and have not, to my knowledge, yet been performed. These are the kind of as yet unperformed "very subtle experiments" that might reveal the existence of cosmic-wide hypersurfaces on which probabilistic events occur.

[10]So far this "propensiton" version of QT has been formulated only for non-relativistic QT; its relativistic generalization has not yet been done.

What really goes on, at the quantum mechanical level, during the process of quantum mechanical measurement, is still a mystery. It is conceivable, however, that the fundamentally probabilistic version of QT that I have proposed, or a version of QT of the type indicated in the previous paragraph, is correct. If so, only experiments that may be very difficult to perform will detect the difference between orthodox QT and these fundamentally probabilistic versions of QT. Cosmic-wide instantaneous "nows" may, in other words, exist and may be detectable experimentally, but only by experiments not so far performed. Experiments required to differentiate the version of QT I have proposed from orthodox QT are, as I have indicted, fiendishly difficult to perform, and have not yet been performed (to my knowledge), even though they are, in principle, possible. It is in this way that SR's denial of the existence of a unique family of instantaneous "nows", required for objectism to be viable, may be misleading. Despite this denial, such a family, associated with probabilistic transitions, may well exist. Despite what SR implies, objectism may well be true.

As I understand the situation, GR does not deny probabilism either. But, in order to be compatible with GR, probabilistic transitions would need to be both highly localized throughout, and such that they do not produce instantaneous changes in the gravitational field. (Unlike SR, GR is a deterministic dynamical theory in its own right, and thus cannot allow probabilistic transitions in the gravitational field to occur.) Probabilistic transitions of the kind considered above do not satisfy these conditions, and are thus incompatible with GR. If it is reasonable to hold that the correct fundamentally probabilistic version of QT, when made compatible with SR (insofar as it can be) postulates a unique family of instantaneous "nows", the same would presumably hold for such a theory formulated within the context of GR.

5. In defence of objectism

Objectism captures the way we ordinarily construe the world. Eventism (the B-theory, the space-time view, the block universe) does extreme violence to the way we ordinarily conceive of the world. Almost everything that we ordinarily take for granted becomes a kind of massive illusion, a shared hallucination, if eventism is true. Such things as: the existence of objects; the supreme reality of the present and the non-existence of the past and the future (except as past and future facts about what exists now); the three-dimensionality of a world in which things persist and change, four-dimensional histories being artificial constructs, facts about things rather than things themselves; and people acting to change the future and not being merely embedded in a space-time that is just atemporally "there" — all these things, that we ordinarily take for granted, becomes illusory if eventism is true. There need to be strong grounds indeed for abandoning objectism in favour of eventism (the B-theory). If such strong grounds seem to arise from science, then we should bravely face the world as it appears to be, and resign ourselves to living with eventism. But if such strong grounds subsequently collapse, and there appears to be no good scientific reason whatsoever for preferring eventism to objectism, we should not — as tends to happen in such situations — continue to accept, or even take seriously, eventism out of a kind of intellectual inertia. Grounds for believing in eventism having collapsed, we should instantly reject this profoundly counter-intuitive view and return to objectism.

The only scientific grounds — the only grounds — for preferring eventism to objectism come from SR and GR. But there are also reasons for doubts, as I have indicated. QT provides grounds for holding that nature is fundamentally probabilistic. If it is, and if quantum gravity, or the true theory of everything, postulates cosmic-wide instantaneous "nows", a unique family of space-like hypersurfaces on which probabilistic transitions occur, then the "strong grounds" for rejecting objectism and accepting eventism collapse. In these circumstances, we should reject eventism and return to objectism. We should not continue to adopt eventism when all reasons to prefer this profoundly counter-intuitive doctrine have collapsed, out of nothing more than a kind of intellectual inertia.

6. Probabilistic dynamic geometry

I conclude with what may well be a very naïve remark concerning quantum gravity.

As I have argued elsewhere (Maxwell, 1993, pp. 275–305), Einstein put a quite specific (if fallible) method of discovery[11] into practice in discovering SR and GR. This involves picking two clashing, empirically highly successful theories, T_1 and T_2, extracting a basic principle, P_1 and P_2, from each, these principles being such that they conflict, in an attempt to get at the root of the clash between the two theories. Some modification is then made, either to P_1 or P_2, or to some other part of physics, which renders P_1 and P_2 mutually compatible, these two principles then being taken as the kernel of the new, unifying theory. Thus, SR arose from the conflict between NT and classical electrodynamics (CE). From NT Einstein took the restricted principle of relativity (P_1); from CE he took the light postulate (P_2). Adjustments to Newtonian conceptions of space and time rendered P_1 and P_2 compatible, which became the two basic postulates of SR. GR arose out of the conflict between SR and NT; P_1 is SR itself; P_2 is the

[11]This method of discovery, created in scientific practice by Einstein, is an important ingredient of AOE (see Maxwell, 1998, pp. 29, 159–163, 219–223, 2004b, pp. 34–39).

principle of equivalence. These are then deployed to reveal that gravitation curves space, or rather space-time, which in turn suggests the key idea of GR that gravitation *is* the curvature of space-time.

This method of discovery should be employed to discover quantum gravity. The two theories are GR and QT (or QFT or SM). If QT is interpreted to be fundamentally probabilistic, we at once have the basic clash between the two theories: determinism versus probabilism. From GR we take deterministic, dynamic space-time geometry, from QT we take probabilism — characteristically quantum mechanical probabilism involving non-local probabilistic transitions. The synthesis requires the development of some kind of probabilistic, dynamic, space-time geometry. This requires, we may surmise, the specification of space-like hypersurfaces on which probabilistic transitions occur — these hypersurfaces forming a unique foliation of space-time, and constituting successive cosmic instantaneous "nows". Do we suppose, with Penrose that space-time has a definite curvature, and permits quantum systems to evolve into superpositions that depart somewhat from the actual curvature until this discrepancy becomes, as it were, intolerable, and collapse occurs? Or do we suppose that something like superpositions of three-dimensional spaces with different curvatures evolve and then collapse into one or other such curved space, in each case on some definite space-like hypersurface? Or is there some other way in which the basic idea of probabilistic dynamic geometry can be realized which, perhaps, leads to the correct theory? If probabilistic QT and deterministic GR can be unified correctly, so as to retain the probabilism of QT and the dynamic geometry of GR, it may well be that the resulting theory will render objectism a viable option. If it is, then it deserves to be accepted.

Acknowledgements

I would like to thank Michael Lockwood and Leemon McHenry for their comments on an earlier version of this paper.

Appendix: Fundamentally probabilistic quantum theory (PQT)

The thesis of this paper might be summed up like this. How seriously we should take the ontological implications of Minkowskian space-time depends crucially on how QT is to be interpreted. If QT is fundamentally probabilistic, and this probabilism is retained by the true theory of everything (with probabilistic transitions occurring on cosmic-wide space-like hypersurfaces), then the case for eventism and the space-time viewpoint would collapse. With this in mind, I now sketch the fundamentally probabilistic version of QT I have spelled out in more detail elsewhere (Maxwell, 1976, 1982, 1988, 1994, 1998, Chapter 7, 2004a).

The basic idea is that probabilistic transitions occur whenever new particles, bound systems or stationary states are created as a result of inelastic collisions. That is, whenever, as a result of an inelastic interaction, a system of interacting "particles" creates new "particles", bound or stationary systems, so that the state of the system goes into a superposition of states, each state having associated with it different particles or bound or stationary systems, then, when the interaction is nearly at an end, spontaneously and probabilistically, entirely in the absence of measurement, the superposition collapses into one or other state.

The problem, here, is to specify precisely "when the interaction is nearly at an end". This can be done as follows. Consider the toy inelastic interaction:

$$a+b+c \rightarrow \begin{cases} a+b+c & \text{(A)} \\ \\ a+(bc) & \text{(B)} \end{cases}$$

Here, a, b and c are spinless particles, and (bc) is the bound system. Let the state of the entire system be $\Phi(t)$, and let the asymptotic states of the two channels (A) and (B) be $\psi_A(t)$ and $\psi_B(t)$, respectively. Asymptotic states associated with inelastic interactions are fictional states towards which, according to OQT, the real state of the system evolves as $t \rightarrow +\infty$. Each outcome channel has its associated asymptotic state, which evolves as if forces between particles are zero, except where forces hold bound systems together.

According to OQT, in connection with the toy interaction above, there are states $\phi_A(t)$ and $\phi_B(t)$ such that

(1) For all t, $\quad \Phi(t) = c_A\phi_A(t) + c_B\phi_B(t) \quad$ with $|c_A|^2 + |c_B|^2 = 1$;
(2) as $t \rightarrow +\infty$, $\quad \phi_A(t) \rightarrow \psi_A(t)$ and $\phi_B(t) \rightarrow \psi_B(t)$

The idea is that at the first instant t for which $\phi_A(t)$ is very nearly the same as the asymptotic state $\psi_A(t)$, and $\phi_B(t)$ is very nearly the same as $\psi_B(t)$, then the state of the system, $\Phi(t)$, collapses spontaneously either into $\phi_A(t)$ with probability$|c_A|^2$, or into $\phi_B(t)$ with probability$|c_B|^2$. Or, more precisely:

Modified Born postulate: At the first instant for which$|\langle\psi_A(t)|\phi_A(t)\rangle|^2 > 1-\varepsilon$ or$|\langle\psi_B(t)|\phi_B(t)\rangle|^2 > 1-\varepsilon$, the state of the system collapses spontaneously into $\phi_A(t)$ with probability$|c_A|^2$, or into $\phi_B(t)$ with probability$|c_B|^2$, ε being a universal constant, a positive real number very nearly equal to zero.

The evolutions of the actual state of the system, $\Phi(t)$, and the asymptotic states, $\psi_A(t)$ and $\psi_B(t)$, are governed by the respective channel Hamiltonians, H,

H_{A} and H_{B}, where:

$$H = -\left(\frac{\hbar^2\nabla_a^2}{2m_a} + \frac{\hbar^2\nabla_b^2}{2m_b} + \frac{\hbar^2\nabla_c^2}{2m_c}\right) + V_{ab} + V_{ac} + V_{bc}$$
$$H_{\mathrm{A}} = -\left(\frac{\hbar^2\nabla_a^2}{2m_a} + \frac{\hbar^2\nabla_b^2}{2m_b} + \frac{\hbar^2\nabla_c^2}{2m_c}\right)$$
$$H_{\mathrm{B}} = -\left(\frac{\hbar^2\nabla_a^2}{2m_a} + \frac{\hbar^2\nabla_b^2}{2m_b} + \frac{\hbar^2\nabla_c^2}{2m_c}\right) + V_{bc}$$

Here m_a, m_b and m_c are the masses of "particles" a, b and c, respectively, and $\hbar = h/2\pi$, where h is the Planck's constant.

The condition for probabilistic collapse, formulated above, can readily be generalized to apply to more complicated and realistic inelastic interactions between "particles".

According to this micro-realistic, fundamentally probabilistic version of QT, the state function, $\Phi(t)$, describes the actual physical state of the quantum system, from moment to moment. Quantum systems may be called "propensitons". The physical (quantum) state of the propensiton evolves in accordance with Schrödinger's time-dependent equation as long as the condition for a probabilistic transition to occur does not obtain. The moment it does obtain, the state jumps instantaneously and probabilistically, in the manner indicated above, into a new state. (All but one of a superposition of states, each with distinct "particles" associated with them, vanish.) The new state then continues to evolve in accordance with Schrödinger's equation until conditions for a new probabilistic transition arise.

Propensiton quantum theory (PQT), as we may call this micro-realistic, fundamentally probabilistic version of QT, can recover all the experimental success of OQT. This follows from four points. First, OQT and PQT use the same dynamical equation, namely Schrödinger's time-dependent equation. Second, whenever a position measurement is made, and a quantum system is detected, this invariably involves the creation of a new "particle" (bound or stationary system, such as the ionization of an atom or the dissociation of a molecule, usually millions of these). This means that whenever a position measurement is made, the conditions for probabilistic transitions to occur, according to PQT, are satisfied. PQT will reproduce the predictions of OQT (given that PQT is provided with a specification of the quantum state of the measuring apparatus). Third, all other observables of OQT, such as momentum, energy, angular momentum or spin, always involve (i) a preparation procedure that leads to distinct spatial locations being associated with distinct values of the observable to be measured and (ii) a position measurement in one or other spatial location. This means that PQT can predict the outcome of measurements of all the observables of OQT. Finally, insofar as the predictions of OQT and PQT differ, the difference is extraordinarily difficult to detect, and will not be detectable in any quantum measurement so far performed.

In principle, however, OQT and PQT yield predictions that differ for experiments that are extraordinarily difficult to perform, and which have not yet, to my knowledge, been performed. Consider the following evolution:

	collision	superposition	reverse collision	
		a + b + c		
a + b + c	$\longrightarrow$		$\longrightarrow$	a + b + c
		a + (bc)		
(1)	(2)	(3)	(4)	(5)

Suppose the experimental arrangement is such that, if the superposition at stage (3) persists, then interference effects will be detected at stage (5). Suppose, now, that at stage (3) the condition for the superposition to collapse into one or other state, according to PQT, obtains. In these circumstances, OQT predicts interference at stage (5), whereas PQT predicts no interference at stage (5) (assuming the above evolution is repeated many times). PQT predicts that in each individual case, at stage (3), the superposition collapses probabilistically into one or other state. Hence, there can be no interference.

If this fundamentally probabilistic version of QT (or something like it) is correct, and the probabilism of the theory is preserved intact in quantum gravity and the true theory of everything (with probabilistic transitions occurring on successive cosmic-wide space-like hypersurfaces), this would suffice to kill the case for eventism and the space-time viewpoint.

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Philosophy and Foundations of Physics
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Chapter 13

Temporal Presentness and the Dynamics of Spacetime[1]

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The purpose of this paper is to pick up the threads of a debate about the ontology of becoming in spacetime that was triggered by a provocative article published by Nicholas Maxwell (1985). This debate is itself merely a recent episode in a long dialogue that goes back at least as far as the time of Parmenides and Heraclitus (Savitt, 2001). Here is the question around which this debate is centred: is change or becoming the distinguishing feature of the natural or physical world, as suggested obscurely by Heraclitus and argued at length by Aristotle? (See Robinson, 1987; Furley, 1967, and Aristotle's *Physics*, in, e.g. McKeon, 1941.) Or is our usual uncritical belief in the reality of change the product of some sort of perceptual illusion or intellectual error, as believed by Parmenides and a small host of recent authors such as Gödel (1949) and Julian Barbour (2002)?

I will not be able to solve the whole of this momentous problem here. However, I intend both to set aside a few unwarranted assumptions, which have for a long time dogged our thinking about the puzzle of becoming, and to assemble some tools which should aid in finding a solution to it. In particular, I will argue that we can do much better than is usually supposed in identifying structures that can both "live" within Minkowski spacetime and represent objective becoming. I shall also discuss whether such structures would necessarily contradict the Principle of Relativity, and finally consider the impact of quantum mechanics on the problem of becoming.

[1]This paper is dedicated with affection and respect to the memory of Rob Clifton — although without any presumption that he would have endorsed the views presented here!

1. Probabilism and spacetime structure

Maxwell's major claim was that probabilism contradicts the special theory of relativity. "Probabilism", says Maxwell (1985, p. 23) "is the thesis that the universe is such that, at any instant [whatever that might mean], there is only one past but many alternative possible futures". Maxwell argues that probabilism derives its strongest support from quantum mechanics, but we can introduce the notion by recalling a famous discussion by Aristotle about the truth conditions of a proposition.

Aristotle invited us to consider the following statement: "There will be a sea battle tomorrow". (See *de Interpretatione*, Chapter 9, in (e.g.) McKeon, 1941, pp. 45–48.) He used this as a counter-example to the claim that all propositions have a truth value, since he took it to be self-evident that a proposition about what may happen tomorrow has no truth value on the day in which it is uttered. (Tomorrow's battle might well be highly probable today, but Aristotle believed that no matter how probable the battle is, there are many factors that are, in principle at least, free to act *today* to change what happens tomorrow; for instance, the naval commanders could decide at the last minute not to fight after all, or a sudden storm could blow up and prevent the battle.) Thus, in this view, while the present consists of coexistent or co-actual realities, and the past is settled but no longer actual, the future is ontologically open. What is to become is merely a possibility, which in itself has no being outside the minds of those who conceive of it — though there is room in such views, as both Aristotle himself and Maxwell indicate in different ways, for reification of propensities or potentialities so long as they are conceived to act in the *present*.

The Newtonian picture differs from the Aristotelian in that Newtonian mechanics conceived of physical processes as entirely governed by deterministic dynamical laws[2]. This meant that at any given time there was only one possible future; or, if there seemed to be many, it would be only due to our ignorance of the details of the physical world at that given time. Still, one can in a Newtonian universe uphold an ontological distinction between present and future, even though, because of determinism, the distinction is moot (Savitt, 2001).

Special relativity calls into question the possibility of ontological distinctions between past, present, and future, because of the relativity of optical simultaneity

[2]Richard Arthur (private communication) has cautioned me to choose my words carefully here, since Newton *himself* believed that God could intervene from time to time in order to pat the planets back into their proper orbits, as it were, should their motion become chaotic. The notion that Newton's laws, expressed in terms of differential equations, are *sufficient* to determine the future of the physical world for all time solidified only with the work of the great mechanicians of the 18th century. This line of thought culminated in the famous quip of Laplace (when asked by Napoleon what role God played in his celestial mechanics) that he had no need of that "hypothesis" (Bell, 1937).

(Mundy, 1986) — that is, simultaneity defined in terms of equality of time coordinates constructed according to the procedures set out by Einstein (Wheeler & Taylor, 1963). Suppose Alice and Bob are two inertial observers moving toward each other. Let O and O' be events on Bob's and Alice's world-lines respectively such that O, O' are simultaneous in Bob's coordinates. Then we can easily see from Minkowski diagrams that the hyperplane of simultaneity in Alice's coordinates that passes through O' will intersect Bob's worldline at some event-point E which is *later* than O (let us say it is a day later) in terms of proper time along Bob's worldline. Therefore, events that are optically simultaneous in Bob's system will not necessarily be optically simultaneous in Alice's, and vice versa. So if *objective* means *invariant* (and it is hard to see what else it could mean in relativistic terms), there is no objective way of partitioning spacetime by means of a hyperplane of simultaneity, and thus no way to ground a global ontological distinction between past and future.

Now, E is tomorrow with respect to O but today with respect to O'. However, O' is today with respect to O; therefore, if the relation "today with respect to" is transitive then we end up with the uncomfortable result that O and E are today with respect to each other!

Of course, I am playing on an ambiguity. If "today" means "at the same date or time" then transitivity does not apply, since such judgements are valid only within a given coordinate system. However, if "today" means something like ontologically coexistent, co-occurrent, co-present, or co-actual, we have a tougher problem, for whether or not something *exists*, and thus whether or not two events coexist or co-occur, can hardly be relative to a mere choice of viewpoint or coordinate system (Petkov, 2001). This follows from the common conception of such notions as marking an ontological distinction. (Perhaps this common conception of coexistence is wrong, but I have no idea what a sensible alternative would be.) In fact, by the usual conception, coexistence ought to define equivalence classes: whatever exists coexists with itself; if e_1 coexists with e_2, then e_2 coexists with e_1; and if e_1 coexists with e_2, and e_2 coexists with e_3, then surely e_1 coexists with respect to e_3. Therefore, if events that are at the same time in *some* coordinate system or other deemed to coexist, then by transitivity *all* events in spacetime are ontologically equivalent, and change conceived of in the Aristotelian way is an illusion.

There are at least two ways in which one could avoid this conclusion (namely, the conclusion that from the relativity of simultaneity we infer that change is unreal). First, we could adopt a notion of becoming which relativizes becoming to world-points or worldlines. This is the position supported by Stein (1968, 1991) and Clifton and Hogarth (1995). Stein argued that all and only the points on the past cone of O have become for O, and Clifton and Hogarth generalized this definition to worldlines. Their relativized conception of becoming has the advantage of precision but it thumbs its nose at the Aristotelian notion of change, according to which the distinction between what has become and what may become must be global.

Another approach, the one I advocate here, is to reject the assumption that two events could be coexistent if and only if their time coordinates are equal; in other words, it is to reject the usually unquestioned assumption that the time coordinate has as much metaphysical significance as is usually given to it. The new approach says that the time coordinate is merely a descriptive device, which need not necessarily be taken to track real physical or ontological changes. I call this approach "new", but it has its roots in Aristotle's argument (*Physics* B) that time is merely a comparative scale used to keep track of motions, not motion itself.

If we want to track real physical changes (such as particle decay, physiological growth and ageing, or any other entropic process) in objects moving in a relativistic universe, the natural way to do it, as Richard Arthur (2003, 2006) has argued, is in terms of elapsed *proper* time. Consider the twin paradox, in which it is shown that initially identical twins who follow different paths through spacetime will, in general, be found to have aged by different amounts when they are brought together again at the end of their journeys. The physiological difference between the twins is strictly a function of their elapsed proper times. Hence, real physical changes are tied to *proper* time (or possibly, as we shall see, other proper quantities), not the time coordinate.

The usually unquestioned assumption that intrinsic physical change is tracked by the time coordinate is an outmoded holdover from the Newtonian worldview, where time is absolute — that is, the same (up to changes in scale) for all observers in all states of motion. It is long overdue that we move beyond this relict of bygone days, and get used to the idea that in a relativistic universe initially-standardized clocks can run at different rates depending on their acceleration history or exposure to gravitational fields[3]. It is not out of the question that two processes (either spatially distant or coincident) might well run at different rates (as judged in one frame of reference) and yet be somehow correlated or linked in some way physically. Thus, the door seems to be open to alternative notions of simultaneity that could give us more useful means to discuss non-local quantum processes, and might even allow us to define global distinctions between what has become, what is becoming, and what may become.

[3]Of course, as a referee has pointed out to me, I have to be very careful about what I mean by saying that standardized clocks may run at different rates. In its momentarily comoving frame a clock will seem to maintain a constant rate even if it is in fact falling into a black hole. Clocks exposed to different accelerations may seem to run at different rates as judged in one frame of reference, however. Furthermore, if such clocks are brought back to rest with respect to each other they may be found to have different elapsed proper times even if they were synchronized to begin with.

2. Generalizing simultaneity

A more general notion of simultaneity is certainly required if we adopt any interpretation or extension of quantum mechanics that explicitly involves spacelike causation or influences. The details of Maxwell's theory need not concern us here, except the key point that it treats state reduction or collapse as a real physical process, which must occur instantaneously. Bohm's theory does not involve state collapse, but changes in the quantum potential have to propagate faster than light, so one is still faced with essentially the same problem. Interpretations of quantum mechanics such as Bohm's or Maxwell's that entertain some sort of non-local "connectedness" are controversial but cogent, and they need to be taken seriously. Indeed, one of their greatest weaknesses has always been that no clear way can be found of making them relativistically invariant (although de Broglie's largely neglected later version of the causal interpretation is already written in terms of four-quantities; see de Broglie, 1960). Examples of such theories are the causal interpretations of the Bohm/de Broglie type (Bohm & Hiley, 1993; de Broglie, 1960) and Maxwell's "propensiton" theory (1985, 1988, 1994).

The problem is that "instantaneous" (in the sense of "occurring without time lapse") has no invariant meaning in special relativity, except in the sense in which two coincident events may be considered instantaneous with respect to each other. As pointed out by numerous authors (see especially Aharonov & Albert, 1980, 1981; Penrose, 1990), it is impossible to get a consistent description of quantum state reduction in spacetime if we assume that reduction occurs over hypersurfaces of constant time. We therefore need a generalized conception of instantaneity or simultaneity that could accommodate the non-locality of quantum mechanics. I will argue that such conceptions are available if we are willing, again, to drop the old Newtonian assumption that physical change must be linked to the time coordinate, and instead try to think in terms of relations between *proper* quantities along worldlines. I will now explore a thought experiment in this spirit.

3. Telepathic twins?

In his science fiction novel *Time for the Stars* (1956), Robert Heinlein proposed a whimsical thought experiment: what would follow if the twins in the twin paradox were telepathic? Would the twin who remains on Earth (Pat in the story) perceive his brother Tom's thoughts to be running slowly as Tom's spaceship approached the speed of light? And would Tom, conversely, perceive Pat's thoughts to be running fast? We know that at the end of the story Pat will have aged much more than Tom, but the usual view does not allow that there is any way of *directly* comparing their local (proper) clock rates during the voyage. But it is not entirely idle to think of what might pertain if there were such non-local interactions since, as noted, there is, arguably, a sort of "telepathy" in quantum mechanics.

We set ourselves the following problem: if Pat attempts to communicate with Tom at a certain proper time τ along Pat's worldline, at what proper time τ' on Tom's worldline is the message received? We cannot tell this story without making a stipulation about how our hypothetical telepathy propagates in space-time. Heinlein's answer was to suppose that telepathy is instantaneous in Earth's rest frame, or at least so close to instantaneous that its time-of-transmission over terrestrial distances would be undetectable. (Of course, Earth is orbiting all the time but the velocities involved are very small compared to the speed of light so we will take Earth as an approximate rest frame.) This means that Tom's and Pat's proper times (calculated from the beginning of the journey when the twins were coincident) will differ only because of their acceleration histories.

On the assumption that Pat remains on Earth throughout Tom's journey, and that Tom moves at constant velocity β, we get the familiar expression

$$\tau' = \sqrt{1-\beta^2}\tau \tag{1}$$

(This can be generalized to variable velocities.) Pat does indeed perceive his brother's thoughts to be running slow while Tom perceives Pat to be running fast.

Clifton and Hogarth (1995) accurately pointed out that in Peacock (1992a) paper I failed to make it clear that a global condition has to be imposed in order to avoid closed-loop paradoxes. (They made a similar criticism of an interesting proposal by F. A. Muller (1992)). Clifton and Hogarth argued that it is necessary to specify a particular worldline (say Pat's) for which the telepathic interaction is deemed to be instantaneous, thereby defining the velocity of the interaction for all other telepaths in the universe. (F. Artzenius made essentially the same point in conversation in 1992.) More precisely, it is not so much that a certain worldline has to be privileged in this way, but that there has to be a spacelike hypersurface over which the interaction propagates superluminally; the interaction will then be instantaneous for any observer whose world-line happens to be orthogonal to that hypersurface.

The question is whether the postulation of such hypersurfaces of invariant simultaneity amounts to a violation of the Principle of Relativity. Clifton and Hogarth (1995, p. 355) themselves state that this privileging of certain world-lines is "unwarranted". I will return to this important point, but first I want to note a very interesting feature of the Heinlein proposal.

4. Invariant simultaneity as equality of action

I will show now that if we assume certain not-implausible initial conditions, the simultaneity-relation Heinlein identifies can be stated elegantly in terms of equality of *action*.

Since Tom and Pat are assumed to be identical twins, we can take it that at the beginning of Tom's journey they both had the same initial energy E_0. At Pat's proper time τ he will possess an action $E_0\tau$. At any point in Tom's journey at which his relative velocity with respect to Pat is β, Tom will have energy as measured by Pat given by

$$E = E_0/\sqrt{1-\beta^2} \tag{2}$$

Hence at such points Tom will have an action

$$E\tau' = E_0/\sqrt{1-\beta^2} \times \sqrt{1-\beta^2}\tau = E_0\tau \tag{3}$$

That is, the world-points along Tom and Pat's worldlines that are simultaneous by the Heinlein criterion of "adjusted" proper times have the same *action*, given plausible initial conditions. (Rietdijk (1985) has also argued for a notion of invariant simultaneity defined in terms of action.) Of course, real twins on real spacecraft will exchange mass-energy with other systems during their journeys, but the story could be reformulated in terms of the very large number of identical elementary particles of which the twins are composed.

In fact, we could go farther and look at this from a cosmological point of view. If anything like the Big Bang picture is correct, in which all particles in the universe radiate from a singular initial state, the whole universe could be foliated by invariant hypersurfaces of action (perhaps possessing a rather complex topology). The interesting question is whether such action hypersurfaces could "play a direct role as a determinant in physical processes" (as D. Dieks put it, 1988, p. 456). Later, I shall sketch an argument to show that something like this could indeed be the case; but we first turn to the very difficult question of whether any picture involving distinguished spacelike hypersurfaces such as I indicate here would be in an unacceptable conflict with the Principle of Relativity.

5. Conflicts with relativity?

I will not be able to do justice here to the large question of the meaning of the Principle of Relativity. We can, however, say enough to rebut the charge that the kind of spacelike connectivity that I explore here is *necessarily* in conflict with relativity.

The Principle of Relativity expresses the postulate that the laws of physics take the same form in any physical frame. Special relativity follows from the assumption that the speed of light in vacuum is independent of the velocity of its source — which is, in effect, to say that it is itself a law of physics. The mathematical structure of Minkowski space and the Lorentz transformations follow from the assumption that the speed of light is an *invariant*, not an upper limit. Should the speed of light turn out to be a limit, that claim would be a theorem of the theory, not a postulate. (There are versions of relativity that take the limiting character of the speed of light as a postulate, but these theories are *reconstructions* of Einstein's original theory.) The core principles of relativity do not explicitly prohibit spacelike propagation.

It is perfectly true that for any superluminal motion (even massless motions such as the searchlight beam effect which certainly do occur) there exists a state of motion in which the given superluminal process is instantaneous. This is merely a reflection of the fact that for every spacelike worldline a frame of reference can be defined for which that worldline is one of the spatial axes. Many authors believe that the invariant distinguishability of such frames is in conflict with the Principle of Relativity. Maxwell (1985, p. 38), for instance, says that his own version of quantum theory which postulates superluminal collapse of spatially extensive "propensitons" into very small volumes

> … irreparably contradicts special relativity. For special relativity asserts that all inertial reference frames are physically equivalent. In only one reference frame, however, will any given probabilistic collapse of propensiton state be instantaneous; in other, relatively moving inertial reference frames the collapse will not, according to special relativity, be instantaneous (though always faster-than-light).

But surely the fact that any hypothetical superluminal propagation is instantaneous in one "distinguished" frame does not violate the Principle of Relativity any more than the fact that any subluminal motion is associated with a distinguished frame (namely, the rest frame of the system). There is a nice near-symmetry between the subluminal and superluminal cases. Any subluminal propagation (such as a baseball flying through the air) will be at rest in one "distinguished" frame (its local co-moving frame), but no one thinks that this violates the equivalence of reference frames. All that is required to satisfy the postulate of relativity is that in both the superluminal and subluminal cases, the description in any frame be consistent with that in any other, and this is possible so long as all such descriptions are understood as projections, as it were, into each frame of a single four-dimensional picture. There can be lots of frames of reference that can be "distinguished" in the sense that they have some invariant characteristic. The instantaneous co-moving rest frame of any ordinary baseball is invariant in the sense that all other observers will agree on which state of motion is distinguished in this way. However, this distinction is contingent; it has to do with the acceleration history of that particular ball. The fact that there are invariant facts about the history of particular objects in spacetime does not violate the Principle of Relativity; they are privileged because of their *dynamical* history, not because of some exception to the laws of nature.

This point is difficult, so I shall repeat the essence of it: any subluminal object is at rest in one and only one frame; this frame is "distinguished" in this way only for historical reasons (that is, only because of the history of the moving object), and its existence does not break the Principle of Relativity. Similarly, any superluminal system moves at infinite speed in one and only one frame, and this frame is also "distinguished" only for historical reasons, and its existence does not violate the Principle of Relativity.

The equivalence of reference frames does not mean that everything looks the same in every possible state of motion — far from it. Rather, it means that the way things look in all the various possible reference frames are consistent with one another in certain specific respects — namely that they respect the *invariance* of certain quantities such as the vacuum speed of light and, in general, the magnitudes of four-vectors such as the energy–momentum or position–time four-vectors. The only sort of phenomenon that would truly violate the Principle of Relativity (in its most general conception) would be something that depended *only* on the observer's position or state of motion, in such a peculiar way that it could not be seen as an aspect of some structure or process that had an equivalent description from other viewpoints. What would violate *Lorentz* invariance (which is not the most general sort of invariance) would not be superluminal propagation, but the breakdown of the non-dispersivity of the vacuum — a possibility that must, in fact, be taken most seriously (Amelino-Camelia et al., 1998; Smolin, 2003).

Clifton and Hogarth's worry is subtler than Maxwell's. Their austere aim was to see to what extent it is possible to define objective becoming relations in Minkowski spacetime whose "recipe" is based "solely on time-oriented metrical relations" (1995, p. 379). In this they took their lead from Stein, who said that any interesting becoming relation should be "definable in terms of the geometric structure" (1991, p. 149). As Dorato puts it, in "Stein's proof the main requirement that a becoming relation should satisfy to be regarded as *objective* in Minkowski spacetime is definability in terms of the geometric structure of the spacetime" (Dorato, 1996, p. 588). But why restrict the inquiry in this way? If one wants to investigate alternative conceptions of simultaneity that could support a global past–future distinction, the interesting question is not what *metrical* structures can *necessarily* be found in *all* time-oriented spacetimes, while assuming from the outset that there are no spacelike dynamical interactions. (To be fair to Clifton and Hogarth, it is mainly Stein who hung his hat on the latter point.) It is about what *dynamical* structures can *possibly* occur in *some* time-oriented systems, while *allowing* for the possibility of spacelike dynamics. The aim is to determine what is possible, not what is necessary. I decided that I would be very happy to find a class of *contingent* structures that can represent a simultaneity-like relation in spacetime so long as they had a covariant description — which both the Heinlein criterion and the action-equality criterion certainly do. But whether or not the specific suggestions explored here can be made to work, the central point is to see that covariant notions of simultaneity could be based on *dynamic* facts (facts about the spacetime distribution of matter, energy, particles, and fields) as well as purely metrical facts, because dynamical relations in spacetime are also covariant, and because simultaneity relations are relations between physical changes in actual physical systems.

The toughest problem with any sort of hypothetical superluminal connection or motion is that it may permit closed-loop paradoxes, in which events can apparently occur if and only if they do not occur! The full solution of this problem may involve thermodynamic or information-theoretic considerations that are outside the scope of special relativity. However, it is very reasonable to suppose that the frame of reference in which quantum collapses or interactions occur is somehow defined cosmologically. In cosmology, we already accept the fact that there is a cosmic rest frame defined by the cosmic background radiation (CBR). This involves no conflict with the Principle of Relativity, though, any more than does the fact that the floor of my office can in principle be used as a universal standard of rest. The CBR frame is, for reasons of cosmological history, merely the largest physical framework that we can identify. So as long as we can find a cosmological story about which frame of reference quantum "telepathy" is instantaneous in, and so long as we can tell this story in four-dimensional Lorentz-invariant manner, there is no conflict with the Principle of Relativity[4].

In sum, the indisputable fact that optical simultaneity is frame-dependent is simply *irrelevant* to whether there can be frame-independent conceptions of simultaneity. There could be any number of invariant simultaneity relations (many, no doubt, trivial — but not all) between spacelike separate points on worldlines so long as they are defined in terms of relations between *proper* quantities along those worldlines.

6. Covariant state reduction based on phase invariance

I will now make a quick pass at the very difficult question of finding a covariant description of state reduction — enough, I hope, to show that the usual discussions of this problem are hobbled by the same unwarranted assumption that has plagued discussions of becoming. The idea I consider here is very simple in essence, though it may turn out to be complicated in its application to concrete cases. If the sort of theory that I sketch here can be made to work, then it is not the case, *pace* Maxwell, that any sort of quantum theory involving state reduction necessarily contradicts special relativity.

Any wave packet in spacetime is a superposition of plane waves (de Broglie waves, or pure momentum states), which have the general form

$$\Psi(x,t) = a_0 e^{i(\mathbf{p}\cdot\mathbf{x} - Ht)/\hbar} \tag{4}$$

[4]An anonymous referee asked whether I claim that "different cosmological models may have different simultaneity properties, and may lack simultaneity relations at all?" The short answer to this question is yes, of course — although a cosmology with *no* interesting simultaneity relations would probably have a structure that was either chaotic or degenerate in some sense.

where $(\mathbf{x},t)$ and $(\mathbf{p},H)$ are the position–time and momentum–energy four-vectors, respectively. Now, if a wave packet reduces, by linearity this amounts simply to the disappearance of some of the plane waves of which it is composed. If we know how an individual plane wave can blink out covariantly we know how a wave packet does it. So we begin by looking for covariant features of plane waves, and an obvious candidate is phase — intuitively, where we are in the cycle. A covariant way for a plane wave to ‘‘blink out’’ is for it to disappear at the same point in its cycle for all observers. That is, we can get a covariant description of state reduction if we specify that if a particular component of a wave packet disappears at (say) 54° along in its cycle as a consequence of a measurement interaction, then all observers will agree that this is the case. A condition that can form the basis for a truly covariant description of state reduction, therefore, is *phase invariance*.

Now, we can relate this in an interesting way to our observation above in the telepathic twin scenario about equality of action as a simultaneity criterion. Suppose a given component of a wave packet pops out of existence at two spacetime points $(\mathbf{x},t)$ and $(\mathbf{x}',t')$, with associated points $(\mathbf{p},H)$ and $(\mathbf{p}',H')$ in momentum–energy space. By the equality of phase criterion, these must be related such that

$$(\mathbf{p}\cdot\mathbf{x} - Ht) = (\mathbf{p}'\cdot\mathbf{x}' - H't') \tag{5}$$

But this is, again, simply equality of action.

A lot of work still needs to be done in order to make this proposal workable for complicated realistic cases, such as correlated wave packets in multiparticle systems. It is also by no means clear that foliations of spacetime in terms of the hypersurfaces of state reduction of the myriad entangled quantum systems in the universe will smooth out to something approximating a global present that would correspond to the ordinary sense of becoming perceived at the physiological level. The topology of the ‘‘present’’ defined by quantum mechanics might correspond only roughly to the present as humans experience it, and there is no reason to think that the hypersurfaces over which state functions reduce are hyper*planes* or that they do not have a complicated topology (connectivity). Still, the crucial point we can take away from this introductory discussion is this: if we free ourselves from the Newtonian assumption that state reduction is tied to hyperplanes of equal *time*, a covariant description of state reduction is open to us[5].

[5]Richard Arthur (private communication) has pointed out to me that somewhat similar ideas were introduced quite some time ago by Eddington (1948/1953) and Dobbs (1951), who argued that a notion of simultaneity appropriate to quantum mechanics could be defined in terms of what they called ‘‘phase time’’. As noted, Rietdijk (1985) has also suggested a notion of simultaneity in terms of equality of action. I hope to explore these parallels in a future work.

7. Quantum mechanics and the ontology of the future

I said at the beginning that the argument of this paper amounts largely to undergrowth clearance, in that what I say here is not sufficient to decide the question of becoming. It removes an obstacle to the notion of global objective becoming (namely, the assumption that the relativity of coordinate simultaneity precludes a covariant notion of global presentness), but it is still conceivable that the covariant phase surfaces identified here are simply structures within a four-dimensional plenum, with no special significance other than their interest for that small coterie of humans who entertain themselves with philosophy of physics. Suppose there are, in fact, sets of space-like separate event-pairs that are correlated by quantum mechanics in a way that is both covariant and physically interesting. This, by itself, does not prove that there is objective becoming. Philosophically, we would be right back where we started, although perhaps with a greater appreciation of the richness of spacetime structure.

Clearly, Maxwell is right that if there is any route to an ontologically open future, it has to be through quantum physics. But even my notion of state reduction in terms of phase invariance is probably not enough to do the job Maxwell wants done; this is hardly surprising, since my theory is still semi-classical (if, for no other reason, because it assumes continuity of action). The best way to find a quantum argument for the openness of the future would probably be to appeal to deep facts about the irreconcilable inconsistencies between the non-Boolean mathematics of quantum mechanics and the classical Boolean picture. A genuinely quantum argument for the openness of the future would be parallel to other "no-go" theorems that show certain classical (i.e., Boolean) structures to be impossible (Bub, 1997); in other words, such an argument would be a Kochen–Specker paradox. One would attempt to show that given a definite assignment of physical values over some point or region (such as a phase surface) taken to be "the present", and given the evolution of the so-defined state according to the dynamics of quantum mechanics, the assumption of definite properties in the future relative to that point or region would generate a contradiction. (By "definite" I mean that the future would already contain answers to all of the possible experimental questions we could ask of it.) In other words, one would try to show that according to quantum mechanics, the future cannot admit of a Boolean property structure. This might not be necessary in order to establish the ontological openness of the future, but it certainly would be sufficient. I do not for a moment think that this project — to show in all generality that by quantum mechanics the future is non-Boolean — would be easy, although in a sense it has already been accomplished, if we presume that existing Kochen–Specker arguments (Bub, 1997) say something about the possible futures that are open to quantum-mechanical experimenters.

One of the major interpretational problems faced by any attempt to find a non-question-begging accommodation between quantum theory and special relativity is whether any such enterprise would turn out to remove special relativity from its present status as a "principle theory". The working assumption of most theorists since the early days of the twentieth century has been that quantum mechanics must somehow in the end turn out to be consistent with relativity. In this spirit, we construct quantum field theories against a classical Minkowski backdrop, and we even believe that we are justified in imposing special "patches" (such as the principle of microcausality) on the generality of quantum theory so as to avoid conflict with relativity. (See Peacock, 1992b; Kennedy, 1995; and Peacock & Hepburn, 1999, for critiques of the generally accepted notion of "peaceful coexistence" between relativity and quantum theory.)

My own view (which is very similar to the position advocated by Misner, Wheeler, & Thorne, 1973) is that relativity theory as it presently stands is a classical limiting approximation to a yet-to-be-developed quantum theory of spacetime that will bear a relation to the present classical picture something like the relation between the quantum and classical theory of fluids, or classical and quantum statistical mechanics (Peacock, 1998). A full and proper consideration of the implications of quantum mechanics for spacetime structure will probably result in a theory that is, in effect, a sort of quantum statistical mechanics of spacetime, in which special relativity is demoted to a limit-case idealization. Nevertheless, we can come far closer than is usually supposed to accommodate many of the non-classical features of quantum mechanics (such as state reduction) within classical relativity. The key is to see that there can be alternative conceptions of simultaneity based upon *contingent* relationships between *proper* quantities along worldlines.

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Chapter 14

Presentism and Quantum Gravity

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Abstract

There is a philosophical tradition of arguing against presentism, the thesis that only presently existing things exist, on the basis of its incompatibility with fundamental physics. I grant that presentism is incompatible with special and general relativity, but argue that presentism is not incompatible with quantum gravity, because there are some theories of quantum gravity that utilize a fixed foliation of spacetime. I reply to various objections to this defense of presentism, and point out a flaw in Gödel's modal argument for the ideality of time. This paper provides an interesting case study of the interplay between physics and philosophy.

1. Introduction

I am a presentist: I believe that only presently existing things exist[1]. Contrast presentism with eternalism: the eternalist believes that past, present, and future things all exist. Assuming that there are three spatial dimensions, the eternalist believes that the universe is four-dimensional, and while there are different events in different regions of this so-called "block universe", the universe as a whole does not change. The presentist, in contrast, believes that the universe is three-dimensional.

[1]At least, I am a presentist on Mondays, Wednesdays, and Fridays — those are the days I am writing this paper.

I am also a Heraclitean: I believe that change is a fundamental aspect of reality. Contrast Heracliteanism with Parmenideanism: the Parmenidean believes that fundamentally, there is no change. It is possible to be a Parmenidean presentist, where the universe simply consists of three dimensions of space, and the state of the things in that space does not change with time. (Julian Barbour (1999), for example, can be construed as holding this position.) From now on, by "presentism" I mean Heraclitean presentism.

The point of this paper is not to argue for presentism, but to defend presentism from a particular type of argument that is often taken to refute it[2]. The form of the argument is as follows:

(1) Presentism is incompatible with relativity theory (usually the focus is on special relativity).
(2) Relativity theory is our most fundamental theory of physics[3].
(3) Presentism is incompatible with our most fundamental theory of physics (from (1) and (2)).
(4) Presentism is false (from (3)).

W.V.O. Quine provides a good example of this argumentative tradition:

> Just as forward and backward are distinguishable only relative to an orientation, so, according to Einstein's relativity principle, space and time are distinguishable only relative to a velocity. This discovery leaves no reasonable alternative to treating time as spacelike. (Quine, 1960, p. 36)

If we have discovered that time is spacelike, then we have discovered that presentism is false, since, just as we do not ontologically privilege events *here* in space as the only events that exist, so we cannot privilege events *now* in time as the only events that exist.

Perhaps the most famous version of the argument sketched above is given by Hilary Putnam. Relying on special relativity, Putnam gives an argument with

[2]Nor is a point of this paper to make clear the difference between presentism and eternalism. Some philosophers (such as Callender, 2000, p. S588) claim not to see the difference, and there is nothing I can briefly say (beyond what I said above) to convince them otherwise.

[3]For those who believe there is no such thing as "our most fundamental theory of physics", (2) can be replaced with

> (2*) There is no theory of physics more fundamental than relativity theory,
> and similarly (3) can be replaced with
> (3*) Presentism is incompatible with a theory of physics *T*, which is maximally fundamental; that is, no theory more fundamental than *T* exists.

This allows that, while one theory can sometimes be declared more fundamental than another, there is no one most fundamental theory (following, e.g., Belot, 2000).

the following conclusion:

> the problem of the reality and the determinateness of future events is now solved. Moreover, it is solved by physics and not by philosophy. We have learned that we live in a four-dimensional and not a three-dimensional world … . (Putnam, 1967, p. 247)

If we live in a four-dimensional world, presentism is false.

The reader will no doubt recognize that the move from (3) to (4) is non-trivial; whether or not one sanctions it depends on to what extent one believes that our best scientific theories give truths about the nature of reality. Debates about this issue have been going on for quite a while now, and the proponents of the various positions are rather entrenched; it would be preferable if the presentist could reject the argument without having to reject scientific realism. My approach to rejecting the argument starts with the relatively uncontroversial claim that (2) is false: general relativity is incompatible with quantum mechanics, so our most fundamental physics can be found in the nascent theories of quantum gravity, which attempt to resolve the incompatibility. It turns out that there are some theories of quantum gravity, which are compatible with presentism. Thus, (3) is false, and presentism is unrefuted.

2. Fixed foliation quantum gravity

There are currently two main approaches to developing a theory of quantum gravity: the particle physics approach, leading to string theory and M theory, and the general relativity approach, leading to canonical quantum gravity and loop quantum gravity. (For a review of the various approaches, see, e.g., Rovelli, 1998.) Canonical quantum gravity faces the much-discussed problem of time: on the standard way of quantizing general relativity, the fundamental dynamical equation does not include a time parameter (see, e.g., Isham, 1993; Kuchar, 1999). One proposed solution to the problem of time is first to specify a foliation: that is, a particular way of dividing up spacetime into spacelike hypersurfaces. In the most-discussed version of this solution, the spacetime is foliated into CMC hypersurfaces — that is, hypersurfaces of constant mean (extrinsic) curvature (Beig, 1994; Fischer & Moncrief, 1997). Then, the theory is quantized, resulting in a fundamental dynamical equation that can describe the evolution of a system over time.

This CMC theory of canonical quantum gravity is not the only version of fixed foliation quantum gravity. Within canonical quantum gravity, there are other ways of fixing the foliation besides relying on CMC; a version of Bohmian quantum gravity has a fixed foliation (Goldstein & Teufel, 2001, p. 284); and there are more radical approaches as well (such as the general ether theory of Schmelzer, 2001).

Fixed foliation quantum gravity is compatible with presentism. To show this, it will be helpful to utilize the semantic view of scientific theories (see, e.g., van Fraassen, 1987). A scientific theory is taken to have two parts, the *theoretical structure* and the *theoretical hypotheses*. The theoretical structure consists of a family of mathematical models. For standard spacetime theories, each model of the theory can be taken to consist (at least in part) of an ordered set, whose members are a four-dimensional manifold and various geometric objects giving the spacetime structure of the manifold. The theoretical hypotheses are propositions expressing how the mathematical models should be taken to represent the world, according to the theory (see, e.g., Giere, 1988, p. 80).

The theories of fixed foliation quantum gravity are spacetime theories, in that the theoretical structure of the theory is such that the models of the theory are four-dimensional spacetime models. This does not mean that fixed foliation quantum gravity entails eternalism, though. To see what the theories say about the world, one must look to their theoretical hypotheses. One could have an eternalist theoretical hypothesis that specifies that the events in the spacetime model all represent existing events, so that past, present, and future events all exist. One could, however, have a presentist theoretical hypothesis that specifies that a particular spacelike hypersurface in the foliation represents the set of existing events, and that the set of existing events changes with time.

In practice, the physicists who put forth theories of fixed foliation quantum gravity do not specify what metaphysics of time their theory entails. This means that the theory simply leaves open that metaphysical issue; the openness can only be resolved with an interpretation[4]. The reason why theories of fixed foliation quantum gravity are compatible with presentism, then, is that they can be interpreted in such a way that they entail presentism.

3. Presentism and relativity theory

It is worth making explicit why I give the defence of presentism at the level of quantum gravity. If presentism was compatible with special and general relativity, but incompatible with quantum gravity, (3) would nevertheless be true — presentism would still be incompatible with our most fundamental theory of

[4]For simplicity, I am speaking as if there is a definite line between theory and interpretation, but in fact I agree with van Fraassen's point:

> The division between the theory proper and the interpretative elements already introduced by its main or earliest proponents is of course to some extent arbitrary. … it would be unrealistic not to see the official theory as to some extent indefinite. (van Fraassen, 1994, p. 7)

physics. Because of this, the compatibility of presentism with special and general relativity is *prima facie* irrelevant to the issue of the truth of presentism[5]. I will argue that this *prima facie* appearance is in fact correct.

Despite the *prima facie* irrelevance, much has been written on the issue of the compatibility of presentism with special and general relativity. The general sentiment among philosophers, which I share, is that presentism is incompatible with special and general relativity. (This general sentiment is expressed by, e.g., Savitt, 2000; Callender, 2000; Saunders, 2000; for dissensions, see Hinchliff, 2000; and Craig, 2000, 2001.) The reason for the general sentiment is that the models of special relativity have spacetimes of the form $<M, n>$, and the models of general relativity have spacetimes of the form $<M, g>$, where M is a four-dimensional manifold, n a Minkowski metric, and g a generalization of the Minkowski metric; these spacetimes do not have a foliation into spacelike hypersurfaces as part of their structure. Granted, such a foliation can sometimes be added to the spacetime: for some models of general relativity, for example, the spacetime structure itself allows one to pick out a foliation, such as the CMC foliation mentioned above (see Isenberg, 1995, for details)[6]. But the point

[5]Many presentists seem unaware of this. For example, Mark Hinchliff (1996) is a presentist, and he expresses concern regarding the compatibility of presentism and special relativity. He considers the possibility of rejecting the special theory of relativity, but writes:

> The special theory is one of our best-confirmed scientific theories of the nature of time. (Hinchliff, 1996, p. 131)

This claim is false; the special theory is a decisively refuted theory of the nature of time. Special relativity is incompatible with such phenomena as the gravitational redshift and gravitational lensing, phenomena that provide evidence for general relativity. (See, e.g., Misner, Thorne, & Wheeler, 1973, pp. 177–191.)

Because Hinchliff thinks that special relativity is a well-confirmed theory, he suggests that presentism needs to be modified to make it compatible with special relativity. Hinchliff mentions various proposed modifications, but seems most sympathetic to relativized presentism, where what is present is relative to a frame of reference. The problem with both relativized presentism and all the other ways of modifying presentism to make it compatible with special relativity is that the modified presentism turns out to be an *ad hoc* and unbelievable doctrine.

[6]John Norton (2000, p. 42) points out that locally (in "mini-spacetime") all spacetimes of general relativity are Minkowskian and respect the relativity of simultaneity, but "Once we relate these mini-spacetimes to the larger spacetime, the richer structure of the larger spacetime may select a preferred simultaneity relation". Moreover, this preferred simultaneity relation "can be projected into the mini-spacetime". This puts in context Steven Savitt's (2000, pp. S572–S573) point that "every general relativistic model (M, g) is required locally to have the structure of Minkowski spacetime".

is that the foliation is not a part of the spacetime structure as given, and thus imposing such a foliation amounts to changing the theory[7].

That is simply a brief explanation of the general sentiment that presentism is incompatible with special and general relativity; it is not the point of this paper to defend that sentiment. Supposing that sentiment is correct, why would one think that it has relevance for the truth of presentism?

One possible answer is that, in the absence of a definite theory of quantum gravity, one would expect results about the nature of time in relativity theory to carry over to quantum gravity. The problem with this answer is simply that there are various extant theories of quantum gravity, and in some of them — such as the theories of fixed foliation quantum gravity — this expectation is not borne out.

This reply leads to another possible answer: instead of just *expecting* the incompatibility of presentism with relativity theory to carry over to quantum gravity, one should *require* that it does so. This view is widely held (at least implicitly) by physicists working on quantum gravity. For example, Carlo Rovelli writes:

> special relativity teaches us something about time which many of us have difficulty accepting … there is no physical meaning in the idea of 'the state of the world right now' … . (Rovelli, 2001, p. 111)

Addressing theories such as fixed foliation quantum gravity, Rovelli says:

> Many approaches to quantum gravity go out of their way to reinsert in the theory what [general relativity] teaches us to abandon: a preferred time. … At the fundamental level we should, simply, forget time. (Rovelli, 2001, p. 114)

In the course of a scientific revolution, scientists do not completely reject old theories and old ways of thinking. Copernicus, for example, attempted to hold on to Aristotelian physics while espousing his revolutionary heliocentric cosmology. Similarly, it is not surprising that physicists draw certain lessons from relativity theory, which they utilize in formulating theories of quantum gravity. Moreover, as has often been pointed out, one of the interesting aspects of the development of quantum gravity so far is that the theories are not being generated subject to the constraint of new experimental data. Physicist C. J. Isham draws this consequence:

> This lack of hard empirical data means that research in the subject has tended to focus on the construction of abstract theoretical schemes that are (i) internally consistent (in a mathematical sense), and (ii) are compatible with some preconceived set of concepts. (Isham, 1994, p. 5)

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[7] It is perhaps worth making this idea more explicit. The idea is that the theory of general relativity implicitly includes the claim that *all it takes* to specify the structure of a general relativistic spacetime is the specification of the manifold M and the metric g. Since imposing a foliation is adding more to the structure of spacetime than the manifold and the metric, imposing a foliation amounts to changing the theory of general relativity.

He also says:

> In practice, most research in quantum gravity has been based on various *prima facie* views about what the theory *should* look like — these being grounded partly on the philosophical prejudices of the researcher involved … . (Isham, 1997, p. 169; cf. Butterfield & Isham, 2001, p. 38)

While Isham does not explicitly give examples of preconceived sets of concepts or philosophical prejudices, presumably he has in mind ideas such as the ones presented above: there is no physical meaning in 'the state of the world right now'; at the fundamental level we should forget time.

The lesson I draw from this is that, in spite of the fact that many physicists believe that relativity theory teaches us that a good theory is incompatible with presentism, there is no compelling reason for presentists to agree. Because of the lack of data to back up the claim that a good theory is incompatible with presentism, and because of the existence of potentially viable theories of fixed foliation quantum gravity, the presentist can simply maintain that the physicists are drawing the wrong lessons from relativity theory.

Moreover, there is historical precedent for physicists drawing a wrong lesson from a particular theory, with the mistake only realized once a more fundamental theory is thoroughly developed. For example, according to the traditional way of understanding electromagnetism, the vector potential is not real, while the electric and magnetic fields are. The advent of quantum mechanics, with its successful prediction of the Aharonov–Bohm effect, suggests that the vector potential is real as well[8].

I conclude that all the literature on the issue of whether presentism is compatible with special or general relativity is, while perhaps intrinsically interesting, irrelevant to the issue of whether presentism is true. Even if presentism is incompatible with special and general relativity, it in no way follows that presentism is incompatible with our most fundamental physics.

4. Belot and Earman's objection

I know of just two passages in the philosophy literature which are directly relevant to my defense of presentism on the basis of quantum gravity. Both passages can be construed as giving objections to my argument. I will consider

[8] Belot (1998, p. 532) takes the approach that "until the discovery of the Aharonov–Bohm effect, we misunderstood what electromagnetism was telling us about our world". Another approach, though, is to say that the Aharonov–Bohm effect shows another way in which electromagnetism is false. This should not be viewed as a deep philosophical issue: what the approaches disagree about is the referent of "electromagnetism". (I grant, though, that which approach one takes may influence how one goes about developing more fundamental theories.)

Gordon Belot and John Earman's objection in this section and Craig Callender's in the next.

Belot and Earman (2001) base their discussion on the following passage from physicist Karel Kuchar:

> foliation fixing prevents one from asking what would happen if one attempted to measure the gravitational degrees of freedom on an arbitrary hypersurface. Such a solution … amounts to conceding that one can quantize gravity only by giving up general relativity: to say that quantum gravity makes sense only when one fixes the foliation is essentially the same as saying that quantum gravity makes sense only in one coordinate system. (Kuchar, 1992, p. 228)

While Belot and Earman do not address Kuchar's first criticism, it is worth replying to. Kuchar is presumably being metaphorical: there is no part of the theory, which implies that one cannot *ask* what would happen if one attempted to perform a particular measurement. I take it that Kuchar is saying either that according to the theory the physical process of engaging in such a measurement is physically impossible, or that the theory makes no predictions for the outcome of such a measurement. If the former, then the theory makes an interesting empirically testable prediction about whether it is possible to perform such a measurement, and it would be best to test the prediction before drawing any conclusions about the theory. I think, though, that Kuchar is making the latter claim, that the theory is incomplete because it does not make predictions for certain physically possible measurements. But this latter claim is unjustified. In Newtonian physics, for example, there is a preferred foliation, and yet one could use the theory to make a prediction for the measurement of the gravitational field on an arbitrary hypersurface, by using the theory to make predictions for the outcomes of measurements at various spacetime locations on the hypersurface. Kuchar has given no reason that one could not do the same sort of thing in fixed foliation quantum gravity.

Belot and Earman comment only on the last part of the Kuchar quote:

> This criticism is extremely telling. To forsake the conventional reading of general covariance as ruling out the existence of preferred co-ordinate systems is to abandon one of the central tenets of modern physics. Unsurprisingly, [fixed foliation quantum gravity] has few adherents … . (Belot & Earman, 2001, p. 241)

Let me be clear: fixed foliation quantum gravity does *not* require a preferred coordinate system. Kuchar does not say that it does: he adds the qualification "essentially", though he does not explain what he means by this. Moreover, Belot and Earman I think agree with my claim that fixed foliation quantum gravity does not require a preferred coordinate system. At the beginning of their article, they say that philosophers

> have all learned that Kretschmann was quite correct to urge against Einstein that the 'General Theory of Relativity' was no such thing, since *any* theory could be cast in a

> generally covariant form, and hence that the general covariance of general relativity could not have any physical content … . (Belot & Earman, 2001, p. 213)

What Belot and Earman go on to argue, though, is that the physical content of the general covariance of general relativity is that the theory *ought* to be formulated in a generally covariant fashion. While Belot and Earman consider different notions of general covariance, they never dispute the claim that any theory can be cast in a generally covariant form, when general covariance is understood as the criterion that there are no preferred coordinate systems. They point out, for example, that one can give a generally covariant formulation of Newtonian mechanics (2001, p. 214). Similarly, one can give a generally covariant formulation of fixed foliation quantum gravity; it follows that such a formulation would not have a preferred coordinate system.

The above discussion leads naturally to the following argument against fixed foliation quantum gravity: its most perspicuous formulation is not generally covariant, and this is a mark against it. This argument has been given by Barbour:

> general covariance is physically vacuous. I believe that the physically significant issue is not whether or not points have a priori individuation, but the relative complexity of rival theories when expressed in generally covariant form. (Barbour, 2001, p. 203)

Here I think the best response for the presentist is to bite the bullet, and admit that fixed foliation theories of quantum gravity in their generally covariant form are more complex than standard theories of quantum gravity in their generally covariant form. The presentist can simply maintain that this particular criterion of simplicity is not a guide to truth.

Before moving on, it is worth pointing out that, in a later paper by Kuchar, he repeats the last portion of the passage from his 1992 paper, with one change:

> foliation fixing … amounts to conceding that one can quantize gravity only by giving up general relativity: to say that quantum gravity makes sense only when one fixes the foliation is essentially the same thing as saying that quantum gravity makes sense only in one reference frame. (Kuchar, 1999, p. 182)

This change from "coordinate system" to "reference frame" is crucial. Focussing on coordinate systems leads to the confusion about general covariance dealt with above. Focussing on reference frames, however, is unproblematic: the proponent of fixed foliation quantum gravity will agree that there is a preferred frame of reference, and can admit that there is a sense in which this is "essentially" the same thing as saying the theory makes sense only in one reference frame.

5. Callender's objection

Craig Callender (2000) also has a discussion that is relevant to my defence of presentism on the basis of quantum gravity. After arguing that tensed theories like presentism are incompatible with special relativity (at least as traditionally formulated), Callender points out that quantum mechanics perhaps gives some reasons to postulate a fixed foliation of spacetime, and mentions fixed foliation quantum gravity. He then writes:

> should the friend of tenses point to these developments in support of tenses, or at least, in support of brushing aside the challenge from special relativity? No. Developments in physics may push us away from the traditional understanding of relativity, but I urge the reader not to allow the tensed theory to do the same. This is not because I believe that only arguments based on physics ought to have a bearing on our interpretations of physics. Good arguments in metaphysics often rightly have some influence on interpretations of physics. The problem is that I simply don't believe that the arguments in metaphysics in favor of tenses are particularly good ones, though this is an argument for another paper. (Callender, 2000, pp. S596–S597)

Callender says that we should not allow a tensed theory such as presentism to push us toward a non-traditional understanding of relativity, because the arguments for presentism are bad ones. But regardless of the strength of the arguments for presentism, the presentist is not required to endorse a non-traditional understanding of relativity. The presentist can simply say that presentism is incompatible with special and general relativity, and hence special and general relativity are false.

Moreover, what Callender says in the above passage does not justify his "No" answer to his initial question. Here is a more precise version of his question: does the existence of fixed foliation quantum gravity give the presentist justification for rejecting the argument against presentism on the basis that presentism is incompatible with special relativity? The point of my paper is to argue for the "yes" answer, and nothing Callender says above casts doubt on that answer.

The passage from Callender continues, though:

> Here I can only ask, if science cannot find the 'becoming frame', what extra-scientific reason is there for positing it? If the answer is our experience of becoming, we are essentially stating that our brains somehow have access to a global feature of the world that no experiment can detect. This is rather spooky. If the answer instead comes from conceptual analysis on metaphysical categories such as change, we must ask whether there is any reason to think that our concept *accurately* mirrors reality. Our concept of (say) change is loaded with pre-scientific connotations. Why think that it reveals something about the properties of spacetime that science cannot? (Callender, 2000, p. S597)

I see no reason that the presentist is committed to the antecedent of the conditional question Callender starts with. The presentist can admit that science has not yet found the 'becoming frame' — that is, the preferred foliation — but the presentist can simply explain that this is because the preferred foliation is a part of a theory of quantum gravity, and there is currently no direct experimental evidence for or against the various theories of quantum gravity. As explained by for example Kuchar (1999, p. 181), the empirical predictions of a fixed foliation theory of canonical quantum gravity will differ depending on *which* foliation is selected as fixed. Thus, assuming that some fixed foliation theory of canonical quantum gravity is true, science can in principle find the becoming frame.

All these conclusions about the nature of theories of quantum gravity are tentative though; suppose that it turns out that Callender is correct to say that science cannot find the becoming frame. I nevertheless find the rest of his argument unconvincing. Consider first those presentists who believe that presentism is true on the basis of our experience of becoming — they hold that, without objective temporal passage, there would not be any experience at all[9]. Callender suggests that these presentists believe that phenomenal experience gives them access to a feature of the world science cannot detect. But what is that feature? Such presentists need not claim that phenomenal experience tells them *which* foliation is the metaphysically privileged one; they can simply say that phenomenal experience demonstrates that there is becoming. Moreover, there is a sense in which they can maintain that all scientific experiments demonstrate this as well: all scientific experiments eventually culminate in a phenomenal experience, such as when an experimenter looks at the record of a measurement apparatus. Since all phenomenal experience involves an experience of becoming, then (according to this sort of presentist) all scientific experiments provide evidence for presentism.

Now consider those presentists who believe that presentism is true on the basis of conceptual analysis. Here I think that Callender's argument is somewhat stronger, if only because arguments on the basis of conceptual analysis are generally more defeasible than arguments on the basis of experience. Again, though, such presentists need not claim that conceptual analysis demonstrates

[9] I find this presentist doctrine plausible, but I do not really see how to give a good argument for it. The best I can come up with is the following. Consider a three-dimensional block universe, with no time dimension, and no temporal passage. It seems clear that no conscious experience could exist in such a universe. But now imagine adding an extra dimension to that universe, so one has a four-dimensional block universe, with no temporal passage. Adding the extra dimension does not seem to be adequate to produce a universe that allows for conscious experience. Just as the three-dimensional block universe is necessarily devoid of conscious experience, so too is the four-dimensional block universe.

This is obviously not an adequate argument, but I am not aware of any better ones. But just because we do not have a good argument for the presentist doctrine in question does not mean that the doctrine is false. In fact, I think that doctrine is part of the motivation that many philosophers have to be presentists.

which foliation is the metaphysically privileged one; they can simply say that conceptual analysis demonstrates that there is becoming. But Callender can be read as asking: science does not show that there is becoming, so why should we expect conceptual analysis to show that? The presentist can reply as follows. The issue of whether or not there is becoming is a philosophical issue; we should not expect science to determine that issue. All we should expect is that science should not turn out to be *incompatible* with presentism, and thus we should expect the correct theory of quantum gravity to be a fixed foliation theory.

At this point a question naturally arises: what should the presentist do if physicists eventually settle on a theory of quantum gravity, which is incompatible with presentism? There is no simple answer to this question. Different presentists would give different answers, depending on the general issue of how they evaluate the relative strength of physics-based arguments as compared to philosophy-based arguments, and depending on specific issues such as the extent to which they are convinced by the philosophical arguments for presentism, and the extent to which they believe that the final theory of quantum gravity was arrived at by a warrant-inducing process.

6. Gödel's modal argument

Kurt Gödel's (1949) famous modal argument for the ideality of time on the basis of general relativity is implicitly an argument against presentism. There has been a fair amount of discussion recently about Gödel's argument (see, e.g., Savitt, 1994; Earman, 1995; Yourgrau, 1999; Dorato, 2002). If Gödel's argument is viewed as being about the nature of time in spacetimes of general relativity, then I find this recent discussion interesting and illuminating. In this section I will show, however, that Gödel's argument tells us nothing about the nature of time in our universe.

Gödel's argument, very briefly, is as follows. Some spacetimes of general relativity, such as the Gödel universe, cannot be foliated into spacelike hypersurfaces. Thus, in those universes, there cannot be an objective lapse of time; in those universes, presentism is false. Gödel then writes:

> It might, however, be asked: Of what use is it if such conditions prevail in certain *possible* worlds? Does that mean anything for the question interesting us whether in *our* world there exists an objective lapse of time? (Gödel, 1949, pp. 561–562)

Gödel then gives the crucial modal step of his argument:

> if someone asserts that this absolute time is lapsing [in our world], he accepts as a consequence that, whether or not an objective lapse of time exists … depends on the particular way in which matter and its motion are arranged in the world. This is not a straightforward contradiction; nevertheless, a philosophical view leading to such consequences can hardly be considered as satisfactory. (Gödel, 1949, pp. 562)

With that, his paper ends.

An implicit assumption of Gödel's argument is that the Gödel universe is physically possible (that is, that the laws of our universe are compatible with those of the Gödel universe). This is made clear in various reconstructions of Gödel's argument: Savitt (1994, p. 468) explicitly says that the Gödel universe is "physically possible"; Yourgrau (1999, p. 47) writes that "the actual world is lawlike compossible with the Gödel universe"; and Dorato (2002, p. 8) calls the difference between the Gödel universe and our universe "non-lawlike". Moreover, as far as I can tell, these philosophers believe this thesis of physical possibility. Only Dorato (2002, p. 29) addresses the issue of quantum gravity, in a footnote: "until a reasonably agreed upon quantum theory of gravity is available, we can assume that [general relativity] *is* a fundamental physical theory".

Pace Dorato, I maintain that, if we are trying to discover the nature of time in this universe, it is crucial to consider quantum gravity. Our most fundamental physics suggests that our universe is one where a theory of quantum gravity is true, and general relativity is incompatible with all the main theories of quantum gravity; hence general relativity is in all likelihood false. In all likelihood, then, no spacetime of general relativity is physically possible, and Gödel's assumption that the Gödel universe is physically possible is false.

To see that this assumption is necessary for Gödel's argument to go through, suppose that a theory of fixed foliation quantum gravity is true, and that the theoretical hypotheses of the theory entail that (or the theory can be interpreted in such a way that) an objective lapse of time exists in all models of the theory. Applying Gödel's argument, one who (correctly) says that absolute time is lapsing in our world

> accepts as a consequence that, whether or not an objective lapse of time exists … depends on the particular way in which matter and its motion are arranged in the world. (Gödel, 1949, p. 562)

But this is manifestly false: according to the hypothetically true theory of fixed foliation quantum gravity, an objective lapse of time exists regardless of how matter and its motion are arranged in the world. In conclusion, Gödel's argument is based on a false assumption about our universe, and thus tells us nothing about the nature of time in our universe.

There is one comment worth making about fixed foliation quantum gravity, inspired by Gödel's modal argument. For at least some versions of fixed foliation quantum gravity, such as the CMC version, which foliation is fixed depends on the distribution of matter in the universe. Belot and Earman (2001, p. 247) point this out, and conclude that "the time which results in this case is certainly not the absolute time of Newton". The presentist can grant this point: Newton wanted time to flow without relation to anything external, while there is a sense in which, in the CMC version of fixed foliation quantum gravity, the flow of time depends on the distribution of matter. But there is no need for the presentist to maintain that the foliation is the same in all physically possible worlds. If there is a foliation in the spacetime model, which represents our world, then presentism can be true in our world, and if there is a foliation in all the spacetime models of the fundamental physical theory of our world, then all versions of Gödel's modal argument are evaded.

7. The future of presentism

Despite this paper's emphasis on fixed foliation quantum gravity, I recognize that it is in no way a popular approach to resolving the incompatibility of quantum mechanics and general relativity. The two most popular approaches, M theory and loop quantum gravity, appear to be incompatible with presentism. Nevertheless, one must be careful: there are two aspects of these theories, which one might think are incompatible with presentism, but which actually are compatible — or so I will argue.

First, there are suggestions from loop quantum gravity that space and time are discrete, in that the quantum observables measuring spatial volume and temporal intervals have discrete spectra (Rovelli & Upadhya, 2001). One might think that the thesis that there is a smallest interval of time is incompatible with presentism. As for example Saint Augustine argues,

> the only time that can be called present is an instant … that cannot be divided even into the most minute fractions … . For if its duration were prolonged, it could be divided into past and future. (Augustine, 1961, Confessions, Book XI, Section 15)

My reply is that presentism need not require that the present lasts only an instant; instead presentism just has to require that the present cannot be divided into past and future, as St. Augustine specifies. If quantum gravity entails that the Planck time of about 10^{-43} s, for example, is the smallest interval of time, then the presentist can simply specify that that is how long the present lasts. It would be impossible to divide the present into past and future, since there would be no time intervals smaller than the Planck time.

Second, there are suggestions from both theories, but especially M theory, that spacetime is not part of fundamental reality, but just emerges in some classical limit. (For a discussion of this emergence, see Butterfield & Isham, 1999.) As Edward Witten puts it,

> 'spacetime' seems destined to turn out to be only an approximate, derived notion, much as classical concepts such as the position and velocity of a particle are understood as approximate concepts in the light of quantum mechanics. (Witten, 1996, p. 134)

Some presentists might believe that time and change have to be aspects of fundamental reality for presentism to be true. I maintain, though, that this is not an essential requirement of presentism. Presentism should not be understood as a theory about fundamental reality, it should be understood as a theory about time. Thus, if time is not part of fundamental reality, presentism is true as long as the time that emerges in the appropriate classical limit is time as described by presentists.

This leads us to the fundamental reason that M theory and loop quantum gravity are in fact incompatible with presentism. For M theory it is known, and for loop quantum gravity it is expected, that the spacetime theory that emerges in the classical limit is general relativity (see, e.g., Rovelli, 1998, pp. 5, 8). Thus, the time that emerges in the classical limit is not time as described by the presentist.

From the standpoint of the committed presentist, proponents of M theory and loop quantum gravity are simply making a mistake. Consider an analogy with quantum mechanics: proponents of the Bare theory — standard Schrödinger evolution with the eigenstate–eigenvalue link — argue that the Bare theory can account for the everyday beliefs we have about measurement outcomes (Albert, 1992, pp. 116–119; Barrett, 1994). Most people believe, though, that the Bare theory has a measurement problem, and hence look for ways of modifying it in order to save our everyday beliefs (Bub, Clifton, & Monton, 1998). Presentists would say that M theory and loop quantum gravity are in the same sort of situation as the Bare theory: they would say that M theory and loop quantum gravity are incompatible with some of our everyday beliefs, in this case our everyday beliefs about time. (Following Callender's distinction, some presentists would say that the theories are incompatible with our experience of becoming, while others would say that they are incompatible with our basic concept of time.) Thus, just as those who endorse our everyday beliefs about measurement outcomes support the development of acceptable alternatives to the Bare theory, so those who endorse presentist beliefs about time should support the development of acceptable alternatives to M theory and loop quantum gravity.

There is something problematic about the sort of image this brings to mind, of a wealthy presentist funding workshops for physicists to encourage them to develop presentist-friendly physical theories. Fortunately, there are other alternatives for presentists besides trying to change the minds of physicists. For a presentist who is not a scientific realist, there is little reason to be concerned, since such a presentist would not take physics to be providing a true account of the world. But there is even room for presentists who are scientific realists to be unconcerned. Such presentists could hold that, even though the aim of science is truth, we are not close yet. They might believe that there are many more scientific revolutions yet to come before we get to the true fundamental theory, and that at our current stage we are really not much closer to the truth than people were when Aristotelian physics was dominant. Such presentists would not take the fact that our current most popular theories of physics are incompatible with presentism to be evidence against presentism, just as they would not take the fact that Aristotelian physics is compatible with presentism to be evidence for presentism. They would hold that our current theories are so far from reality that we cannot take them to provide any guide to the fundamental nature of time.

Given that physics is currently moving in the direction of M theory and loop quantum gravity, presentism's future prospects do not look good, at least from the standpoint of scientific realists who take current developments in quantum gravity as getting us close to a true account of reality. Nevertheless, based on the existence of potentially viable theories of fixed foliation quantum gravity, I conclude that presentism is compatible with our most fundamental physics — for now.

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