The End of Time?

Jeremy Butterfield, All Souls College, Oxford OX1 4AL, England

Abstract

I discuss Julian Barbour's Machian theories of dynamics, and his proposal that a Machian perspective enables one to solve the problem of time in quantum geometrodynamics (by saying that there is no time!). I concentrate on his recent book *The End of Time* (1999). A shortened version will appear in *British Journal for Philosophy of Science.*

1 Introduction

Barbour is a physicist and historian of physics, whose research has for some thirty years focussed on Machian themes in the foundations of dynamics. There have been three main lines of work: in classical physics, quantum physics, and history of physics—as follows. He has developed novel Machian theories of classical dynamics (both of point-particles and fields), and given a Machian analysis of the structure of general relativity; (some of this work was done in collaboration with Bertotti). As regards quantum physics, he has developed a Machian perspective on quantum geometrodynamics; this is an approach to the quantization of general relativity, which was pioneered by Wheeler and DeWitt, and had its hey-day from about 1965 to 1985. More specifically, Barbour proposes that a Machian perspective enables one to solve an outstanding conceptual problem confronting quantum geometrodynamics, the so-called 'problem of time'. In short, his proposal is that there is no time! (Hence the title of this book.) As regards history, he has uncovered the tangled tale of the reception (and often misinterpretation) of Mach's ideas in twentieth century physics (including general relativity); and also written a two-volume history of the theory of motion, stretching from the ancient Greeks to the twentieth century.

Barbour has now written what is in effect an intellectual autobiography, in the form of a book of popular science ([1999]: page references are to this book). It covers all three of his lines of work. It of course emphasises the first two, especially the second (the speculative proposals about quantum gravity). The work on classical physics is discussed in Parts 2 and 3 of the book; and the quantum speculations in Parts 1, 4 and 5. But Barbour also weaves in a considerable amount of historical material.

Although it is a popular book, there are three reasons, of increasing importance, to review it in this Journal. The first relates to the style of the book: it is not a hack popularization. Like all good popular science, it makes a real attempt to expound the details, both of established theories and speculative proposals; rather than just stating the main idea—or worse, just gesturing at it with a metaphor which is liable to be as misleading as it is helpful. (The obvious comparison here is with e.g. Penrose's *The Emperor's New Mind*, as against Hawking's *A Brief History of Time*; or as regards magazines, with e.g. *Scientific American*, as against *New Scientist*.) The book contains plenty of detailed exposition—exposition often enlivened by metaphors that are helpful as well as vivid. (Some readers will also enjoy the anecdotes of Barbour's various intellectual struggles, journeyings and collaborations.) Barbour also moderates his passionate advocacy of his ideas, especially his quantum speculations, with occasional reminders that they are controversial.

The second reason is that, although *cognoscenti* will know Barbour's previous work on Machian themes in classical physics (both relativistic and non-relativistic), it is worth having an accessible exposition in a single book. For in some respects, this work goes against prevailing opinion in the philosophy of space and time; and perhaps for this reason, it is still not very well known. I shall devote Section 2 to this material. To set the scene, I shall first describe prevailing opinion, and a problem it faces. Then in discussing Barbour's Machian theories, I will emphasise how Barbour takes space rather than spacetime as fundamental, and how this is in tension with relativity.[1]

The third reason relates to Barbour's denial of time. Philosophers of physics, and indeed metaphysicians, are bound to want to know what this denial amounts to. Fortunately, I can present the main ideas in terms of familiar metaphysical categories, without recourse to quantum theory, let alone quantum gravity. I shall do so in Section 3.1; we shall see that it is a curious, but coherent, position which combines aspects of modal realism *à la* David Lewis and presentism *à la* Arthur Prior. Then finally, in Section 3.2, I shall discuss how Barbour argues for his denial of time from certain claims about the

[1]Fortunately, Barbour's work on classical physics is now becoming better known: Belot ([1999], Sections 6-7; [2000], Section 4) discusses it; and Pooley ([2001]), to which I am much indebted, is a full analysis, both technically and philosophically. An early philosophical discussion by Barbour himself is in this journal ([1982]). I should add that as to Barbour's historical work, the main source is the first volume ([1989]) of his two-volume history; it covers the history of dynamics up to Newton. The second volume of course includes a history of Machian ideas in the twentieth century, but is not yet published; in the meantime, Barbour ([1999a]) is an accessible summary of that history.

interpretation of quantum theory, and about quantum gravity.[2]

But beware: although my strategy of postponing quantum theory and quantum gravity, with all their obscurities, until Section 3.2 makes for an exposition more accessible to philosophers, it also carries a price. Namely, it emphasizes those aspects of Barbour's denial of time which can be explained in terms of classical physics (i.e. roughly, in terms of instantaneous configurations of matter), in particular Barbour's idea of a 'time capsule'; and it downplays a technical quantum-theoretic aspect, which Barbour (private communication) sees as prior to, and more important than, time capsules. So I should at the outset summarize this aspect, 'the price', and say why I think my strategy is justified.

Barbour believes that his Machian analysis of general relativity gives the best understanding of (and justification for) the two equations that sum up the theory in the form in which it is most easily quantized. (The equations are called the momentum and the Hamiltonian constraint equations; the form of the theory is called the Hamiltonian, or canonical, form.) Since quantizing general relativity (in this form) by an otherwise successful method leads to a static i.e. time-independent quantum state, Barbour concludes that we must accept such a state and somehow reconcile it with the appearance of time and change. He takes this to be his main conclusion: and time capsules to be his admittedly conjectural suggestion for how to make the reconciliation.

Nevertheless, there is good reason for me to emphasize time capsules, at the expense of the arguments leading to a static quantum state. For as we shall see in Section 3.2, most of these arguments have been well known in the physics literature for many years, and some are even prominent in the growing philosophical literature about quantum gravity. Besides, the literature contains several (mostly very technical) strategies for reconciling a static quantum state with the appearance of time and change. Barbour's time capsules proposal is but one of these, with the advantage that it can be explained non-technically: so in a review of his work, I have of course chosen to focus on it, ignoring the others.

I shall finish this Introduction with my three main criticisms of the book as a popularization. First, the book gives the misleading impression that Barbour's various views are closely connected one with another. In fact, Barbour's views are by no means a package-deal. In particular, the straightforward and craftsmanlike work in classical physics and in history of physics can be 'bought'; while the denial of time, and the speculations about quantum theory and quantum gravity, are left on the shelf.

The other two criticisms both concern 'the end of time'; the first from a metaphysical viewpoint, the second from a physical one. First: Barbour often (not just in the 'prospectus', Part 1, but also in Parts 4 and 5) states his denial of time in a way that philosophers will immediately interpret as just denying temporal becoming. This is misleading: his view *is* different from the familiar tenseless ('B-theory') view of time—as we will see in Section 3.

Second: As I mentioned above, the quantum gravity programme on which Barbour focusses, quantum geometrodynamics, has been superseded. Agreed, it has a distinguished descendant, the loop quantum gravity programme, which is one of the two main current

[2] For a brief discussion in this journal of these claims, cf. Brown ([1996]).

programmes; (the other being the superstrings programme, which is utterly different, not just technically, but also in its motivations and framework). But the central notion of a configuration is very different in loop quantum gravity than in quantum geometrodynamics; and Barbour has yet to tell us how his proposals, e.g. about time capsules, would carry over to it. Besides, even on its own terms, quantum geometrodynamics is very problematic. In particular, its main equation, the Wheeler-DeWitt equation, is not mathematically well-defined, and its 'derivation' is questionable. Though Barbour briefly mentions the rival programmes, and the quantum geometrodynamics programme's internal difficulties (at pp. 38-39, 166, 192, 351), the bulk of the book is devoted to presenting his Machian vision of exactly this programme. So a reader who is a newcomer to the subject will inevitably get the impression that geometrodynamics is still 'one of the runners' in the race of quantum gravity research. Agreed, that race has no clear running-track or rules: it is rather like orienteering in a blizzard—without a map! So indeed, quantum geometrodynamics just might 'come from the back of the field to win the race'. But newcomers be warned: it seems unlikely.[3]

These three criticisms aside, the book is, overall, very good popular science: we can happily go along with Barbour when he announces that he has 'tried to write primarily for the general reader ... but shall be more than happy if my colleagues look over my shoulder' (p. 7).

2 Machian themes in classical physics

I shall first summarize the prevailing opinion in the philosophy of space and time, as three claims; and describe how they face a consistency problem. This problem is not insoluble, nor unrecognized; but it is substantive (Section 2.1). This will set the scene for discussing Barbour's own work (Section 2.2).

2.1 The status quo

2.1.1 Orthodoxy

In contemporary philosophy of space and time, the prevailing opinion is that the development of physics from the mid-nineteenth century (especially the rise of field theories culminating in general relativity) was the death-knell of the relationist tradition, stemming from Leibniz to Mach, of conceiving space and time as systems of spatiotemporal relations between bodies, rather than entities in their own right. More precisely, there are three prevalent claims which need to be articulated here. I shall list them in what I believe to be the order of increasing controversy![4] These claims concern, respectively:

[3] Agreed, these considerations of physics do not nullify the metaphysical interest of articulating and assessing Barbour's denial of time—cf. Section 3.1. And his denial of time just might help with the conceptual problems faced by the rival programmes.

[4] Anyway, we will see in Section 2.2, that Barbour agrees with the first two claims, and maybe with the third. I should also explain that my phrase 'prevailing opinion' refers to the last 30 years. Before that,

(1) field vs. matter, (2) whether metrical structure is 'reducible' to matter, and (3) the status of spacetime points.

(1) The first claim concerns the rise of field theory since 1850. Thus, on the one hand, physics revealed some traditional characteristics of bodies—such as impenetrability and continuity—to be only apparent. And on the other hand, the electromagnetic field was discovered to possess mechanical properties like momentum, angular momentum, energy and (after the advent of special relativity) mass-energy. Besides, matter itself was eventually modelled, with outstanding success, as a field on spacetime; namely in quantum field theories. Thus Leibniz's and Mach's 'bodies' had become diaphanous and omnipresent fields.

(2) Second, the various familiar theories—both classical and quantum, relativistic and non-relativistic—postulate a metrical structure of spacetime that seems not to be 'reducible to spatiotemporal relations of bodies' (in various precise senses of that phrase). Two well known (probably the best known) ways of making this claim precise concern: (a) absolute rotation, and (b) dynamical metrics.

For (a), the idea of the argument goes back to Newton's globes thought-experiment. The two cases—one in which the mutually stationary globes rotate at some constant velocity about their common centre of gravity, and the other with no rotation—are intended to show that the metric is irreducible; the idea is that the two cases exhibit the same spatiotemporal relations of bodies but different metrical facts. But one needs to be careful about 'metrical facts'. For in any theory, such as Newtonian mechanics or special relativity, in which the metric structure is the 'same in all models' (and so is not dynamical, i.e. not correlated with the distribution of matter), there will be a sense of 'metrical facts' in which these facts cannot differ between two models—and so are trivially determined by, i.e. supervenient upon, spatiotemporal relations between bodies. (Compare the idea in modal metaphysics that a proposition M true in all of a certain class of worlds trivially supervenes on the truth of any proposition S true at some of the worlds: for any two worlds in the class that make S true, also make M true.)

There is an obvious strategy for otherwise interpreting 'metrical facts' in such a way that pairs of cases like the two globes nevertheless show some kind of irreducibility of the metric. The idea is that such a pair of cases shows that not all physical possibilities are distinguished by a full description of each of them in terms of the masses, relative distances and relative velocities of bodies; so that there are physically real properties or relations not determined by these. What these are will differ from one proposal to another. But irreducibility will follow, provided the 'metrical facts' include some of the facts involving such undetermined properties or relations. Here the obvious candidate is facts about how the bodies are related to the affine structure of spacetime—in short, about whether their worldlines are geodesics.[5]

Reichenbach and others had maintained that relativity's abolition of absolute space and time vindicated Leibniz's and Mach's relationism against Newton's absolutism. As we will see, Barbour could, and I think would, agree that the *detail* of Reichenbach's position is wrong, as argued by the 'young Turks' of the 1960s and 1970s—authors such as Stein, Earman and Friedman; (cf. e.g. Earman [1989], p. 6f.). But Barbour would add that Reichenbach misinterprets Mach, as egregiously as he does Newton!

[5] However, perhaps one does not have to express such facts only in terms of such 'absolutist' postulates.

As to (b): For a theory with a dynamical metric such as general relativity (or any theory that 'geometrizes gravity' in the sense of coding gravitational force as an aspect of the metric), the above problem of 'metrical facts' being 'the same in all models', and so trivially determined by the matter distribution, does not arise. Nor is the correlation (or even causal relation) between the metric and the matter distribution, as coded in the field equations, a sign of reduction or even determination (i.e. supervenience). First, we cannot in general specify the matter distribution without the metric. Second, general relativity admits pairs of solutions which agree on their matter distributions but differ metrically. For general relativity, the most-cited cases are the various vacuum (i.e. matter fields zero) solutions. But there are other examples, e.g. the Schwarzschild and Kerr metrics—representing respectively, a non-rotating and a rotating mass in an otherwise empty universe.[6]

(3) Third, the formalisms of field theories, both classical and quantum, suggest that their basic objects are just spacetime points. For in these formalisms, everything apart from these points—matter, whether conceived as point-particles or as fields, and even the metrical structure of spacetime—gets represented as mathematical structures defined on points. This suggests the doctrine nowadays called 'substantivalism': that spacetime points are genuine objects—indeed are the basic objects of these theories, in that everything else is to be construed as properties of points, or relations between them, or higher-order properties and relations defined over them.

Agreed, this doctrine is controversial even among those with no sympathy for relationism. There are two well-known good (though disputable!) reasons for denying it. (a): The first reason is 'the hole argument'. It is natural to formulate these theories, especially those with a dynamical metric (like general relativity), in such a way that their only 'fixed structure' is the local topological and differential structure of a manifold. Intuitively, this means that any map preserving this structure (i.e. any diffeomorphism) preserves the content of the theory. Such a theory is called 'diffeomorphism invariant'; and diffeomorphism invariance is often taken to indicate that spacetime points are indeed not objects: their appearing to be is an artefact of how we formulate the theory. (b): The second reason is a general philosophical point about objects or ontology. Namely: we should be wary of taking as the basic objects of our ontology (according to some theory) those items that are postulated as the initial elements in a mathematical presentation of the theory. For it might be just a happenstance of our formulation of the theory that these objects

Some authors assume that the theory concerned includes gravity, so that the non-rotating globes would fall towards each other, while the rotating pair can be assumed to rotate at just the speed that compensates gravity and gives a stable orbit. On this approach, one can take the moral to be that the distribution of bodies over a period of time is not reducible to the masses, relative distances and relative velocities of the bodies at an initial instant—even in a deterministic theory like Newtonian gravitational theory. Thanks to Oliver Pooley and Simon Saunders for this point.

[6] Agreed, this is also an idealized, indeed vacuum example, in that for both solutions, the central mass is at a singularity which is not *in* the spacetime; and I for one do not know whether there are such pairs of solutions with extended matter in the spacetime. In any case, even if such pairs show that the metric is not determined by, i.e. supervenient upon, matter, there are "Machian effects", such as inertia-dragging, in general relativity. Some were found as early as 1918; indeed, Einstein found similar effects in the course of his struggle towards general relativity.

'come first': a happenstance avoided by another formulation that can be agreed, or at least argued, to be better.

2.1.2 The consistency problem

These three claims lead to what I will call 'the consistency problem'. This is not a straightforward matter of the claims entailing the problem. Rather, these claims, and the presentations of spacetime theories that are now typical, both in physics textbooks and the philosophy of physics literature, make us think of the metrical structure of spacetime in a certain way—roughly, as 'on all fours' with the matter fields.[7] And it is this conception that leads to the consistency problem. As I said at the start of the Section, I do not claim that this problem is insoluble: rather it is a lacuna that needs to be filled. Nor is the problem unrecognized: as we will see, Einstein himself recognized it (and dubbed it a problem of 'consistency'). Furthermore, we can nowadays state in broad terms how the problem can be solved (the lacuna filled). But the problem is worth stressing, since it is rarely addressed—and it leads into Barbour's Machian proposals.

I shall present the problem by first describing the lacuna in typical modern presentations of spacetime theories. In such presentations, one postulates first a spacetime manifold; then, some metric (and affine) structure on it, typically as metric fields; then also some matter fields; these fields, both metric and matter, obey differential equations; etc. So far, so good. Indeed, so far, so pure mathematical. The connection with observation is then made, for metric fields, by postulating that (ideal) rods and clocks measure the metric, i.e. yield its values as their pointer-readings. Or maybe the connection is made more generally than *via* the proverbial rods and clocks—by postulating that the behaviour (perhaps ideal) of matter fields gives us access, in principle, to the metric fields. But—here is the rub—there is, typically, little or no discussion of how the rods and clocks are constructed and how they 'do their stuff'—display pointer-readings that are veridical about spacetime's metric. (Similarly, for more general accounts of how matter gives access to metric.) If one does not notice this lacuna[8], one naturally ignores the question of how indeed they do their stuff; and so falls into thinking of the metric as simply 'read off' by rods and clocks.

But of course it is a question that cannot be ignored. In any branch of physics, one has a right to expect a theory of how the instrument works (very often calling on other

[7]It is tempting to formulate the conception as treating the metric as intrinsic to spacetime. But this is not quite right. For although the notion of a property being intrinsic to an object, and correspondingly of a relation being intrinsic to the collection of its relata, is hard to analyse (witness recent effort in analytic metaphysics, e.g. Langton and Lewis ([1998])), people's judgments of what is intrinsic tend to agree. And it seems that a metric that was wholly reducible to matter fields might yet be called 'intrinsic to spacetime'; especially if, as usual, the theory postulates a manifold of spacetime points which then function as the relata of the intrinsic metric. In Section 2.2, we will see that Barbour works with such theories; so his Machianism seems content with the metric being intrinsic to spacetime in this sense.

[8]As is tempting! For example, think of the almost mesmerising power of the purely diagrammatic explanation of time-dilation and length-contraction in special relativity, using just the hyperbolae that are the locus of points of constant Minkowski interval from the origin—and the postulate that rods and clocks measure this interval!

branches of physics, on which the instrument's functioning depends). In this regard rods and clocks (or whatever else, such as radar signals, is postulated as measuring the metric) are no different from other instruments.

An account that filled this lacuna would proceed: from (i) the postulation of fundamental metric and matter fields on spacetime; to (ii) a theoretical description of how (at least idealized) rods and clocks (or whatever else) behave, powerful and accurate enough to secure that: (iii) such rods and clocks (or other matter) would indeed do their stuff—their pointer-readings report the metric. There are four remarks to make about such an account. Broadly speaking, they are positive: there are good prospects for such an account, though the details would of course be very complicated. (Or rather, there are good prospects if we set aside the usual deep controversies about how the macroscopic world emerges from the quantum one.)

- The way that (iii) returns to (i) is in no way a suspicious circularity. An account of how things are should be compatible with the explanation how we come to know or believe that very account; and it is even better if the account coheres with, or even is itself a part of, that explanation.

- As I mentioned, Einstein himself emphasised the need for such an account, and called the lacuna a problem of 'consistency'. In his *Autobiographical Notes*, he writes in connection with special relativity:

  > One is struck [by the fact] that the theory introduces two kinds of physical things, i.e. (1) measuring rods and clocks, (2) all other things, e.g. the electro-magnetic field, the material point, etc. This in a certain sense is inconsistent; strictly speaking, measuring rods and clocks would have to be represented as solutions of the basic equations (objects consisting of moving atomic configurations), not, as it were, as theoretically self-sufficient entities. However, the procedure justifies itself because it was clear from the very beginning that the postulates of the theory are not strong enough to deduce from them sufficiently complete equations for physical events sufficiently free from arbitariness, in order to base upon such a foundation a theory of measuring rods and clocks ... it was better to permit such inconsistency—with the obligation, however, of eliminating it at a later stage of the theory. But one must not legalize the mentioned sin so far as to imagine that intervals are physical entities of a special type, intrinsically different from other physical variables ("reducing physics to geometry", etc.). ([1949], pp. 59-60.)

- So the consistency problem is recognized. Indeed, some expositions of relativity, less imbued with the geometric style of presentation, sketch such an account of rods and clocks: trying to discharge, in Einstein's phrase, the obligation of eliminating the inconsistency. I say 'sketch' because it is very hard to describe, in terms of one's fundamental physical theory, most types of clock (and most types of any other instrument): Einstein notes this for special relativity, but the point is of course equally valid for other theories, such as continuum mechanics in Newtonian spacetime. As a result, the expositions that sketch such an account often focus on some artificially simple models; e.g. the light-clock, or (as a model of length-contraction) the distortion in a classical atom of the electron's orbit, due to the atom's motion; cf. Bell [1976].[9]

- Besides, we have good reason to think we can go beyond such simple models, and in particular accommodate the quantum nature of matter. To take one example, let me sketch a quantum description of length-contraction for a moving rod. (Many thanks to David Wallace for this sketch.) I suppose that we start with some quantum field theory of electrons, the electromagnetic field, and a charged field of much higher charge and mass than the electron field (to simulate atomic nuclei of some particular element). This is a reasonable place to start, because: (i) we certainly need to go beyond classical physics since it cannot describe solid bodies other than phenomenologically (e.g. stipulating *a priori* that rods are rigid); (ii) on the other hand, to require that we start with the Standard Model and work our way up through quark-quark couplings etc. would be unduly harsh—since after all, we don't believe it provides the final theory of matter.

  We then need to establish that there are certain states of this multi-field system describing a non-relativistic regime of particles coupled by effective Coulomb forces, with respect to a 3+1 split given by some Lorentz frame; and that in this regime, there are states corresponding to rigid non-relativistic matter, say a crystal. Suppose we succeed in this. Of course this is conceptually and technically difficult, given the interpretative problems of quantum field theory, and the complexities of solid state physics. But given that there are such states, we can argue that a rod made of this crystalline matter will exhibit length contraction; as follows.

  If the rod is accelerated gently enough, the internal vibrations (phonons) due to the acceleration will be small and will rapidly thermalise (heating the crystal up slightly until the heat is lost to the environment), and the crystal will enter the state $\hat{B} \mid \psi\rangle$; where $\hat{B}$ is the Galilean boost operator for the final velocity attained, and $\mid \psi\rangle$ is the original state of the rod i.e. the state of a rigid crystal with length (say) l given by the metric in our initial frame. The fact that sufficiently small Lorentz boosts can be approximated by Galilean boosts then implies that we can iterate boosts to move $\mid \psi\rangle$ into the state $\hat{B}_L \mid \psi\rangle$, where state $\hat{B}_L$ is any Lorentz boost. Since the underlying quantum-field-theoretic dynamical laws are Lorentz-covariant, it follows that $\hat{B}_L \mid \psi\rangle$ has length l as given by the metric in the boosted frame. So we have established that the crystal accurately measures the metric in its rest frame, i.e. length contraction. (Or more accurately, we would have established this if our sketch were filled in!).

To sum up: though one faces a consistency problem if one postulates a metric 'on all

[9] Some of the philosophical literature also recognizes the consistency problem (though without using that label). For example, Brown ([1993], [1997]) and Brown and Pooley ([2001]) discuss how it bears on the foundations of special and general relativity.

fours' with matter fields, our current theories of matter seem able to solve the problem, at least in outline.

2.2 Machianism

In this subsection, I will first make two general points about Barbour's variety of Machianism, and discuss his attitude to Section 2.1.1's three claims (1) to (3) (Section 2.2.1). This will lead to some details of his Machian theories (Section 2.2.2). I will end with some evaluative comments about these proposals, especially the central ingredient of the Machian theories—the notion of an instantaneous configuration (Section 2.2.3).

2.2.1 The temporal metric as emergent

One naturally expects that *ceteris paribus*, the consistency problem will be easier to solve, the weaker the metrical structure of spacetime that one postulates 'on all fours' with matter fields: for there will be less structure that, for consistency, instruments' pointer-readings have to 'reveal'. On the other hand, one needs to postulate enough structure to be able to write down a dynamical theory: one cannot expect all such structure to be reducible to matter (cf. (2) of Section 2.1.1). So the question arises whether there are interesting dynamical theories that postulate less metrical structure than the familiar theories. Barbour's work shows that the answer is 'Yes'.

There are two immediate points to make about this 'Yes'. First, in the theories Barbour has developed so far, the gain mostly concerns the temporal aspect of the spacetime metric: though the temporal metric 'emerges' from the rest of physics, the spatial metric is still postulated.[10]

Second, a point about the notion of 'emergence'. Usually, this notion is vague: and philosophers think of making it more precise in terms of various definitions of reduction, or some weaker analogue, such as supervenience. It will turn out that in the context of Barbour's views, two more precise versions play a role, one for the classical context (this Section), and one for the context of quantum gravity (Section 3). In the classical context, Barbour's notion is logically strong, indeed surprisingly so. For Barbour provides examples of theories in which a temporal (though not spatial) metric is emergent in the strong sense of being fully definable from the rest of the physical theory. So this is emergence in as strong a sense of reduction as you might want. On the other hand, in the context of quantum gravity, Barbour's notion is logically weak (though again the detail is surprising). For his denial that there is time leads to his saying that our illusion to the contrary—that there is time—is a partial and misleading 'appearance' of the timeless underlying reality.

[10] This is not to say that Barbour faces a consistency problem *only* for how rods measure spatial geometry, and not at all for how clocks measure time. But as we shall see, the problem of how a clock measures time will be easier for Barbour, in the sense that his Machian theory in a sense explains why different clocks "march in step".

I turn to discussing Barbour's attitude to Section 2.1.1's claims, (1) to (3), of 'prevailing opinion'; in particular to justifying my statement (in footnote 4) that he agrees to (1) and (2), and maybe also (3). Since claim (2), about the irreducibility of metric to matter, concerns 'the various familiar theories', it is already clear that he can accept it while nevertheless seeking theories in which there is some kind of reducibility. The kind of theory he seeks emerges more clearly from his replies to (1) and (3).

As to the claim (1), Barbour accepts that physics since 1850 has 'abolished body'. But he takes this to mean just that we should state Machian proposals in terms of the modern conception of matter, namely as matter fields. So although Barbour presents Machian theories of point-particles (pp. 71-86, 115-120; and similarly in his technical articles), that is intended as a piece of pedagogy and/or heuristics—a path I will follow in Section 2.2.2. As he stresses, the main physical ideas of these theories carry over to field theories.

This of course prompts the question: how exactly does Barbour conceive field theories? In particular, does he accept the existence of spacetime points, as advocated by claim (3)? It will be clearest to break the answer to these questions into two parts. The first part concerns Barbour's different attitudes to spacetime, and to space: this part relates closely to the physical details of his proposals, and will engender several comments. The second part concerns Barbour's relationist understanding of space; it is more philosophical, and will crop up again later—at this stage, it can be dealt with briefly.

The first part of the answer is, in short, that Barbour seems happy to accept the existence of *spatial* (but not spacetime) points, and to postulate that these points form a 3-dimensional manifold with metric (spatial geometry). For he discusses field theories (relativistic and non-relativistic) in terms of the evolution through time of instantaneous 3-dimensional configurations, i.e. states of a 3-dimensional spatial manifold. But one needs to be careful; (and here lies the second part of the answer). Since Barbour seeks a relationist understanding of space, he wants to treat metrical relations in a field theory, not in terms of a metric field tensor on a 3-manifold of spatial points, but as very similar to inter-particle distances in theories of point-particles. This kind of treatment will become clearer in Section 2.2.2.2. Here it suffices to say two things. (i) The main idea is that, just as a Machian theory of N point-particles will treat metrical relations as essentially a matter of $N(N-1)/2$ inter-particle distances, a Machian field theory will postulate point-like parts of a matter field and then treat metrical relations in terms of the continuous infinity of all the pairwise distances between these point-like parts. (ii) As we shall see in a moment (and again in Sections 2.2.2.2 and 2.2.3), this sort of Machian treatment of field theories has difficulties with general relativity.

The first part of the answer—that Barbour postulates space, and spatial geometry, but is leary of spacetime—also needs to be clarified in other ways. Indeed, it holds good for his discussion of both classical non-relativistic field theories, and quantum theories. By his lights, spacetime notions have no central role in either of these types of theory. But his reasons are rather different for the two types (as I hinted above, in discussing strong and weak emergence). For classical non-relativistic field theories, the temporal structure (and so spacetime structure) is fully defined, in Barbour's Machian theories, by the rest of the theory: but (*modulo* the attempt to understand space relationally) these theories postulate a spatial manifold and metric *ab initio*; (cf. Section 2.2.2). On the other hand, for quantum theories, time (and so spacetime) emerges only as an approximately valid notion within a timeless quantum physics of matter, which again postulates *ab initio* a spatial manifold with a metric; (cf. Section 3.2).

But Barbour also qualifies this acceptance of space but not spacetime in two other ways. First, he admits (pp. 180-181) that for classical relativistic field theories, and especially for general relativity, spacetime notions *are* central. Though he discusses these theories mostly in terms of configurations evolving in time (a so-called '3+1' picture), he agrees that in the end the best way to make sense of the 'meshing' of different histories of 3-dimensional configurations is by thinking of each history as a foliation of a single spacetime (cf. Section 2.2.2.2 and 2.2.3).

Second, Barbour is perfectly willing, indeed happy, to postulate less structure for space than a fully-fledged manifold and metric. He has hitherto postulated this rich structure for reasons, not of philosophical conviction, but of pragmatism: so far, this structure seems needed, if one is to get a precise Machian theory. But as he reports (pp. 5, 349), he has work in progress (jointly with Ó Murchadha) that aims to 'gauge away length', i.e. to weaken the postulated metric structure so as to dispense with length, retaining only the conformal structure (i.e. the structure of angles and shapes).[11]

So to sum up this two-part answer:– First, Barbour embraces the development of field physics in that he seems content to postulate space, and even to postulate that it has the rich structure of a manifold with metric. But he is leary of spacetime, and would like to postulate as weak a structure for space as possible, e.g. by dispensing with lengths while retaining angles. Second, Barbour seeks to understand space relationally; and in field theory this amounts to thinking of spatial geometry as a matter of distances between point-like parts of matter fields—a strategy that seems viable outside general relativity.

2.2.2 Machian theories

In Barbour's technical work in classical physics, there have been two main endeavours, the first leading in to the second. First, he has developed (together with Bertotti) novel Machian theories of classical dynamics (both of point-particles and fields). Second, he has given a Machian analysis of the structure of general relativity. I will first motivate, partly from a historical perspective, the simplest example of the first endeavour, namely point-particles in a non-relativistic spacetime. That will introduce Barbour's brand of Machianism, and in particular his central concept of instantaneous configurations. After presenting this example in some detail, I will briefly describe how its main ideas can be generalized to field theories and relativity, including general relativity—and thereby touch on Barbour's second endeavour.[12]

[11] These two qualifications are connected; part of the motivation for conformal theories is that they promise to yield a preferred foliation of spacetime. For the joint work, cf. Barbour and Ó Murchadha ([1999]).

[12] In this Section, I am much indebted to Oliver Pooley, and to his [2001], which gives many more technical details.

2.2.2.1 Point-particles in a non-relativistic spacetime Let us suppose that N point-particles move in a spacetime that we assume is equipped with an absolute simultaneity structure and Euclidean geometry in each simultaneity slice; and maybe also with an absolute time metric. That is already to assume a lot of abstract structure. But let us ask what further information (facts) about the motion of the particles would be acceptable ingredients in a Machian theory; in particular, what would be acceptable initial data for the initial-value problem. Mach himself gives no precise answer, though of course his relationism and empiricism means he would favour facts about relational and/or observable quantities. But as Barbour says (p. 71), in 1902 Poincaré did suggest a precise answer. He proposed that the theory should take as initial data: (i) the instantaneous relative distances between the particles (but *not* their positions in any putative absolute space); and (ii) these distances' rate of change. (Poincaré's (ii) reflects his assuming an absolute time metric.)

One may well worry about the empiricist credentials of Poincaré's proposed initial data. For example: though instantaneous inter-particle distances are no doubt relational, are they observable? After all, ascertaining them takes time and a considerable amount of theory: think of what it takes, in terms of laying out rods and calculating. But it is best to postpone further discussion of such qualms to a more general context (Section 2.2.3). Let us for the moment focus on the technicalities of Machian theories.

The first point to note is that Poincaré's proposal can be partly motivated by considerations about geometric symmetries. Thus the homogeneity and isotropy of Euclidean geometry suggest that the instantaneous positions of the particles relative to any putative absolute space, and the orientation of the whole system of N particles relative to such a space, will be unobservable. More precisely, they suggest that any such absolute positions and orientation will have no effect on the subsequent evolution of inter-particle distances. And this prompts the idea of formulating a theory that describes the evolution of inter-particle distances (now setting aside any empiricist qualms about these!)—while excluding such positions and orientations from the initial data.[13]

Second, Poincaré saw that his proposed data, (i) and (ii), is nearly, but not quite sufficient, to secure a unique future evolution ('solve the initial-value problem') in *Newtonian* mechanics. We can nearly, but not quite, express the usual Newtonian initial data (positions and velocities in absolute space) in terms of this data. To be precise: in order to rewrite the Newtonian initial data in terms of inter-particle quantities, we need not only the inter-particle distances and their first derivatives, but also three second derivatives; or alternatively, one third derivative, and the values of the total energy and the magnitude of the angular momentum. This is a very curious circumstance, especially since the need for just three extra numbers is independent of the value of N. In any case, the challenge to the Machian who accepts Poincaré's proposal for what is acceptable as initial data (and who believes in point-particles!) is clear: find a theory for which this data *do* give a

[13] A Machian should presumably resist the corresponding line of argument appealing to kinematic symmetries. Familiarity with Galilean relativity may suggest that a uniform motion of the whole system of N particles relative to any putative absolute space will not affect the subsequent evolution of inter-particle distances. But it equally suggests that a rotation *might* do so. Thanks to Oliver Pooley for correcting me about this.

unique future evolution—and show, if you can, its empirical equivalence, or superiority, to Newtonian theory!

There is a history of such attempts; a tangled and ironic history (unearthed over the last 20 years by Barbour himself, together with other historians like John Norton). But I shall not linger on it, and instead proceed directly to the eventual outcome, Barbour and Bertotti's ([1982]) theory. As we shall see, this theory does away with the absolute time metric; and its main ideas allow for generalization to field theories and to relativistic theories.

The configuration space for the Newtonian mechanics of N point-particles moving in an absolute three-dimensional space is $3N$-dimensional Euclidean space E^{3N}.[14] Representing Newtonian time by the real numbers $\mathbb{R}$, a possible history of the system is represented by a curve in $E^{3N} \times \mathbb{R}$. We can project any such curve down into E^{3N}, the image-curve being the system's orbit (in configuration space). It will be convenient to write the configuration space E^{3N} as Q (so that in later generalizations, we can again write the 'absolutist' configuration space as Q); and to write its product with $\mathbb{R}$ as QT (with T for 'time'). So we talk of projecting a curve in QT down into Q.

We now introduce the idea of *relative* (instantaneous) configurations of point-particles, and so the idea of a relative configuration space (written 'RCS')—the set of all such configurations. (Barbour calls an RCS a 'Platonia'; p. 44.) Intuitively, a relative configuration is a specification of all the inter-particle distances (and so of all the angles) at some instant, without regard to (a) where the system as a whole is in absolute space, nor to (b) how it is oriented, nor to (c) its handedness. We can formally define relative configurations in terms of an equivalence relation on the 'absolutist' configuration space $Q = E^{3N}$. Let us say that two points $x, y \in E^{3N}$ are equivalent, $x \sim y$, if for each pair of point-particles, m_i, m_j say, x and y represent the same inter-particle distance between m_i and m_j. In other words, if we think of x and y as specifying polyhedra $\pi(x)$ and $\pi(y)$ in physical space (with each vertex labelled by its particle), we define: $x \sim y$ iff $\pi(x)$ is transformed to $\pi(y)$, with the m_i-vertex in $\pi(x)$ being transformed to the m_i-vertex in $\pi(y)$, by some element of the improper Euclidean group on E^3. ('Improper' so as to identify oppositely handed polyhedra, i.e. incongruent counterparts.) The quotient space $E^{3N}/\sim$ consisting of the equivalence classes is the relative configuration space. We can project any curve in E^{3N} down into this RCS. It will be convenient to write this RCS as Q_0, so as to have a convenient notation later for other RCSs; so we speak of projecting a curve from Q to Q_0.

As discussed above, the initial data for the Newtonian mechanics of point-particles consists of a bit more than the inter-particle distances and their rates of change. In terms of the configuration spaces we have just introduced, this means that an initial point in Q_0, together with an initial vector at that point (representing inter-particle distances' rates of change), are not in general sufficient to pick out the unique future evolution prescribed by Newtonian mechanics; (where the curve representing this evolution is projected from

[14] Incidentally, the once-for-all labelling of the particles, and the particle-labelling of the axes of any Cartesian coordinate system $E^{3N} \to \mathbb{R}^{3N}$ need not involve assuming a so-called 'transcendental identity' for the particles: they might have different masses.

$QT = E^{3N} \times \mathrm{I\!R}$ first to $Q = E^{3N}$ and then to Q_0). But if we specify a small amount of further information, then we can succeed; and such information can be specified in various ways. Of course from a Newtonian perspective, there will be little to choose between these ways. Any such specification will seem an artificial form of initial data, the need for which arises from our having chosen to follow Poincaré in focussing on purely relational data.

But from a Machian perspective, the various ways to secure from relational initial data a unique trajectory (which in principle need not be a possible Newtonian one) are of central interest. And it turns out that we can secure a unique trajectory with a specification that includes, not an initial vector at the initial point in Q_0, but merely an initial direction: that is, it includes the inter-particle distances' rates of change only upto an overall scale factor, which would set 'how fast the absolute time elapses'. A bit more precisely: it turns out that if we impose zero total angular momentum and a fixed energy, then an initial point in Q_0, and an initial direction at that point, secures a unique trajectory which is a solution of the Newtonian theory.

So the Machian aims to find a theory that has just these solutions as all its solutions. Any such theory will deserve to be called 'relational' in the sense that its dynamics can be formulated wholly in terms of the RCS Q_0. And it will deserve to be called 'timeless', in that there is no time metric in Q_0; rather, as we will see in a moment, the time metric is definable from the dynamics. Barbour and Bertotti ([1982]) state such a theory. I first state the three fundamental ideas of the theory, as (i) to (iii); and then state results arising, as (1)-(3).

(i) We begin by postulating an RCS Q_0 of relative configurations of N point-particles (distinguished once-for-all from each other, e.g. by having distinct masses) and we require each configuration to obey 3-dimensional Euclidean geometry. This requirement means that if we embed a relative configuration in Euclidean space E^3, the particles' $3N$ coordinates in a Cartesian coordinate system will not be independent. More generally, it gives the RCS a very rich structure; (discussed on e.g. pp. 40-46, 71-86).

(ii) Suppose given an (isometric) embedding θ of two relative configurations x, y into E^3. Given an ordering of the particles, this induces an embedding of x, y as points in E^{3N}, $\Theta : x, y \mapsto \Theta(x), \Theta(y) \in E^{3N}$. Then the usual Euclidean metric d^E on E^{3N} defines a distance depending on Θ, and so θ, between x and y: $d_\theta(x, y) := d^E(\Theta(x), \Theta(y))$. Given a Cartesian coordinate system on E^{3N}, this distance can be expressed in the usual way as the square root of a sum of squares of differences of coordinate values. Of course, $d_\theta(x, y)$ gives no measure of the intuitive similarity of x and y since $\theta(x)$ and $\theta(y)$ can be arbitrarily far apart in E^3, and so $\Theta(x)$ and $\Theta(y)$ can be arbitrarily far apart in E^{3N}, no matter how similar x and y are.

Barbour and Bertotti define a measure of intuitive similarity, i.e. a metric on Q_0, by considering for any x and y, all possible embeddings θ of x and y into E^3, and taking the minimum value of a metric, $\bar{d}_\theta(x, y)$) say, which is just like d_θ except that each squared difference of coordinate values is weighted by the mass of the particle concerned; (cf. pp. 115-118). Think of putting an overhead transparency with N differently coloured dots, on top of another transparency with N such dots, in such a way as to minimize the weighted sum of the squared distances for red-to-red, green-to-green etc., with the weights given by a mass associated with each dot. Some terminology: the minimization procedure is called 'best matching'; the resulting metric is called the 'intrinsic difference' (or infinitesimally, 'differential') between the relative configurations x and y; and the theory we are constructing is called 'intrinsic dynamics'.

This metric also provides a solution to a problem that arises once we think of each relative configuration as in its own instantaneous space (a copy of E^3): the problem of identifying spatial points (not point-particles) between two such spaces—a problem which Barbour calls the 'problem of equilocality'. The solution is that two spatial points in the instantaneous spaces of two relative configurations x, y are equilocal if they have the same coordinate values in those Cartesian coordinate systems on E^3 that minimize $\bar{d}_\theta(x, y)$). More terminology: two relative configurations with their spatial points thus identified are called 'horizontally stacked'. The idea is that, as usual in spacetime diagrams, the vertical dimension ('up the page') represents time, so that 'horizontal stacking' refers to placing relative configurations relative to one another in the horizontal dimensions while stacking them in a vertical pile (i.e. in the time dimension).[15]

(iii) Barbour and Bertotti now combine the intrinsic metric with some remarkable work on Newtonian point-particle mechanics by Jacobi. Jacobi showed that for a conservative Newtonian system the orbit in the absolute Newtonian configuration space, i.e. $Q = E^{3N}$, can be found from a variational principle defined solely on E^{3N} (instead of $QT = E^{3N} \times \mathbb{R}$ as in Lagrange's approach). According to this principle (now called 'Jacobi's principle'), the 'action' to be extremized is the integral along a curve in Q of the square root of T times $E - V$, where T is a generalized kinetic energy, E is the total energy and V is potential energy. That is, we are to extremize $I_{\text{Jac}} := \int d\lambda \sqrt{[T.(E-V)]}$; where λ gives an arbitrary parameterization along the curve, so that there is no use of a time metric. (Thus each value of the total energy E specifies a different variational principle.)

The idea of intrinsic dynamics is to replace the generalized kinetic energy T in I_{Jac} by an analogue, T_{Mac}, that uses the intrinsic differential; (T_{Mac} becomes T in horizontally stacked coordinates). More precisely, the theory postulates that the system's evolution is given by a variational principle on Q_0, viz. by extremizing the expression obtained by substituting T_{Mac} for T in I_{Jac}. Let us call this expression $I_{\text{Mac}} := \int d\lambda \sqrt{[T_{\text{Mac}}.(E - V)]}$. (So, since the intrinsic differential itself involves an extremization, there is a double variation to extremize I_{Mac}.)

Thus defined, intrinsic dynamics yields the following results. (1) All curves in $Q = E^{3N}$ that project down to the same curve in Q_0 have the same value for I_{Mac}. So intrinsic dynamics' postulate that evolution is given by extremizing I_{Mac} really is, as desired, a variational principle on Q_0. We have a dynamics that specifies unique curves from data in the RCS.

(2) If we use spatial coordinates corresponding to horizontal stacking, then extremizing I_{Mac} reduces to extremizing I_{Jac}.

[15] The idea that one should identify places across time in such a way as to minimize the resulting motion of bodies has also been discussed in the philosophical literature: for example, *pro* Peacocke ([1979], p. 50-51) and *con* Forbes ([1987], pp.300-304).

(3) We can recover the familiar Newtonian time metric, as follows. The equations of motion given by intrinsic dynamics become the familiar Newtonian ones if we choose the arbitrary parameter λ along curves in Q_0 in such a way that $T = E - V$. And analogously to the terminology of horizontal stacking, we say that this choice of λ (this assignment of time differences between configurations in a possible history) 'vertically stacks' the configurations. So 'vertical stacking' refers to how far apart the configurations should be placed in the time dimension.

This choice of λ, which recovers the Newtonian time, is made once-for-all for the entire system (the universe). But intrinsic dynamics also provides an explanation of why subsystems that are effectively isolated from one another behave as if they evolved according to a common time parameter. For it turns out that if for such subsystems, we make the corresponding choice of λ (i.e. we again impose $T = E - V$), then their different times 'march in step' with each other. This is a significant result just because the observed fact, that mutually isolated subsystems of the universe behave as if they evolved according to a common time parameter, is so striking.[16]

Two final comments on this theory, which fill out its claim to be a 'timeless' as well as 'relational' theory. First, these results, especially (2) and (3), give a clear sense in which the absolute time of orthodox Newtonian mechanics emerges within intrinsic dynamics. And as I said in Section 2.2.1, this is not emergence in the typical philosophical sense of 'approximate validity', or some other weak analogue of reduction. The Newtonian time parameter is exactly definable within intrinsic dynamics. More precisely, in a formalization of intrinsic dynamics using a sufficiently powerful background logic (including e.g. multivariate calculus), the Newtonian time parameter would be finitely definable (not just supervenient).[17]

Second, the idea in result (3), of fixing the time metric by means of the dynamical evolution of the whole system, is reminiscent of a development in conventional, i.e. Newtonian, astronomy; (discussed by Barbour, pp. 97-99, 104-108). In Newtonian astronomy, the assumption that there is an absolute time parameter governing all bodies' evolutions, gives no guarantee that any single body's motion is exactly periodic with respect to it. In particular, there is no guarantee that solar time and sidereal time (given by the return to a 'position' of the sun, and of a given star, respectively) measure absolute time (i.e. stay in step with it). But remarkably—and very luckily for the development of physics!—solar and especially sidereal time proved sufficiently accurate until about 1900, when the errors due to inter-planetary interactions began to show up. In order to obtain still greater accuracy, astronomers then resorted to the idea of assuming that Newtonian mechanics

[16]Or rather, it is striking once it is pointed out! I suppose Newton may well have had it in mind when he wrote the famous remark in the Scholium that absolute time 'from its own nature flows equably without relation to anything external.' But nowadays, after the rise of relativity, this remark is most commonly read, not as a statement of the absoluteness (system-independence) of the temporal metric (durations), but as a statement of the absoluteness (frame-independence) of simultaneity—which presumably Newton did *not* have in mind!

[17]Agreed, we can also write the usual Newtonian theory in a generally covariant form in which we can explicitly define absolute time in terms of the covariant timelike vector field t_a; but in this case, the absolute time is clearly 'already there' and 'non-dynamical' in the given formalism—and so not emergent.

with some absolute time parameter (called 'ephemeris time') governed the solar system *as a whole*; they then deduced where the various heavenly bodies would be at given values of the assumed parameter—in fact using the Moon as the 'hand' on the face of the 'clock'. This idea of ephemeris time is obviously similar to the idea in result (3).[18]

2.2.2.2 Field theory and relativity I turn to sketching how these ideas of intrinsic dynamics are adapted to classical field theory and relativity, including general relativity. But before giving details, I should first recall (from Section 2.2.1) that Barbour wants to understand space relationally; and so he hopes to understand field theories as postulating point-like parts of matter fields and treating spatial geometry in terms of distances between these point-like parts. Though this stance will not much affect the formal details to follow,[19] it is interpretatively significant—not least because it obviously looks less plausible for theories like general relativity that have a dynamical metric, interacting 'on all fours' with matter fields.

But let us start with the easier case of a non-dynamical metric. For a field theory using a non-dynamical Euclidean spatial structure (with absolute time, or in special relativity), the RCS, which I again call Q_0, will consist of all possible instantaneous relative field configurations in Euclidean space. As in the point-particle case, Q_0 can be obtained as a quotient of a configuration space Q consisting of 'absolute' field configurations, quotienting by the action of the Euclidean group. But this Q_0 is a much more complicated RCS than that in the point-particle case. In particular, since there are infinitely many independent ways that two field configurations can differ, this RCS will be infinite-dimensional. So let us only aim to consider the simplest possible case: a scalar field with compact spatial support. In this case, one can define 'best matching' and so an intrinsic metric on the configurations. Furthermore, in the relativistic case, one can pass from a Lorentz-invariant action principle of the usual Lagrangian kind (i.e. defined on a relativistic QT, extremizing a 4-dimensional integral $\int d^4x \ldots$) to a Jacobi-type principle on Q; and thereby to a Machian action principle, defined on Q_0 and extremizing I_{Mac}.

Just as in the case of point-particle mechanics: all curves in the absolute configuration space Q that project to the same curve in Q_0 have the same value for I_{Mac}. So the Machian action principle really is a variational principle on Q_0. In this sense, we have a genuinely relational field theory.

Furthermore, the original action principle being Lorentz-invariant secures that the corresponding intrinsic dynamics is special-relativistic in the sense that: any of the theory's dynamically possible curves in Q_0, once it is horizontally and vertically stacked, represents a (4-dimensional) solution of the original (orthodox) special-relativistic field theory.

But there is also another sense of being special-relativistic that we need to consider; (which is closer to the idea of a principle of relativity). Namely: suppose we apply a passive Lorentz-transformation to such a 4-dimensional solution, and analyse it as a

[18] The history of this topic goes back to Ptolemy! Cf. Barbour ([1989]), pp. 175-183.

[19] But this is partly a matter of suppressing subtleties for the sake of expository clarity and brevity. In particular, I have suppressed discussion of the relationist's need to deal with symmetric configurations, where the field takes identical values at intuitively distinct locations.

sequence of instantaneous 3-dimensional configurations in the new frame. This sequence will of course define a different curve in Q_0 from that defined by the description in the original frame. So let us ask: is this new curve in Q_0 also dynamically allowed by the corresponding intrinsic dynamics? That is, is it a geodesic of the variational principle on Q_0? The answer is Yes provided that the principle satisfies some restrictions. That is again a satisfying result; but it prompts an interpretative question about the sense in which the '3+1'-perspective favoured by Barbour can be taken as fundamental. However, I will postpone this question until after discussing general relativity from an intrinsic dynamics perspective (i.e. until the next subsection), since the very same question also arises for general relativity.

Despite having a dynamical metric, general relativity can be formulated in a '3+1' form, i.e. in terms of the coupled evolution over time of spatial geometry and matter-fields. Though Einstein himself always thought of it instead in spacetime terms (epitomized by his field equations applying to each spacetime point), the '3+1' approach, called 'geometrodynamics', was developed in the 1950s and 1960s by Dirac, Wheeler and others. In this approach, the theory is expressed not by Einstein's field equations, but by the momentum and Hamiltonian constraint equations mentioned in Section 1. But note that in some ways, this approach represents only part of general relativity. For it involves fixing the global topology of spacetime to be a product of the topologies of some spatial 3-manifold and of the real numbers (representing time); and it therefore forbids the kind of topology change that general relativity allows—and that occurs or at least seems to occur, for instance in black holes.

Nevertheless, suppose we adopt this approach and again consider the simplest possible case. We begin by representing space as a compact 3-manifold $\mathcal{M}$, so that spatial geometry is given by a Riemannian metric h on $\mathcal{M}$; and let us ignore matter fields, so that we are concerned with the time-evolution of geometry alone—so-called 'pure (i.e. vacuum) geometrodynamics'. From the traditional relationist perspective, this last will surely be an unacceptable simplification. But let us here set aside this qualm, since: (i) in fact Barbour himself willingly discusses pure geometrodynamics (both in this book and his technical papers), though it is hard to square with the idea (cf. Section 2.2.1) of treating spatial points as point-like parts of a matter-field; and (ii) relationism aside, the conceptual issues about geometrodynamics arise in an undistorted but technically simpler form, for the compact manifold and vacuum case. Then the obvious configuration space to consider is the set $Riem(\mathcal{M})$ of all Riemannian metrics on $\mathcal{M}$. Again, this is a very complicated space; in particular it is infinite-dimensional.

But in fact, much technical work in geometrodynamics uses another space, the quotient space of $Riem(\mathcal{M})$ under the action of spatial diffeomorphisms. That is, one defines an equivalence relation on $Riem(\mathcal{M})$, saying that $h \sim h'$ iff h, h' can be mapped into one another by a diffeomorphism of $\mathcal{M}$. The resulting quotient space, which we can write as $Riem(\mathcal{M})/Diff(\mathcal{M})$, is called 'superspace'. The use of this quotient space corresponds to imposing the momentum constraint; and it is of course in the spirit of the hole argument (mentioned in Section 2.1.1), since the conclusion of that argument is precisely that we should attribute no physical significance to *which* point of $\mathcal{M}$ has a given array of metrical properties. So general relativity, once formulated as geometrodynamics on superspace, already seems close to the spirit of Barbour's views, with $Riem(\mathcal{M})$ serving as the 'absolutist' Q, and $Riem(\mathcal{M})/Diff(\mathcal{M})$ as Barbour's preferred RCS Q_0.

Indeed, Barbour shows that there is a stronger connection; (this is his Machian analysis of general relativity, pp. 170-177). Recall how intrinsic dynamics for point-particles used the metric on the absolutist configuration space $Q = E^{3N}$, together with the idea of best matching, to define a metric, and thereby a variational principle for dynamics, on the RCS Q_0. In a similar way, an intrinsic dynamics approach to geometrodynamics will aim to have a metric on $Riem(\mathcal{M})$ induce a metric on $Riem(\mathcal{M})/Diff(\mathcal{M})$, the geodesics of which will represent the dynamically possible histories of 3-geometries. Barbour shows[20] that this approach leads to a certain general form of the 'action' to be extremized on superspace—and it turns out that under certain conditions, the orthodox 4-dimensional action of general relativity can be put in a form—the Baierlein-Sharp-Wheeler form—that instantiates Barbour's general form. (The passage from the orthodox 4-dimensional action principle to the Baierlein-Sharp-Wheeler form is analogous to the corresponding passage in special relativity: from QT to Q to Q_0.) Furthermore, in order to obtain the Baierlein-Sharp-Wheeler form, one does not need to impose restrictions on general relativity, analogous to the fixed energy and zero angular momentum restrictions that earlier had to be imposed, in order to get the same solution space as given by intrinsic dynamics. Thus Barbour says that general relativity is already (i.e. without extraneous restrictions being needed) a 'frameless' theory.

Besides, general relativity is a timeless theory, in the same sense in which we saw non-relativistic point-particle intrinsic dynamics is: viz. that the time metric is explicitly definable from the dynamics. For starting with Barbour's general form for the Machian geometrodynamic 'action', we can choose the parameter λ on geodesic curves by imposing the local analogue of the global condition $T = E - V$ that we chose in the point-particle case. And if in particular, we do this starting with the Baierlein-Sharp-Wheeler action of general relativity, we recover precisely general relativity's usual notion of proper time. So as Barbour puts it, we can think of proper time as a local ephemeris time.

Finally, I turn to the topic of different foliations of a single spacetime. I already discussed this briefly for special relativity, but for general relativity the situation is more interesting, and indeed more positive. Suppose we again start with Barbour's general form for the Machian geometrodynamic 'action', and choose λ in the way just discussed to construct a 4-dimensional spacetime from an extremal sequence of 3-geometries (i.e. a sequence that extremizes Barbour's form). Now consider a different foliation of the spacetime just constructed, but with the same end-points (initial and final 3-surfaces); and consider the sequence of 3-geometries thus defined. Now let us ask: is this different sequence also a solution to our Machian theory? Does it also extremize Barbour's form? The answer in general is 'No'. But general relativity is one of a very small class of theories for which the answer is 'Yes'. Indeed, given some simplicity conditions, general relativity is the only such theory.

[20]Of course not here! Cf. e.g. his ([1994]), pp. 2864-2869.

2.2.3 Assessing intrinsic dynamics

I shall make three general comments about Barbour's theories of intrinsic dynamics; proceeding from 'the good news' through to 'the bad news'. I shall first state what I take to be these theories' main novelty and merit. Then I shall discuss the empiricist credentials of Barbour's instantaneous configurations. Finally I shall raise a difficulty about relativity. It is a difficulty that Barbour recognizes: and it will lead to the discussion of quantum theory in Section 3.

(1) The main novelty and merit of these theories is of course their use of relative configurations, and their timelessness, in the sense that the time metric is wholly defined by the dynamics. It is indeed remarkable that there are classical theories of mechanics and field theory with these features, that are nevertheless close cousins, theoretically and observationally, of the usual ones. Since I will discuss configurations in (2) (and since time is our main topic!), I shall here just make one remark about timelessness, supplementing the end of Paragraph 2.2.2.1. The familiarity of classical theories 'with time'—meaning, not absolute simultaneity, but that time is treated independently of the matter content of universe—should not blind us to the timeless alternative; (more precisely: blind us, once we set aside general relativity, whose dynamical metrical structure is nowadays also familiar). Indeed, as Barbour himself stresses, these theories' success depended on a remarkable and fortuitous circumstance: that until 1900, the frame defined (roughly speaking) spatially by the fixed stars and temporally by the rotation of the Earth, was within observational limits an inertial frame in which Newton's laws held good. As Barbour puts it (p. 93), there really seemed to be a 'clock in the sky'.

(2) We have seen that the main ingredient of the various theories of intrinsic dynamics are 3-dimensional instantaneous configurations. So it is reasonable to ask how well the notion of configuration accords with the tradition of Mach, or of relationism in general. Though the exact meaning of 'configuration' of course differs from one theory to another, we can reach some general conclusions.

The Machian or relationist must favour configurations that involve only 'observable' and/or 'relational' facts or physical quantities. Maybe we can rest content that in our first case, that of point-particles, the inter-particle distances are both observable and relational. But in general, the two notions may well come apart. Instantaneous facts, and similarly physical quantities whose values encode a configuration, can surely be observable but non-relational; (e.g. the absolute temperature of a state of a matter field at a spacetime point or local region). And vice versa: such facts and quantities can be relational but unobservable; (e.g. the distance between simultaneous spacetime points). In view of this, one might suggest that for a truly Machian or relational theory, the facts and quantities encoding a configuration should be both relational and observable.

Here there are two points to be made: the first, (a), is a general problem; and the second, (b), concerns Barbour's own views about what counts as a Machian configuration.

(a) There remains the problem I mentioned at the start of Paragraph 2.2.2.1, about the empiricist credentials of the very idea of a configuration: ascertaining even 'elementary' facts such as inter-particle distances takes time and a considerable amount of theory.

Besides, one can perfectly well press Section 2.1.2's consistency problem for configurations, just as for other aspects of physical geometry. Accordingly, an empiricist should think twice about taking instantaneous configurations as the basic ingredients of a dynamics.

A similar point applies to our everyday impression that we see the present state of objects situated across a stretch of space. For Barbour, this impression is important for motivating configurations as the basic ingredient of dynamics. For example, he writes:

> Is not our most primitive experience always that we seem to find ourselves, in any instant, surrounded by objects in definite spatial positions? Each experienced instant is thus of the nature of an observation .... Moreover what we observe is always a collection, or totality, of things. We see many things at once. (p. 265)

This impression is indeed striking. But I doubt that it has any heuristic value for dynamics, or indeed for physics in general. For it clearly arises from the fact that perception is usually sufficiently rapid, compared with the time-scale on which macroscopic objects change their observable properties, that we can take perception to yield information about objects' present states, i.e. their states at the time of our perceptual judgment. This fact is worth remarking; it even has some philosophical repercussions (Butterfield [1984]). But it is also clearly a contingent fact about our perceptual system, albeit an adaptive, and no doubt evolved, one—and unlikely to be a clue to the structure of dynamics.

(b) To judge from the theories that Barbour himself has constructed or studied, and called 'Machian', he sets much less store by observability than by being relational. Though he wants to understand space relationally (as discussed in Section 2.2.1), he nevertheless counts as Machian a theory whose initial data include the instantaneous state of a scalar field; which is hardly observable, being defined at every point on a spacelike surface. Furthermore he says the same for pure geometrodynamics. That is, he counts as Machian a theory whose initial data specify a Riemannian geometry, but zero matter fields, on a 3-dimensional manifold.

On the other hand, it is of course important to Barbour that the configurations, and the quantities that encode them, be 'as relational as possible'. This is clear from the theories discussed above. And as I mentioned in Section 2.2.1, he is currently working on 'conformal' Machian theories in which there is no length scale, so that for the case of point-particles, three particles can form a unique equilateral triangle—and in general, not only are congruent triangles of Euclidean geometry, differing from one another in their location and orientation in Euclidean space, to be identified, but so also are the *similar* triangles.

(3) In Paragraph 2.2.2.2, I reported that intrinsic dynamics can respect relativity's freedom to foliate a spacetime in countless different ways, in the following sense. For both special and general relativity, if we are given a spacetime constructed from one solution of intrinsic dynamics (one extremal sequence of 3-dimensional configurations) and we consider any foliation of the spacetime, then the resulting sequence of configurations on that foliation is also a solution of intrinsic dynamics. I also mentioned that though these

are satisfying results, they prompt the question whether the '3+1'-perspective favoured by Barbour can be taken as fundamental.[21] This is the question to which I now turn.

Of course, 'fundamental' can mean different things, and the verdict about this question is likely to depend on the meaning chosen. Here it will be enough to indicate two reasonable connotations of the word, and to remark that one of them implies that a 'Yes' answer (i.e. saying that configurations are fundamental) would conflict with another desideratum, determinism—the conflict arising in a way analogous to the hole argument.

According to intrinsic dynamics, instantaneous configurations are certainly fundamental in the senses that comparison of their internal structures defines equilocality and the temporal metric, and that the dynamical law is a geodesic principle on the RCS, so that a geodesic completely describes a possible history of the universe. But we need to be more precise about 'complete description'. Do we mean that such a geodesic determines a history though not *vice versa*, thus allowing that distinct geodesics might determine the same history? If so, then the different foliations of a relativistic spacetime will correspond to different geodesics describing the same possible history. Or do we mean, more strongly, that such a geodesic describes a history of the universe, not only completely but also non-redundantly (in physics jargon: with no gauge-freedom)—so that a history corresponds to a unique geodesic? If so, then the countless different foliations of a relativistic spacetime will commit us to saying that such a spacetime contains countless different histories. This conclusion seems implausible. Furthermore, since in general relativity (or even special relativity if we allow a foliation's slices not to be hyperplanes), two foliations can match upto a slice and diverge thereafter, this conclusion implies indeterminism of histories, in a manner reminiscent of the hole argument.[22]

Barbour is aware of this tension between the spacetime viewpoint of relativity and his advocacy of configurations and a '3+1' viewpoint; though he does not express it in these philosophical terms (in this book or elsewhere). His answer, at least in this book, is to concede that for classical physics, the tension is resolved in favour of the spacetime viewpoint. He writes:

> If the world were purely classical, I think we would have to say ...that the unity [of spacetime, which] Minkowski proclaimed so confidently is the deepest truth of spacetime. (p.180)

But as the antecedent suggests (and the rest of the passage, pp. 180-181, makes clear), he also believes that in a quantum world, this tension is resolved in the other way: his advocacy of configurations wins—cf. Section 3.

[21] I set aside the more basic physical objection mentioned in Paragraph 2.2.2.2, that the '3+1' perspective captures only part of general relativity, since it forbids topology change.

[22] This 'hole argument for Barbour' is due to Pooley ([2001]), Section 3.5. Pooley concedes that Barbour could reply to this argument that his recent work on conformal theories promises to give a preferred foliation; cf. footnote 11.

3 The End of Time?

I turn to Barbour's view that there is no time. In this Section, I will emphasise philosophy not physics; and not just for lack of space, and as befits this journal—there are two other reasons. As I said in Section 1, Barbour's denial of time can be to a large extent understood and assessed independently of physics, in particular the technicalities of quantum geometrodynamics, i.e. the approach to quantum gravity which Barbour favours.[23] Also, he does not relate his denial of time very precisely to various philosophical positions; in particular, the tenseless ('B-theory') of time. So to understand his denial, we need to be careful.[24]

It will be clearest to begin in Section 3.1 by stating three possible meanings of the slogan that 'time is unreal', which all make sense more or less independently of physics. More precisely: to the extent that physics is relevant, one can ignore the peculiarities of quantum theory, and focus entirely on classical physics. Then I will be able to state the main idea of Barbour's own denial of time. It will give a fourth meaning of the slogan. It has some similarities to the first and third meanings; but it also has distinctive features of its own, related to Barbour's notion of a special type of configuration called a 'time capsule'. Then in Section 3.2, I will turn to quantum physics. This fills out the discussion of Barbour's denial of time in two main ways. First, Barbour urges, on the basis of some previous orthodox work, that in quantum physics time capsules get high probability (according to the quantum state). Second, he discusses the problem of time of quantum geometrodynamics. He argues that the best solution to this problem is to deny time in the way he proposes.

3.1 Time unreal? The classical case

I will first state three possible meanings of the slogan that 'time is unreal'.[25] To philosophers, the first two (Section 3.1.1) are familiar broadly defined positions: the denial of temporal becoming, which I will call 'detenserism' (an ugly word, but only one); and the claim that only the present is real, which is nowadays called 'presentism' (also ugly, but so be it!). The third, which I call 'Spontaneity', is probably unfamiliar (Section 3.1.2). But once we have grasped it, we can state the essential idea of Barbour's own denial of time, for the context of classical physics (to which this Subsection is confined). In effect the idea is a hybrid of Spontaneity and a Lewis-like modal realism (Section 3.1.3).

It will be clear from this Subsection's discussion that *all* of the classical theories mentioned in Section 2, whether traditional or Machian, fit very well with the first meaning of time being unreal, i.e. detenserism. That is a familiar point, and I will not belabour

[23] In particular, the denial of time is not just the claim that the temporal metric is emergent *a la* Section 2.2.2: which would anyway no more be a denial of time than the reduction of light to electromagnetic waves is a denial of light.

[24] Besides, the issues are in any case confusing! As we shall see, even such an exact thinker as John Bell was similarly imprecise, when he formulated a 'denial of time', in an essay which strongly influenced Barbour.

[25] Of course there are yet other meanings; for example, McTaggart's suggestion of a 'C-series'.

it.[26] But more importantly, it will also be clear that *none* of Section 2's classical theories give any support to the other meanings of time being unreal. And here by 'other meanings', I intend not only the second and third, presentism and Spontaneity; but also the fourth—Barbour's own denial of time. That denial is most easily grasped in the context of classical physics (as are the other meanings). But as we shall see in Section 3.2, Barbour's reasons for believing it, rather than just formulating it, come entirely from quantum physics. Indeed, they come from the problem of time in quantum gravity, in the form that problem takes within quantum geometrodynamics.

3.1.1 Detenserism and presentism

Saying that time is unreal could mean denying so-called 'temporal becoming', i.e. advocating the 'block universe' or 'B-theory of time'. The idea is that past and future things, events and states of affairs (or however one conceives the material contents of spacetime) are just as 'real' as present ones. Abraham Lincoln is just as real as Bill Clinton, just as Venus is just as real as Earth: Lincoln is merely temporally 'far away from us', just as Venus is spatially far away. Similarly for my first grandchild, supposing I have one: where this caveat simply reflects the fact that it is hard to know about the future (even harder, perhaps, than it is to know about the past)—not that the future, or its material contents, is of some different ontological status than the present or past.

On the other hand, saying that time is unreal could mean 'the opposite', i.e. presentism. The idea is that only the present is real: past and future things etc. are unreal. Here, I say 'things etc.' for simplicity: as regards the main idea of presentism, it does not matter how you conceive the material contents of spacetime—though of course in more precise versions, it can matter.

Thus the debates about these two positions turn on the contrast between the real and the unreal: no wonder both are controversial! I shall not try to contribute to them, but I need to stress three points: about dangers of ambiguity, about modality and about semantics, respectively. Each point leads to the next one.

First, beware of the ambiguities of 'is real', 'exists' and similar words. Detenserism is not just an insistence that for example, we should use 'is real' as short for 'has existed or presently exists or will exist'. And presentism is not just a table-thumping insistence on using 'exists', 'is real' etc. for 'presently exists'. Rather, each doctrine assumes that some distinction between real and unreal, in intension though not of course in extension, is common ground to the parties to the debate; or at least that it is common ground, as applied to material things, events etc.—I here set aside mathematical and other abstract objects. Then detenserism says, with 'real' (or 'exists' etc.) as applied to material items: all past, present and future things etc. are real. And presentism says, with the same sense of 'real' (or 'exists' etc.): only present things etc. exist.[27]

[26]This familiarity is one reason why it is tempting to misread Barbour's denial of time as merely denying temporal becoming.

[27]Again I say 'with the same sense of 'real'', for simplicity: it secures a direct contradiction between detenserism and presentism. But of course different authors can and do assume different distinctions

Second, the debates obviously connect in various ways with those about modality. The principal connection is via using modality to gloss the real/unreal distinction. Thus 'unreal' is often glossed as 'merely possible'. Tensers (i.e. opponents of detenserism) typically say that the future, and maybe the past, is not actual, but merely possible. And similarly presentists say (in terms of things, for simplicity): Abraham Lincoln and Sherlock Holmes are on a par; so are my first-born grandchild (supposing there is one—it is hard to know, and, not knowing, hard to name him or her), and Darth Vader (supposed fictional, as intended!).

This connection with modality means that the debates have been invigorated by recent developments in modal metaphysics. In particular, Lewis' bold advocacy of the equal reality of all possible worlds ([1986]) gave a clear modal analogue of detenserism; and similarly made the contrasting actualist view an analogue of presentism. Not that these analogies made everything cut and dried. In particular, as Lewis himself brought out: (i) one should not just identify 'being real' with 'being concrete', since the concrete-vs.-abstract distinction is itself in bad shape ([1986], Section 1.7); (ii) one cannot expect the debates about the identity of items, through time and across possible worlds, to be strictly parallel—not least because here the distinctions between things, events, states of affairs etc. come to the fore ([1986], Chapter 4).

My third point follows on from the first two. In short, it is that we should not assimilate detenserism and presentism to various rival semantic proposals. There is a temptation to do so; (indeed, I think the literature of the 1950s to 1970s was wont to do so). Thus it is tempting to say that detenserism goes with a simple bivalent semantics of temporal discourse. Detenserism seems to go with a semantics that, prescinding entirely from all the complexities of natural language, uses either (i) a single domain of quantification containing all objects that ever exist, or (ii) a linear order of domains, each containing the objects that exist at a single time, so that the quantifier represents present-tensed 'exists'. (Here 'object' covers things etc.) In either case, 'now' and other temporal indexicals get a straightfoward time-dependent reference. (For example: If times are treated as objects in the domain, then 'now' can be assigned a time as reference.) Correspondingly, tenserism and presentism seem to go with more complex semantic proposals: say with using three truth-values, or a branching future; or both of these.

But we should beware of the gap between semantics and metaphysics: each discipline is and should be beholden to considerations, substantive and methodological, that the other ignores. In the present context, not only might linguists have reasons for or against these semantic proposals, which ride free of metaphysics; also, the proposals do not straightforwardly express the metaphysical positions, just because formal semantics is not concerned with what is 'real'. Thus the use of a single big domain of quantification, as on the first proposal, is not implied by all its members being real; so the detenser may well endorse one of the more complex semantics. And the tenser will note that even these proposals do not capture her metaphysical thesis about reality. In particular, any

between real and unreal; with the result that—even if their distinctions are precise—the contradiction between one man's detenserism and another's presentism can be much less obvious. Indeed, their choice of distinctions might, at a pinch, make their positions compatible.

such semantics requires 'now' and other temporal indexicals to be treated just as they were in the simple bivalent semantics. It is part and parcel of doing semantics—whether with two truth-values or more, whether with branching or not—that such indexicals get a straightfoward time-dependent reference. So the 'movement of the now', which for the tenser and presentist is the crucial fact about time, is represented only by the semantics' use of a family of interpretations, related to each other by 'sliding along' the reference assigned to 'now' etc.—exactly as in the simple semantics favoured by the detenser![28]

3.1.2 Spontaneity

The third meaning of 'time is unreal' is much less familiar in philosophy: I will call it 'Spontaneity'. For philosophers of physics, and for Barbour himself, the most influential formulation is that of Bell ([1981]). But his formulation is combined with a discussion of Everettian interpretations of quantum theory (cf. Section 3.2); and Spontaneity makes just as good (maybe better!) sense in the context of classical physics, and even metaphysics. That is one reason why it is worth stating Spontaneity, before we tangle with quantum theory. A more important reason is that discussing Spontaneity will enable me to state the essentials of Barbour's own position. Besides, some of the comments below about Spontaneity carry over directly to Barbour's position.

Spontaneity presupposes the idea of a set of many possible courses of history, where each course of history is a 'block universe' in the sense of Section 3.1.1. But Spontaneity then proposes that unbeknownst to us, the actual history jumps between disparate instantaneous states.

To explain this, suppose we are given, in metaphysics or in physical theory, a set of possible courses of history. We naturally think of one of these as 'real', 'actual', 'realized' or 'occupied'; (setting aside now Section 3.1.1's issues about temporal becoming!). And—especially in physics, if not metaphysics—we think of these possible histories, including the actual one, as continuous in time. That is, we think of a possible history as a sequence of instantaneous states of the world (in metaphysics) or of the system (in physics); and we think of the set of all possible instantaneous states as having a topology, or some similar 'nearness-structure', so that it makes sense to talk of states being close to each other. And because, as we look about us, we seem to see the state of the world changing continuously, not in discrete jumps, we naturally think that the possible histories should be not merely sequences of instantaneous states, but continuous curves in the (topological or similar) space of such states. So we think of a collection of curves, each curve representing a possible course of history; and we think of one such curve as real, as actual—just as in Section 2.[29]

[28] I believe this point is not affected by the complexities of allowing for relativization of truth-value to circumstances of assessment, as well as circumstances of utterance; but I cannot argue the point here.

[29] Two qualifications. (1) I have deliberately avoided being precise about technical matters such as the topology of states, and whether to require some kind of smoothness (differentiability) as well as continuity. For they differ from one theory to another; and make no difference to the discussion to follow. (2) Agreed, not all of our experience, nor all our physical theories, suggest that change is smooth or at least continuous. Examples include Brownian motion and flourescing ions. But so far as I know, physics

Now I can state Spontaneity. It denies that the possible histories (including the actual one) need to be continuous in this sort of sense, and even that 'larger' discontinuous changes need be less probable. It urges that the possible histories, in particular the actual one, jump about arbitrarily in the space of instantaneous states. This mind-bending doctrine calls for six comments: rather a lot, but they will shed a lot of light on Barbour.

(1) At first sight, Spontaneity seems flatly incompatible with our impression that the state of the world changes continuously. But it might just be compatible. For the advocate of Spontaneity will argue that our evidence for that impression—indeed, all evidence for all empirical knowledge!—consists ultimately in correlations between experiences, memories and records that are defined at an instant. Thus: a present observation is not checked against a previous prediction, but rather against a present record of what that prediction was. This predicament, that epistemologically we are 'locked in the present', implies that any jumps of the type Spontaneity advocates would not be perceived as such. Immediately after the jump, the new instantaneous state, at which the actual history has arrived, contains records fostering the illusion that the state in the recent past was near (in the topology of the state-space) *it*—and so not near the actual predecessor, which is now a jump away.

Barbour does *not* advocate Spontaneity, though his denial of time will be similar (and equally mind-bending). But he *does* endorse the idea just mentioned, of our being epistemologically 'locked in the present'. For example, he writes:

> But what is the past? Strictly, it is never anything more than we can infer from present records. The word 'record' prejudges the issue. If we came to suspect that the past is a conjecture, we might replace 'records' by some more neutral expression like 'structures that seem to tell a consistent story. (p. 33)

John Bell formulates the idea similarly:

> ... we have no access to the past. We have only our 'memories' and 'records'. But these memories and records are in fact *present* phenomena. The instantaneous configuration ... can include clusters which are markings in notebooks, or in computer memories, or in human memories. These memories can be of the initial conditions in experiments, among other things, and of the results of those experiments. ([1981], p. 136; cf. also [1976a], p. 95.)

(2) But philosophers will recognize that this idea, that we are 'locked in the present', is very questionable. One obvious objection one might offer against it is that even our most immediate mental states have a duration; and for some states, a long duration may even be necessary—can you feel deep grief for only a second? This undermines Spontaneity's claim to be able to characterize our evidence as records etc. at an instant.

has very largely succeeded in modelling change as continuous, and models allowing discontinuous change at least assign decreasing probability to 'larger' changes; (at least once we set aside the instantaneous jumps that some invoke to solve quantum theory's measurement problem!).

Here, I say 'philosophers will recognize' and 'obvious objection', because Spontaneity is in effect a form of scepticism: viz., scepticism about what occurred in the past. More precisely: Spontaneity becomes such a form of scepticism, if one defines it as saying, not that the actual past course of events *was* a discontinuous sequence of states, jumping about very differently from what we naively believe; but rather that for all we know, the actual past could have been such a sequence.

So an obvious strategy for replying to Spontaneity is to adapt strategies fashioned for the more familiar case of scepticism about the external world. And the objection above is just the analogue against Spontaneity of the familiar objection against scepticism about the external world: that our evidence cannot be characterized except in terms of that world.[30]

(3) This objection against the idea that we are epistemologically 'locked in the present' (and hence against Spontaneity) should be distinguished from a different idea, which also seems to be evidence against Spontaneity—but which is readily enough answered. It is worth emphasising the distinction, since unfortunately Barbour does *not* address the objection in (2). But he does explicitly raise this second idea, and he gives the ready answer. For the idea seems to be evidence against his own view, as well as Spontaneity.

This second idea is that in some cases the *content* of perception requires continuity. (So the distinction from (2) turns on the familiar contrast between a mental state and its content.) The obvious cases involve visual perception of motion: Barbour takes the example of watching a kingfisher in flight (pp. 17, 264). Such cases are indeed evidence against Spontaneity, *if* the content is veridical—e.g. if the kingfisher really has a continuous flight-path.

But an advocate of Spontaneity can dig in her heels; (in an ugly philosophical jargon, she can adopt an 'error theory'). That is, she can say that the contents of such perceptions just are *not* veridical, except occasionally—when no 'jump' occurs in the relevant time-period. And she can explain away the compelling appearance of continuous motion, by saying that the state to which history jumps, when one judges, say, 'the kingfisher is flying to the right over the centre of the pond', involves the simultaneous presence in the brain at that time of (delusive!) 'records' of configurations of the kingfisher a bit to the left of the pond's centre. (Barbour's answer will be similar. He will also appeal to the simultaneous presence in the brain of delusive records; but with the difference that according to him, there is no actual past motion, not even a jumpy one!)

(4) This comment and the next mostly concern Bell. First, I should emphasise that though Bell formulates Spontaneity, he does not advocate it. In fact, he makes a wry comparison with another now notorious case 'where the presumed accuracy of a theory required that the existence of present historical records should not be taken to imply that any past had indeed occurred' (ibid.). This case is the strategy of reconciling Archbishop's Ussher's biblical calculation that the Earth was created in 4004 BC, with the fossil evidence of a much greater age—by holding that God

> would quite naturally have created a going concern. The trees would be cre-

[30] As it happens, I think the analogue against Spontaneity is more plausible than the familiar objection.

> ated with annular rings, although the corresponding number of years had not elapsed. (ibid.: cf. also [1976a], p. 98).

But Bell *does* think Spontaneity is a natural way to understand the Everettian interpretation of quantum theory (which he also does not endorse). More precisely, he thinks an analogue of Spontaneity that allows many actual histories, including discontinuous ones, is a natural way to understand Everett; (details in Section 3.2). And following Bell, Spontaneity has been discussed in that context; (a recent example is Barrett ([1999]), pp. 122-127). So those sympathetic to Everett, if not the rest of us, need to carefully consider Spontaneity's merits.

Here Barbour differs from Bell. Since Spontaneity and the Everettian interpretation are both close to Barbour's own position, he of course believes they are both close to the Truth.

(5) Spontaneity is not presentism, as understood in Section 3.1.1. The difference is clear. Spontaneity is about dynamics: it claims that the actual past course of events was a discontinuous sequence (or could have been, for all we know). Presentism is about reality: it claims that there is no actual past course of events. (And similarly for the future.)

But this difference is worth stressing since Bell sometimes expresses himself in a way that suggests presentism. He calls Spontaneity 'a radical solipsism—extending to the temporal dimension the replacement of everything outside my head by my impressions, of ordinary solipsism or positivism' ([1981], p. 136): words which better suit presentism.

(6) Finally, Spontaneity faces a problem about relativity. It is an aggravated form of the problem at the end of Section 2: viz. the tension between having instantaneous configurations as the fundamental ingredients of a '3+1' dynamics, and relativity's allowing spacetime to be foliated in countless different ways. We saw that this tension was allayed in those '3+1' theories (like Barbour's various intrinsic dynamics, and general relativity) in which there was a suitable 'meshing'; i.e. in which any foliation of a spacetime constructed from a given solution to the '3+1' theory yields another such solution. But given Spontaneity, with its allowance that histories jump about the state-space, what sense if any can be made of such meshing?

With his usual acuity, Bell saw this problem, though he expressed it very concisely:

> The question of making a Lorentz invariant theory on these lines raises interesting questions. For reality has been identified only at an instant [I read this, not as presentism, but as: instantaneous configurations are the fundamental ingredients of dynamics—JNB] ... In a Lorentz invariant theory would there be different realities corresponding to different ways of defining the time direction in the four-dimensional space? Or if these various realities are to be seen as different aspects of one, and therefore correlated somehow, is this not falling back towards the notion of trajectory? ([1981], p. 136)

Hard questions, which an advocate of Spontaneity would have to face. But not Barbour: he sidesteps the problem by denying that there is even one actual sequence of states!

3.1.3 Barbour's vision: time capsules

All the ingredients are to hand: I can now let the cat out of the bag, and state the essentials of Barbour's denial of time. ('Essentials' because in Section 3.2, quantum theory will add some features.) In short, it is a hybrid of Spontaneity and a strong realism about all the possible instantaneous configurations—a realism analogous to Lewis' well known realism about all possible worlds ([1986]).

Recall that Spontaneity has a single real course of history among the many merely possible ones: its novelty is to hold that this single actual history jumps about—instead of being a continuous curve in state-space. On the other hand, Lewis' modal realism—adapted to the state-space of some theory, rather than to Lewis' set of all logically possible worlds—makes no heterodox claims about dynamics. Its novelty is to hold that the possible courses of history (each nicely continuous) are all equally real—instead of just one curve in state-space being picked out as real.

Barbour proposes to go further than Spontaneity's denial that the actual history is continuous. He denies that there is an actual history (either past or future): there is *just* the space of all possible instantaneous configurations of the universe. Here 'all possible configurations' does not mean all logically possible configurations, but rather all the relative configurations of some suitable Machian theory (i.e. an RCS). Indeed, we will see later that for quantum theory, Barbour suggests that it means all configurations ascribed a non-zero amplitude by the quantum state; (cf. Section 3.2.1, especially (B)(2)).

And on the other hand, Barbour takes these configurations to be all equally real, just as Lewis holds the various possible worlds (i.e. possible courses of history) to be equally real. He of course concedes that one can mathematically define sets of configurations; and in particular continuous curves (since the RCS will presumably have a topology), and even curves that obey some variational principle, as in Section 2's theories. But these sets and curves are 'just mathematical': there is no actual physical history faithfully represented by one of the sets—not even (*à la* Spontaneity) by a discontinuous set.

That is Barbour's core idea. He obviously needs, as Spontaneity does, to explain away our impression that there is history, and a continuous one to boot. More specifically, he needs to argue that we are epistemologically 'locked in the present', and that the content of any perception that requires temporal duration (e.g. motion-perception) is, despite appearances, false. (Note that the second challenge is harder than that faced by the advocate of Spontaneity: she only needs to rule false contents that require continuity.)

As we saw in (1)-(3) of Section 3.1.2, Barbour can and does go part of the way to doing that.[31] In particular, as regards the second issue—the delusiveness of motion-perception—he takes (what we call!) perception of a kingfisher flying to the right over a pond to involve the brain containing a whole collection of (what we call!) records of configurations of the kingfisher and the water. But not just any collection. Not only are these configurations similar, i.e. near each other in some topology or metric on configurations, like those used in intrinsic dynamics; also, they can naturally be given a linear order, so that they

[31] Though not all the way, as we noted at the start of (3).

correspond to points along a curve in the configuration space; (pp. 29-30, 264-267). As we saw in Section 2, intrinsic dynamics suggests how even a metric for this linear order can be defined from just the structures of the configurations. And as we noted before, the advocate of Spontaneity who 'digs her heels in' has a similar position: she says that motion-perception involves the simultaneous presence in the brain of records that are misleading about what occurred in the actual past—a similar position, except that for her, 'simultaneous' and 'actual past' make sense!

Note that both positions are much more radical than the claim that motion-perception involves the simultaneous, or roughly simultaneous, presence in the brain, of records of very recent low-level perceptual states. *This* claim is nowadays a commonplace of empirical psychology, albeit a vague one: how else but by some sort of integration or coarse-graining of several such records could perception of motion be distinguished from perception of stasis? So the difference between this claim and the radical metaphysical positions, Spontaneity and Barbour's position, is clear. But it is worth stressing. For Barbour's popular formulations (pp. 29-30, 266-267) blur the difference, so that the plausibility of the former accrues invalidly to the latter.

So according to Barbour, our impression that there is history arises from some configurations of the universe (including those we are part of) having a very special structure: namely, they 'contain mutually consistent records of processes that took place in a past in accordance with certain laws' (p. 31). More precisely, they contain subconfigurations that falsely suggest such a past. Barbour has a memorable name for such configurations; he calls them 'time capsules'. So in short: a time capsule is any instantaneous configuration that encodes the appearance of history, for example a history of previous motion; and Barbour proposes that time capsules explain away our impression that there is history.

Barbour develops this vision in several ways. Perhaps the most important is his suggestion that in quantum physics, the quantum state gives time capsules relatively high probability (in which case his explanation of our impression of history is stronger, in that our impression is to be expected). I postpone this to the discussion of quantum physics in Section 3.2. But I can already explain two further points developing the idea of a time capsule. Barbour puts them somewhat metaphorically; (I think they are clearest at pp. 302-305). But they are worth stating precisely and generally; since together they give Barbour a kind of coarse-grained surrogate of history, and they might also help him give an account of the direction of time.

(1) The first point is that one time capsule can 'record' another. That is, one time capsule can contain records of another, without the other similarly containing records of the first. Here the phrase 'C_1 contains records of C_2' is of course colloquial—we are 'speaking with the vulgar'. According to Barbour, it is short for something like 'C_1 has sub-configurations that according to 'vulgar' dynamical laws are time-evolutes, or causal consequences, of some sub-configurations of C_2'. Furthermore, C_1's records of C_2 are often in its fine details, rather than its more obvious features. The intuitive idea (with an actual history, and the records existing later in time!) is familiar, both in science and everyday life. For example, a rock from one epoch contains in its fine details a fossil which records the structure of an organism that lived in some prior epoch. The scene of the crime today

contains in its fine details fingerprints which record the suspect's being there yesterday.

(2) The second point is that one time capsule can in this sense contain myriadly many records of another, and even many records of one and the same sub-configuration of the other. Again the intuitive idea is very familiar. Many different fossils from one epoch (all sub-configurations of one vast configuration) tell overlapping but mutually consistent stories about some prior epoch. Today the suspect's fingerprints are all over the scene of the crime, and furthermore, his handkerchief soaked in the victim's blood is under the desk. Furthermore, we must allow that in general, the different records will not be wholly consistent with each other: geologists and detectives often confront conflicting pieces of evidence—and today's newspapers tell overlapping but not wholly consistent stories about yesterday's events.

By putting points (1) and (2) together, Barbour can recover a coarse-grained surrogate of history. We have already seen the main idea in his treatment of motion-perception: the intrinsic structures of each of a set of configurations can define a linear order on the set. But now we are to suppose that the set of configurations being considered is not just a relatively simple set of (what we call!) perceptual records of a moving object, but a vastly complex set of time capsules, each containing many fine details. Indeed, Barbour's vision is that we should consider configurations of the whole universe. So now any such linear order will be defined by the way that the fine details of a configuration C_1 are records of another C_2. It will not be defined just by a relatively simple comparison of the more obvious features of the configurations—like inter-particle distances or distances to portions of water, in the simpler examples of intrinsic dynamics or perceiving a bird's flight over a pond.

Furthermore, Barbour proposes that these fine details will not prescribe a unique curve (linear order) through each configuration. Again, the intuitive idea is familiar in everyday life; (and even in science, apart from the special, albeit familiar, cases of physical theories that are deterministic—such as Newtonian mechanics once we consider not only configurations but also their rates of change). All the fossils in all the rocks from one epoch do not record every detail of life in the prior epoch. All the details of the scene of the crime today may record who is the murderer, but do not record every detail of the murder—did the murderer breathe an even number of times while in the room? In general, today's fine details only record some of the more obvious features of yesterday.

But of course, Barbour, with his denial of history and belief in the equal reality of all configurations, proposes to boldly extrapolate this intuitive idea. According to him, the fact that today's fine details do not prescribe a unique past is not just a matter of our having lost information about the actual past—there was no such past.

Barbour sums up these proposals, using the example of the possible configurations of a swarm of bees. He takes as its obvious features the overall position of the swarm and its size; in physics jargon, he takes as the coarse-grained or collective variables, the position of the centre of mass of the swarm, and the swarm's radius. The fine details are given by the relative positions of the bees within the swarm. So a possible (fine-grained) history of the swarm (if there were such histories!) is given as usual by a curve in configuration space: for 5,000 bees treated as point-particles, a space with dimension 15,000. A coarse-grained history is then a projection of such a curve onto the 4-dimensional subspace coordinatized by the four coarse-grained variables: viz. the three components of the position of the centre of mass, and the swarm's radius. Thus Barbour writes:

> For each point along the [coarse-grained history] there will be a corresponding cloud of points that record the same history up to that point in different ways. There will be a 'tube' of such points in the configuration space. No continuous 'thread' joins up these points in the tube into Newtonian histories. The points are more like sand grains that fill a glass tube. Each grain tells its story independently of its neighbours. In any section of the tube, the grains all tell essentially the same story but in different ways, though some may tell it with small variations. (p. 304-5).

This completes my exposition of Barbour's vision (neglecting quantum physics). I will end with three comments. The first is a suggestion to Barbour about how to treat the direction of time; the second is an objection to his vision; and the third sums up so far.

(a) In my discussion so far of Barbour's denial of time, I have not had to mention the direction of time, i.e. the various asymmetries between past and future. Indeed, this topic is not central to his denial of time: in fact, he treats it briefly in terms of entropy increase, though only in the context of proposals about quantum physics (pp. 289, 318). But there is an approach to the direction of time, within the philosophical literature about causation, which emphasises the role of records—and which therefore might be fruitful for Barbour. The starting-point of this approach is the observation that, as in our examples of fossils and fingerprints, an event typically has many later traces. Admittedly, 'trace' is here a term of art, understood differently by different authors; for example it might be understood as an event that is nomically sufficient for the given event. The idea of the approach is then that we can define 'trace' in a time-symmetric fashion (such as my example, 'event that is nomically sufficient for the given event'), and nevertheless maintain that an event typically has many *more* later traces than it has earlier ones.[32]

The relevance of this idea to Barbour is clear enough. If indeed there is such a past-future asymmetry in traces (i.e. in Barbour's jargon, records) then Barbour might be able to advert to it so as to give a sense to the 'tubes' that define his coarse-grained histories, and even to the many possible curves within such a tube. However, I should note two wrinkles. (i) It is not clear that any of the conventional arguments for such an asymmetry, relying as they do on the existence of time, will carry over to Barbour's framework, with its denial of time. (ii) In any case, the relation of such an asymmetry to an asymmetry of entropy (which Barbour believes important to past-future asymmetry), is obscure; (as Lewis notes ([1979], p.51); cf. Sklar ([1993] pp. 401-404), for a more recent discussion).

(b) Barbour's vision leads to a curious problem about the explanation of our experience. Namely, why should we find ourselves with a perception of anything having happened, or indeed of anything now happening? That is, why should beings in an 'encapsulated instant' be endowed with such sophisticated but delusive experiences? After

[32] Perhaps the best known statement of this past-future asymmetry is by David Lewis, in the course of defending his counterfactual analyis of causation under determinism; ([1979], pp. 49-50).

all, what could these experiences be good for? Any sort of evolutionary explanation is obviously ruled out! (Thanks to Adrian Kent for this point.)

(c) To sum up, let me reiterate the point made at the start of this Subsection: that while all of Section 2's classical theories, whether traditional or Machian, fit perfectly well with detenserism, *none* of them give any support at all to this Subsection's other three meanings of the slogan that time is unreal. Now that we have presented those meanings—presentism, Spontaneity and Barbour's denial of time—I think the point is clear: all too clear to need spelling out case by case, for each theory and each meaning of the slogan.[33] So accepting that classical theories, even Machian ones, do not support Barbour's denial of time, one naturally asks: why on earth should we believe it? As I said at the start of this Subsection, Barbour's own reasons derive entirely from quantum physics—to which I now turn.

3.2 Evidence from quantum physics?

At first sight, quantum theory seems as unpromising a place to look for evidence of the 'unreality of time' as were Section 2's classical theories. In particular, there are two features of the treatment of time in quantum theory that are often noted, and are perhaps the most obvious features of the treatment—but neither seems to support the unreality of time in any of Section 3.1's four senses.

The first feature is that quantum theory is traditionally interpreted as indeterministic.[34] But indeterminism does not support any of Section 3.1's senses: in particular, the detenser can perfectly well admit many alternative possible futures, as well as the actual one. The second feature is that quantum theory treats time as a parameter 'external' to the system, like the time of Newtonian mechanics and special relativity—but unlike general relativity or intrinsic dynamics. But that no more supports the unreality of time than did the corresponding treatments of time as 'external', in some classical theories.

Agreed, first impressions can be deceptive; and here the danger is all the greater since the interpretation of quantum theory is notoriously controversial. But as I see it, none of the four main approaches to interpreting quantum theory, and especially to solving the main problem (of measurement), seem to support the unreality of time. To spell this out a bit, I take the four main approaches, as follows. One can aim to solve the measurement problem in terms of physics, with or without revising the unitary dynamics: this strategy yields respectively, dynamical collapse models, or models that postulate extra 'beables' such as the pilot wave theory. Or one can aim for a distinctively philosophical solution to the measurement problem, again with or without revising the unitary dynamics: this

[33]Incidentally, such an exercise yields various minor comments, though none helpful to the unreality of time. For example, some tensers and presentists may be disquieted at the emergence of the temporal metric in intrinsic dynamics, i.e. at the idea that something so fundamental as the 'rate' at which 'time passes' should be fixed by the world's material contents (via the condition that $T = [E - V]$).

[34]Though the idea that quantum theory is indeterministic is in fact controversial, it is perhaps the most widely accepted 'fact' about quantum theory, among the general public; who confusedly suppose it to be part and parcel of Heisenberg's uncertainty principle.

strategy yields respectively, some version of the Copenhagen interpretation, or some kind of Everettian interpretation.

Lack of space means I cannot here consider *seriatim* whether each of these four approaches is somehow related to the unreality of time in one of Section 3.1's senses. It must suffice to make three comments. First: there seem to be no close connections. Second: in any case, no such connection was made (so far as I know) until Bell ([1981]) suggested that Spontaneity was the natural way to understand time in Everettian interpretations. Third, and more importantly for us: no one before Barbour (so far as I know) suggested that quantum theory, more specifically quantum gravity, supported denying time in his sense (Sections 3.1.3 and 3.1.4).

It will be clearest to think of Barbour's appeal to quantum physics as proceeding in two main stages. The first stage (Section 3.2.1) concerns the basic structure and interpretation of any quantum theory. Here Barbour emphasises some orthodox work (going back to the 1920s) on 'semiclassical approximations' in quantum theory; and combines this with a kind of Everettian interpretation. But he does not claim that this work and his interpretation directly support his denial of time. He only claims that they 'make room for' his denial; namely by implying that time capsules can get (relatively) high probability, according to the quantum state. The second stage (Section 3.2.2) concerns the problem of time in quantum geometrodynamics. In this second stage, Barbour does argue for his denial of time: he thinks that the best solution to the problem of time is to deny time, and 'save the appearances' by invoking time capsules and their high probability.

3.2.1 Suggestions from Bell

Barbour's first stage is inspired by Bell ([1981]). As we have seen, Bell suggests that Spontaneity is the natural way for an Everettian interpretation to treat time; and Barbour's denial of time is close to Spontaneity. But there are both other similarities, and other differences, between Bell and Barbour. So it will be clearest to present Bell's points, pointing out Barbour's responses as we go.

Bell is concerned with how best to develop an Everettian interpretation of quantum theory. Not that Bell advocates such an interpretation. In fact, Bell makes clear that his suggestions are partly influenced by his sympathy for a rival, the pilot wave interpretation. In a slogan, his overall idea is that one should develop the Everettian interpretation as 'the pilot wave interpretation, but without the trajectories'.

This idea yields four suggestions about how to be a 'good Everettian'; which I will letter (A) to (D). The first two are about the core ideas of Everettian interpretations: here Bell suggests Everettians should take a leaf from the 'pilot waver's' book. Barbour will take the first leaf but not the second, i.e. accept (A) but not (B). Bell's last two suggestions are about time: as the phrase 'without the trajectories' hints, Bell here suggests disanalogies between the Everettian and pilot wave interpretations. More specifically, Bell introduces both Spontaneity (his third suggestion, (C)) and time capsules ((D)): ideas which as we saw in Sections 3.1.2-3.1.4, Barbour further develops.

(A) Bell emphasises how natural it is that the pilot wave interpretation takes position as its 'preferred quantity', i.e. as the quantity that is always definite in value and whose extra values answer the measurement problem's threat of macroscopic indefiniteness. For it is above all the positions of macroscopic objects that we intuitively want to be definite in value; in particular, measurement outcomes are recorded in positions, e.g. of a pointer. Accordingly, Bell suggests that an Everettian interpretation also does best to choose position as its 'preferred quantity', i.e. as the quantity in terms of whose eigenstates one should resolve the interpretation's postulated quantum statevector of the universe.

Barbour in effect endorses this suggestion. This is evident enough from Section 2's discussion of Barbour's treatment of classical theories in terms of configurations. But note that the Bell-Barbour agreement here need not concern just configurations for point-particle theories, i.e. arrays of point-particle positions. Though the pilot wave interpretation is best known (and most developed) for the quantum theory of a fixed number of particles, it can be extended to field theory. Though the details vary, the common idea is that a configurational variable, such as the value of a scalar field, is a preferred quantity that has a definite value at every point in space—cf. Barbour's treatment of field theories in Section 2.2.2.2. The difference is of course that the pilot wave interpretation also postulates that these definite values evolve by a guidance equation—and such a trajectory is of course anathema to Barbour.[35]

(B) Bell's second suggestion, again arising from his sympathy with the pilot wave interpretation, will need more discussion: both because it is less welcome than his first, to both Everettians in general and Barbour in particular, and because it raises various philosophical issues. It concerns the most familiar aspect of Everettian interpretations, viz. the 'many worlds': the idea, roughly, that the various components into which the quantum statevector of the universe should be resolved are 'all real'. To be more precise, we should distinguish mathematical statevectors and the physical situations they purport to represent. So the idea is: each component, or perhaps each component with non-zero amplitude, represents a 'world' which is just as 'real', or 'concrete', as the one apparent world (including macroscopic objects and measurement outcomes) that we see about us.

Bell suggests that the Everettian can simply drop this idea: why not have just one real 'world'—just as the pilot wave interpretation has one actually possessed value of position (or whatever corresponds in field theory), among the many that are given non-zero amplitude by the quantum state? Thus he writes:

> It seems to me that this multiplication of universes is extravagant, and serves no real purpose in the theory, and can simply be dropped without repercussions ... Except that the wave is in configuration space, rather than ordinary three-space, the situation is the same as in Maxwell-Lorentz electron theory. Nobody

[35] I should add that though Bell and Barbour may thus agree on preferring position or some similar configurational variable, their view is contentious. Various authors urge that avoiding macroscopic indefiniteness requires definite momenta as much as definite positions (i.e. localization in phase space not configuration space). Also Everettians nowadays appeal to the dynamical process of decoherence to select only an approximately preferred quantity; though admittedly, this is often 'close to' position, or to some similar configurational variable.

ever felt any discomfort because the field was supposed to exist and propagate even at points where there was no particle. To have multiplied universes, to realize all possible configurations of particles, would have seemed grotesque. ([1981], pp. 133-134; cf. [1976a]. pp. 97-98)

The first thing to say about Bell's suggestion is that Barbour of course rejects it. For recall (from the start of Section 3.1.3) that Barbour advocates an analogue of the 'many worlds' idea: viz. he advocates the equal reality of all the instantaneous relative configurations in some suitably Machian RCS; or at least the equal reality of those ascribed non-zero amplitude by the quantum state. (We will see another reason for Barbour's rejection in (C) below.)

Apart from Barbour's disagreement with Bell, the main point I need to discuss is simply that the Everettian 'worlds' are *not* possible worlds, in the sense used in modal metaphysics; but are rather aspects, or 'branches' of the single actual world—after all they are determined by the actual quantum state of the universe. This point is obvious enough: but it is important for us, because it bears upon Bell's and Barbour's views—as I will spell out in three comments.

(1): I noted in Section 3.1.1 that the debate about whether past and future were 'real' had been invigorated by analogies with recent modal metaphysics; and that one should not identify 'being real' with 'being concrete', since the concrete-vs.-abstract distinction is itself in bad shape. *Mutatis mutandis*, the debate between 'many worlds' and Bell's 'one world' alternative should be duly informed by metaphysics. In particular, one should be careful about this distinction between possible worlds and aspects of the actual world; and about whether the concrete-vs.-abstract distinction is in good enough shape to bear on the debate. Though I cannot pursue these issues, they are relevant to the next two comments.

(2): As I said in Section 3.1.3, Barbour's idea of the equal reality of all the instantaneous configurations is like Lewis' modal realism. But they differ in that for Barbour a physical theory, not modal metaphysics, is to define the space of equally real possibilities, i.e. the RCS. (Which physical theory? In short, quantum geometrodynamics–cf. Section 3.2.2.) But this point shows a further disanalogy with Lewis' modal realism. For it shows that Barbour, indeed any Everettian, needs more than just a theory to define the 'space of equally real possibilities': they also need a quantum statevector (and some sort of 'preferred basis' in which to resolve it).[36]

(3) This comment follows on from (2). The state-dependence just noted causes trouble for a suggestion that might be made: viz. that the 'many worlds' idea has an advantage over Bell's 'one world' alternative, as regards explaining why the apparent (macroscopic) world is as it is. I will briefly spell out the suggestion, and then note the trouble—and thereby support Bell (and the pilot-waver) over Barbour and the Everettians.

The suggestion is that with only one world, any such explanation must eventually

[36] I should add that Barbour unfortunately does not register these disanalogies, and sometimes seems to deny them. For example, he says that the RCS contains 'everything that is logically possible' (p. 267). Maybe this is an artefact of writing a popular book.

resort to one or more unexplained 'brute' facts, often facts about what the physical laws and/or initial conditions of the universe are; and since such facts seems arbitrary, the explanation is ultimately unsatisfactory. On the other hand, with many worlds, there is such a fact, or more likely a group of them, for each of the equally real worlds; and as a consequence (says this suggestion), each such fact, or group of facts, is *not* arbitrary, and the corresponding explanation is satisfactory.

This suggestion might be supported by two analogies (perhaps in combination). The first is with indexicality: the many worlds idea is supposed to make the fact that many propositions true of the apparent world (e.g. 'the pointer reads "1"') are false in other worlds, as straightforward as the fact that indexical propositions (e.g. 'Barbour is here at noon, 21 June 2000') are not true at all contexts of utterance (even all those in the apparent world!). The second analogy is with modal metaphysics: Lewis' modal realism has been alleged to have a parallel advantage over actualist alternatives, that it can explain satisfactorily (as simply indexical) what actualists must treat as arbitrary, and so as unexplained. (But note that Lewis himself rejects the allegation: [1986], pp. 128-133.)

As it happens, I reject this suggestion, primarily because of disagreements about what is involved in explanation. But I will not enter into details; (cf. my [1995], 139-142, 151-154). Here I only need to point out that the suggestion faces trouble if—as is usual for Everettian interpretations—the set of worlds is specified by the quantum state of the universe (say, as the worlds ascribed non-zero amplitude), and this state is a matter of happenstance, rather than being somehow picked out as unique. For in that case, 'brute' unexplained facts of just the kind that the suggestion wants to avoid will reappear at the 'next level' of explanation. That is to say: although there will not be unexplained facts at the 'first level', i.e. about the apparent world being thus and so, as against some other way (which also enjoys non-zero amplitude), there *will* be such facts about what the quantum state is.[37]

(C) We need not linger very long on Bell's third suggestion: that Everettians should adopt Spontaneity. We have already covered its essentials, and Barbour's attitude to it as 'close to the Truth', in Section 3.1.2. But the context of quantum theory prompts two further remarks. First: discussions of Everettian interpretations often (rightly) point out that the interpretation needs to lay down, not only a probability distribution over the various alternatives at each time (given by the squared amplitudes of the resolution of the statevector at that time, in the preferred basis), but also transition probabilities (i.e. conditional probabilities between alternatives at different times). In such discussions, Bell's suggestion to the Everettian about how to treat time is often taken to be, not Spontaneity in the qualitative sense used in Section 3.1.2 ('history jumps about; or for all we know, it does'); but rather the quantitative suggestion that 'history jumps about randomly', i.e. there are no correlations between alternatives at different times, so that probabilities of conjunctions are products of the probabilities of the conjuncts.

[37]But Barbour might at a pinch avoid this trouble. That is, he might avoid the undermining just mentioned. For as we will see, he conjectures that the quantum state of the universe is very special, in that it assigns high amplitude to time capsules—and he might just take it to be uniquely picked out by this condition.

The second remark is conceptual, and concerns Barbour's denial of time; and it relates as much to Bell's second suggestion, (B), as to (C). It is that if Barbour is to deny time as he wishes to (cf. Section 3.1.3), he *cannot* adopt Bell's 'one world' suggestion (B). For if one adopts (B), then there is indeed an actual history (a unique 'real' trajectory through the configuration space), albeit one that might jump about in accordance with Spontaneity. So in order to deny time, Barbour needs to believe in the 'equal reality' of enough of his configurations to prevent such a unique real trajectory, even a jumpy one.

(D) Bell's fourth suggestion is crucial for Barbour. Bell reviews a standard example from quantum mechanics; his aim is primarily to illustrate the measurement problem, but also to introduce the topic of records for the sake of his discussion of Everettian interpretations and Spontaneity. This example suggests to Barbour the idea that in some cases, the quantum state assigns relatively high amplitude to configurations that encode records of the past: i.e. to what he calls 'time capsules'. So again, there are differences, as well as agreements, between Bell and Barbour; and it will be clearest to first outline Bell's discussion, and then Barbour's response.

Bell's example is the analysis by Mott and Heisenberg (in 1929-30) of the formation of tracks in a cloud-chamber when a decaying nucleus emits an α-particle which then ionizes atoms in the chamber. Bell's main aim in presenting this example is to exhibit what he calls the 'shifty split': how orthodox quantum theory leaves open where one should draw the boundary between the quantum system and the classical background—in particular, where one should apply the projection postulate. In this example, the simplest approach is to consider only the α-particle as a quantum system, and treat the atoms as classical. On this approach, the α-particle's wave-function would at first be a spherically symmetric wave travelling out from the decayed nucleus. The first ionization would involve a collapse of the wave packet, corresponding to an approximate position measurement; the resulting wave function then propagating like a 'jet', with a small angular dispersion, along the line from the nucleus to the ionized atom. The shape of this jet means that the second ionization would probably be approximately colinear with the nucleus and first atom. It would involve a second collapse of the wave packet, producing a second jet, probably nearly parallel to the first and therefore making for a third ionization probably nearly colinear with the first and second. So even this simple approach gives an answer to the initial puzzle (posed by Mott himself), why a spherically spreading wave leads to colinear ionizations, i.e. straight tracks.[38]

On the other hand, one could also treat the atoms quantum mechanically, postponing the application of the projection postulate until, say, the formation of a water droplet (or even later, such as the taking of a photograph). The simplest such approach takes the atoms as fixed and non-interacting, but with two energy levels: a ground state and an excited state. On this second approach, an initial multiple-product state of the α-particle and many atoms in their ground states evolves into a complicated entangled state correlating different components of the initial spherical α-particle wave-function with excited states of different atoms (corresponding spatially to the α-particle wave-

[38]In fact, as the α-particle loses energy, the angular dispersion of the jets increases, and so the ionizations tend to be less exactly colinear.

function's components). On this approach there is of course no single first ionization; but instead a superposition of many possible first ionizations, which then evolves with each component developing correlated (approximately colinear) ionizations: first a second, then a third etc. Indeed, on this approach there are no ionizations at all, until the projection postulate is applied, say at the formation of a water droplet. At least this is so, unless one adopts some 'no-collapse' solution to the measurement problem, such as an Everettian or pilot-wave interpretation.

Bell points out that in this example, as in others, there are various different choices of the boundary between quantum and classical that make no difference to practical predictions; though of course not *every* such choice gives practically correct predictions—as Bell says, 'the first kind of treatment would be manifestly absurd if we were concerned with an α-particle incident on two atoms forming a single molecule' ([1981], p. 123). The reason for this agreement is essentially the ubiquity and efficiency of the decoherence process. But Bell of course goes on to urge that the ambiguity of this boundary, the 'shifty split', is not satisfactory in principle; and therefore to discuss the Everettian and pilot-wave interpretations.

Barbour's interest in the Mott-Heisenberg analysis is different from Bell's. He does not use it to motivate the Everettian's denial of the shifty split. Rather he sees it as a promising toy-model for the creation of time capsules, which are so central to his vision. Indeed, he goes so far as to say that it 'is more or less the interpretation of quantum mechanics' (p. 284). To set the scene for Barbour's argument about quantum gravity in Section 3.2.2, I need to mention here two points about Barbour's discussion. Though these points lead to technicalities (which we can avoid), the main ideas are non-technical; and the first shows up a significant lacuna in Barbour's work.

(1) The first point is the remarkable fact that the Mott-Heisenberg analysis uses the time-*independent* Schrödinger equation, which governs eigenstates, ψ_E say, of energy that are independent of time; so in position representation they are written $\psi_E(\mathbf{r})$ not $\psi_E(\mathbf{r}, t)$. That is to say, Mott and Heisenberg find a time-independent wave-function $\psi(\mathbf{r})$ that assigns (relatively) high amplitude to colinear ionizations; i.e. to many straight tracks radiating out from the decaying nucleus. There is no real conflict between their use of the time-independent equation and Bell's 'narrative' account of the creation of records, which I summarized above. At least this is so, as regards Bell's second approach where the successive collapses of the wave packet are not officially countenanced. For once we set aside the measurement problem, the issue whether there is a conflict is the technical one whether the Mott problem satisfies the conditions for quantum mechanics' time-independent scattering theory to agree with its (more general) time-dependent scattering theory; and in effect it does (p. 309).

That a time-independent wave-equation can encode (through its various solutions) varied and intricate spatial structure is no great surprise. As Barbour emphasises, the various intricate structures of energy eigenstates in atomic and molecular physics are determined just by the time-independent Schrödinger equation and the potentials involved (which are themselves determined by the structure of the configuration space). But for Barbour, the use of this equation is significant for two reasons. First, he points out that quantization of the intrinsic dynamics of point particles leads to this equation (pp. 231-2, 237, 241). Second, Barbour will later draw an analogy between the time-independent Schrödinger equation and the fundamental equation of quantum geometrodynamics; for that equation is also apparently time-independent (cf. Section 3.2.2).

These points show up a lacuna, and perhaps an objection, for Barbour. His work focusses on classical physical theories with matter treated as point-particles or as fields, and their quantizations in terms of configurations (i.e. wave-functions on configuration space). He says next to nothing about our best theories of matter, viz. quantum field theories. To be sure, quantum field theories can be described in terms of wave-functions on the space of all possible field configurations, and this is presumably how Barbour would like to treat them. But if so, the fact that in quantum field theory the field operator does not commute with particle-number and similar particle-like operators means that Barbour cannot expect any simple relation to the point-particle theories with which his Machian proposals, both classical and quantum, began. In particular, this might undermine these proposals' heuristic value. (Thanks to David Wallace for this point.)

(2) The second point Barbour stresses is that the creation of records (or, in language that is time-independent, and neutral about the collapse of the wave packet: the assignment of high amplitude to time capsules) requires special conditions. The most obvious one is the ordered nature (low entropy) of the initial state: i.e. the α-particle's initial spherically symmetric wave-function and the surrounding atoms being initially in their ground states. Barbour also stresses how Mott consistently postulates outgoing, rather than incoming waves, to represent the result of scattering. That is of course physically reasonable: the opposite would seem as perverse as postulating advanced solutions in electromagnetic theory—but it is not strictly derived from the assumptions of the problem; (pp. 288-289, 310). In Section 3.2.2, I will again touch on the question how special these conditions are. For Barbour will want the creation of records by a Mott-like mechanism, to be generic rather than exceptional in quantum cosmology.[39]

To sum up this Section: Barbour in effect agrees with Bell's suggestions (A) and (D), regards (C) as close to his own denial of time—but is forced by that denial to reject Bell's (B).

3.2.2 Solving the problem of time?

Finally, I turn to what at the start of this Section I called Barbour's 'second stage': in which he positively argues for his denial of time (rather than just making room for it). The idea is that denying time is the best solution to the problem of time in quantum geometrodynamics (i.e. the approach to quantum gravity which Barbour favours). The

[39]Barbour also emphasises a third point about which I disagree. He says ([1994a], p. 2890) that unlike the usual accounts of the emergence of records using decoherence, he takes the records to reside not in classical, but in quantum variables—for Mott scattering, in the electrons of the excited atoms. But surely this is a false contrast. All agree that the micro-constituents that 'seed' records are quantum in nature, but are decohered rapidly by their environment, be it only the microwave background; thus in Mott scattering, the atoms' coupling to their environment, and in particular to each other, is crucial to the formation of water droplets.

illusion of time is to be explained by the quantum state of the universe assigning high probability to time capsules.

Here I propose to cut short a story which, though fascinating, is not only long, but also complicated and controversial. There is no space; and besides it is told, at about the level of this paper, elsewhere. It must suffice to say the following. Though it is clear that quantum theory and general relativity conflict with one another, it is very controversial how best to reconcile them. There are several disparate motivations: that one should somehow avoid the singularities of general relativity, or unify gravity with the other forces, or solve the measurement problem, or avoid postulating a spacetime continuum—to name but four! Though one can consistently endorse several of these (e.g. all these four), in practice different motivations prompt very different research programmes. And the situation is not helped by the dire lack of data: the characteristic length at which quantum gravity effects are expected to be important (the Planck length) is as many orders of magnitude smaller than the proton, as the proton is smaller than the Earth!

In any case, one strategy is to quantize general relativity. In effect, one tries to follow in the footsteps of the quantization of the other successful classical theory of a fundamental force—classical electromagnetic theory. But the situation for gravity is much more complex than for electromagnetism. One first writes general relativity in the kind of '3+1' ('Hamiltonian' or 'canonical') form discussed in Paragraph 2.2.2.2; with a view to then applying established methods for quantizing a classical Hamiltonian theory. As noted in Paragraph 2.2.2.2, writing general relativity in this 3+1 form is restrictive, since it forbids topology change. But in any case, if one adopts this approach, one naturally expects, on analogy with the way that quantizing the classical mechanics of point-particles yields wave mechanics, that one will get a theory which in Schrödinger picture has a wave-function, with a 3-geometry h say and perhaps matter fields ϕ as its argument: $\psi[h, \phi]$. Hence the name 'quantum geometrodynamics'. (The square brackets are used to reflect the fact that the arguments h and ϕ are themselves functions.)

At first sight, this approach succeeds: applying the quantization methods in an informal, heuristic way, one gets equations for a ψ whose arguments lie in the infinite-dimensional space of the h and ϕ fields. But there are horrendous problems about giving these equations (and associated measures, inner products etc.) a proper mathematical meaning. But suppose we set aside these technical obstacles: still, there is a more conceptual problem, about time.

It turns out that when one writes general relativity in 3+1 form, there are more variables in the formalism than there are physical degrees of freedom; (we saw this implicitly in Paragraph 2.2.2.2's discussion of quotienting by the action of spatial diffeomorphisms). These extra variables mean that there are constraints, i.e. equations that relate some or all of the variables to one another. These are the momentum and Hamiltonian constraints mentioned in Section 1; they roughly correspond, respectively, to the action of spatial diffeomorphisms, and to the time-evolution. And as discussed in Paragraph 2.2.2.2, Barbour provides a Machian analysis of them.

In the 1950s, Dirac and others developed a method for quantizing a Hamiltonian theory with constraints: a classical constraint $C = 0$ becomes a requirement that the quantum state is annihilated by a corresponding operator: $\hat{C}(\psi) = 0$. When in the 1960s, Wheeler, DeWitt and others applied this method to general relativity, it turned out that—*modulo* the technical obstacles just mentioned—the Hamiltonian constraint, representing the time-evolution of classical general relativity, did not become a Schrödinger time-dependent equation of the familiar form $\hat{H}\psi = i\hbar d\psi/dt$, by which the quantum mechanical Hamiltonian $\hat{H}$ usually governs the time-development of ψ. Instead, one got a constraint equation of the form $\hat{H}(\psi) = 0$. This is the famous Wheeler-DeWitt equation. Apparently, it no more contains a time-variable, than does the time-independent Schrödinger equation (with energy eigenvalue zero).

Since the 1960s, there has been a lot of work, trying to somehow recover time from the Wheeler-DeWitt equation and its associated 'frozen formalism', or from related formalisms for quantized general relativity. (Of course this work goes hand in hand with trying to surmount the technical obstacles.) There have been three main strategies. (1): One tries to eliminate the extra variables (called 'solving the constraints') before quantisation, so as to identify a time variable; so that one can then quantise, without using Dirac's special method of constrained quantisation. Or (2): one applies Dirac's method and so endorses the Wheeler-DeWitt equation, but tries to identify time as a function of the variables that appear in it. Or (3): one abandons the idea of a state-independent notion of time: rather, time is to be an approximate concept associated with some kind of semiclassical solution to the Wheeler-DeWitt equation. It is this last strategy that is relevant to Barbour.[40]

Barbour's own proposal is a version of strategy (3). For he proposes that the Mott-Heisenberg analysis is a 'prototype' for the solution to the problem of time in quantum geometrodynamics; and this analysis uses some ideas, in particular a semiclassical state, that are central to this strategy. But I should emphasise that he is a heterodox follower of strategy (3). In particular, his denial of time leads him to say that the gravitational field has three degrees of freedom, while the conventional verdict is two (pp. 243-246); and he also criticizes (3)'s treatment of the direction of time (pp. 257-264).

More precisely, Barbour makes two conjectures, corresponding to his points (1) and (2) at the end of Section 3.2.1. (1'): He conjectures that just as in elementary wave mechanics, the structure of configuration space (and the interaction potentials defined on it), together with the time-independent Schrödinger equation, determine intricately structured energy eigenstates; so also in quantum geometrodynamics, the structure of the configuration space (which will be a product of Paragraph 2.2.2.2's superspace and the configuration space of matter fields), together with the Wheeler-DeWitt equation, determine states $\psi[h, \phi]$ that are peaked on time capsules.

(2'): He conjectures, more specifically, that the kind of state thus determined will be a generalization of the wave-mechanical states written down by Mott and Heisenberg. As we saw, those states are special, in two ways: a special initial state (in fact a semiclassical

[40]This strategy was studied intensively by Banks, Hawking, Halliwell and others in the mid 1980s. That only this strategy is related to Barbour is hardly surprising, at the level of slogans: since Barbour cuts the Gordian knot of the problem of time, by denying time, he will surely reject general strategies, like (1) and (2), for recovering it. For his rejection, cf. pp. 244-248; for recent philosophical reviews of all three strategies, cf. Kuchar [1999], Butterfield and Isham [1999], Belot and Earman [2001].

state with low entropy) is chosen, and for each scattering, only outgoing waves are considered. Nevertheless Barbour hopes that in quantum geometrodynamics, the creation of records (i.e. peaking on time-capsules) by a similar mechanism, will be generic rather than exceptional.

In his last Chapter, he discusses these conjectures, while admitting (p. 308, 320) that he has no hard and fast arguments, let alone proofs. As I read him (and the corresponding discussion in [1994a], pp. 2891-2895), he admits to having no inklings why the special chosen state should be favoured.[41] But he thinks the extreme complexity and asymmetry of the configuration space might favour Mott's second kind of 'specialness': the use of outgoing waves, or their generalizations. Here his idea is that just as in wave mechanics, the wave-function can be significantly constrained by being required to be regular at a boundary (e.g. being zero at spatial infinity), so in quantum geometrodynamics the requirement that the wave-function be suitably regular at the point or points (called 'Alpha') of configuration space that represent all space and matter contracted to a point will prohibit states with waves 'ingoing' to Alpha.

Clearly, there are a great many issues here that one could pursue; and I must conclude. I hope that Section 2 brought out the foundational interest of Barbour's work on Machian themes in classical physics, and that Section 3.1 brought out that his denial of time shows striking intellectual imagination. Here, I shall make no bones about my main criticism: that Barbour does not offer anything like enough evidence for these last conjectures—though fortunately, other authors have just recently offered some.

Agreed, quantum gravity is very controversial: recall Section 1's image of orienteering in a blizzard. But suppose we give Barbour the chain of technical and conceptual assumptions he wants: (i) that quantum geometrodynamics is the way to do quantum gravity—somehow its ferocious technical obstacles can be overcome; (ii) that strategy (3) for recovering the notion of time, is right; (iii) that Barbour's version of strategy (3) is right, both technically (so that e.g. the gravitational field has three degrees of freedom) and conceptually (so that e.g. we need not construct histories as curves through configuration space, but can rest content with coarse-grained 'tubes'). Still we need to be given an argument why some solutions of the Wheeler-DeWitt equation should give high relative probability to time capsules.

Agreed, physics is hard: it would be far too much to demand a general argument applying to a realistic infinite-dimensional configuration space (superspace). But we can reasonably ask for some kind of toy-model of Mott scattering in quantum geometrodynamics, perhaps using one of the much-studied finite dimensional mini-superspaces. Barbour has not given us such a model. But without a model, one can only conclude that quantum gravity gives no reason to believe Barbour's denial of time. On the other hand, some physicists influenced by Barbour have recently developed such models (Castagnino and Laura [2000], Halliwell [2000]). I cannot enter details: suffice it to say that (speaking in the temporal vernacular), Barbour can draw some hope from this recent work!

[41] Of course, various authors (such as Hawking, Hartle and Vilenkin) have tried to give a theoretical motivation for one 'wave function of the universe' ψ, rather than another; and have studied semiclassical approximations to their heuristic formulas for ψ. Barbour mentions this but does not go into it (p.312).

Acknowledgements For comments on a previous version, I am very grateful to: Julian Barbour, Harvey Brown, Craig Callender, Adrian Kent, Lee Smolin, Peter Morgan, Abner Shimony, Jos Uffink and David Wallace: if only I had the time and space to act on them all! And special thanks to Oliver Pooley for discussion.

References

Barbour, J. [1982]: 'Relational Concepts of Space and Time', this journal, **33**, pp. 251-274. Reprinted in J. Butterfield, M. Hogarth and G. Belot eds., *Spacetime*, Aldershot: Dartmouth, pp. 141-164.

Barbour, J. [1989]: *Absolute or Relative Motion?*, volume 1, Cambridge: Cambridge University Press.

Barbour, J. [1994]: 'The timelessness of quantum gravity: I. The evidence from the classical theory', *Classical and Quantum Gravity*, **11**, pp 2853-2873.

Barbour, J. [1994a]: 'The timelessness of quantum gravity: II. The appearance of dynamics in static configurations', *Classical and Quantum Gravity*, **11**, pp. 2875-2897.

Barbour, J. [1999]: *The End of Time: The Next Revolution in Our Understanding of the Universe*. London: Weidenfeld and Nicholson.

Barbour, J. [1999a]: 'The Development of Machian Themes in the Twentieth Century', in *The Arguments of Time*, ed. J. Butterfield, British Academy and Oxford University Press, pp. 83-110.

Barbour, J. and Bertotti, B. [1982]: 'Mach's principle and the structure of dynamical theories', *Proceedings of the Royal Society of London*, **A 382**, pp. 295-306.

Barbour, J. and Ó Murchadha, N. [1999]: 'Classical and Quantum Gravity on Conformal Superspace', gr-qc/9911071.

Barrett, J. [1999]: *The Quantum Mechanics of Minds and Worlds*, Oxford: Oxford University Press.

Bell, J. [1976]: 'How to Teach Special Relativity', in Bell [1987], pp. 67-80.

Bell, J. [1976a]: 'The Measurement Theory of Everett and de Broglie's Pilot Wave', in *Quantum Mechanics, Determinism, Causality and Particles*, ed. M. Flato et al. Dordrecht: Reidel, pp. 11-17. Reprinted in Bell [1987]; page references to reprint.

Bell, J. [1981]: 'Quantum Mechanics for Cosmologists', in *Quantum Gravity II*, eds. C. Isham, R.Penrose and D. Sciama, Oxford: Clarendon Press, pp. 611-637. Reprinted in Bell [1987]; page references to reprint.

Bell, J. [1987]: *Speakable and Unspeakable in Quantum Mechanics*, Cambridge: Cambridge University Press.

Belot, G. [1999]: 'Rehabilitating Relationism', *International Studies in the Philosophy of Science*, **13**, pp. 35-52.

Belot, G. [2000]: 'Geometry and Motion', this journal, **51** pp. 561-595.

Belot, G and Earman, J [2001]: 'Presocratic Quantum Gravity', in Callender and Huggett [2001].

Brown, H. [1993]: 'Correspondence, Invariance and Heuristics in the Emergence of Special Relativity', in *Correspondence, Invariance and Heuristics*, eds. S. French and H. Kamminga, Dordrecht: Kluwer Academic, pp. 227-260. Reprinted in J. Butterfield, M. Hogarth and G. Belot eds., *Spacetime*, Aldershot: Dartmouth, pp. 205-238.

Brown, H. [1996]: 'Mindful of Quantum Possibilities', this journal, **47** pp. 189-200.

Brown, H. [1997]: 'On the Role of Special Relativity in General Relativity', *International Studies in the Philosophy of Science*, **11**, pp. 67-81.

Brown, H. and Pooley, O. [2001]: 'The Origins of the Spacetime Metric: Bell's 'Lorentzian Pedagogy' and its Significance in General Relativity', forthcoming in *Physics Meets Philosophy at the Planck Scale*, eds. C. Callender and N. Huggett, Cambridge: Cambridge University Press; gr-qc/9908048.

Butterfield, J. [1984]: 'Seeing the Present', *Mind* **93**, pp. 161-176. Reprinted in *Questions of Time and Tense*, ed. R. Le Poidevin, Oxford: Oxford University Press, pp. 61-75.

Butterfield, J. [1995]: 'Worlds, Minds and Quanta', *Aristotelian Society Supplementary Volume* **69**, pp. 113-158.

Butterfield, J. and Isham, C. [1999]: 'On the Emergence of Time in Quantum Gravity', in *The Arguments of Time*, ed. J. Butterfield, British Academy and Oxford University Press, pp. 111-168.

Callender, C. and Huggett, N. eds. [2001]: *Physics Meets Philosophy at the Planck Scale*, Cambridge: Cambridge University Press.

Castagnino, M. and Laura, R. [2000]: 'Functional Approach to Quantum Decoherence and the Classical Final Limit: the Mott and Cosmological problems', *International Journal of Theoretical Physics* **39** pp. 1737-1765; gr-qc/0006012.

Earman, J. [1989]: *World Enough and Spacetime*, Cambridge Mass.: MIT Press.

Einstein, A. [1949]: 'Autobiographical Notes', in *Albert Einstein: Philosopher-Scientist*, ed. P.A. Schilpp, La Salle, IL: Open Court, pp. 1-96.

Forbes, G. [1987]: 'Places as Possibilities of Location', *Nous*, **21** pp. 295-318.

Halliwell, J. [2000]: 'Trajectories for the Wave Function of the Universe from a Simple Detector Model', gr-qc/0008046.

Kuchar, K. [1999]: 'The Problem of Time in Quantum Geometrodynamics', in *The Arguments of Time*, ed. J. Butterfield, British Academy and Oxford University Press, pp. 169-195.

Langton, R. and Lewis, D. [1998]: 'Defining 'Intrinsic'', *Philosophy and Phenomenological Research*, **58** pp. 333-345; reprinted in D. Lewis [1999]: *Papers in Metaphysics and Epistemology*, Cambridge: Cambridge University Press, pp. 116-132.

Lewis, D [1979]: 'Counterfactual Dependence and Time's Arrow', *Nous*, **13** pp. 455-

476. Reprinted in his *Philosophical Papers*, volume II, Oxford: Oxford University Press, 1986; page reference to reprint.

Lewis, D. [1986]: *On the Plurality of Worlds*, Oxford: Blackwell.

Peacocke, C. [1979]: *Holistic Explanation*, Oxford: Oxford University Press.

Pooley, O. [2001]: 'Relationism Rehabilitated?', this journal, **??** pp. ??.

Sklar, L. [1993]: *Physics and Chance*, Cambridge: Cambridge University Press.