On the Persistence of Homogeneous Matter

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Abstract

Some recent philosophical debate about persistence has focussed on an argument against perdurantism that discusses rotating perfectly homogeneous discs (the 'rotating discs argument'; RDA). The argument has been mostly discussed by metaphysicians, though it appeals to ideas from classical mechanics, especially about rotation. In contrast, I assess the RDA from the perspective of the philosophy of physics.

After introducing the argument and emphasizing the relevance of physics (Sections 1 to 3), I review some metaphysicians' replies to the argument, especially those by Callender, Lewis, Robinson and Sider (Section 4). Thereafter, I argue for three main conclusions. They all arise from the fact, emphasized in Section 2, that classical mechanics (non-relativistic as well as relativistic) is both more subtle, and more problematic, than philosophers generally realize.

The first conclusion is that the RDA can be formulated more strongly than is usually recognized: it is not necessary to "imagine away" the dynamical effects of rotation (Section 5.5). The second is that in general relativity, the RDA fails because of frame-dragging (Section 5.6).

The third is that even setting aside general relativity, the strong formulation of the RDA can after all be defeated (Section 6). Namely, by the perdurantist taking objects in classical mechanics (whether point-particles or continuous bodies) to have only temporally extended, i.e. non-instantaneous, temporal parts: which immediately blocks the RDA. Admittedly, this version of perdurantism defines persistence in a weaker sense of 'definition' than *pointilliste* versions that aim to define persistence assuming only instantaneous temporal parts. But I argue that temporally extended temporal parts: (i) can do the jobs within the endurantism-perdurantism debate that the perdurantist wants temporal parts to do; and (ii) are supported by both classical and quantum mechanics.

Contents

1 Introduction

This paper is an attempt to connect what modern physics, especially classical physics, says about matter, with the debate in analytic metaphysics whether an object persists over time by the selfsame object existing at different times (nowadays called '*endurance*'), or by different temporal parts, or stages, existing at different times (called '*perdurance*'). This is a multi-faceted debate, with various connections to physics and the philosophy of physics. This paper focusses on just one such connection. I will assess, from the perspective of the philosophy of physics, a metaphysical argument against perdurantism, which is based on the idea of rotating homogeneous matter, and is nowadays often called the 'rotating discs argument' (RDA). I will argue, against much of the literature, that the argument fails, because of some features of classical mechanics (including how it should be interpreted in the light of quantum mechanics). But my larger hope is to connect the philosophy of physics, and metaphysics, communities. In this hope, I will sometimes expound details familiar to one community or the other—at the cost of some length!

I begin by outlining the argument, the kinds of reply usually made to it, and my own preferred reply (Section 1). This will lead to an discussion of how physics, and philosophy of physics, is relevant to the argument (Section 2). This will include a more detailed prospectus of the later Sections (Section 2.3). But in short, I will:

(i): present some more details about the RDA's assumptions and scope (Section 3);

(ii): discuss some replies made to it in the metaphysical literature (Section 4);

(iii): present some details of how physics describes rotation, and thereby formulate a stronger version of the RDA than the usual one—albeit one that fails in general relativity (Section 5);

(iv): present my own two replies to the RDA (Sections 6-8); of which I favour the second. This reply involves some novel proposals about the intrinsic-extrinsic distinction among properties. It is also supported by the way in which the objects of classical mechanics emerge from quantum theory.

This paper is a part of a larger project. My (2004, 2004a) describe some other connections between the endurantism-perdurantism debate and aspects of physics and its philosophy. In particular, my (2004) presents in more detail both the endurantism-perdurantism debate, and my arguments against philosophers' tendency to interpret classical mechanics in what I will call a *pointilliste* way (cf. Section 2.1). For the moment, suffice it to say that I conceive the endurantism-perdurantism debate in much the same way as Sider's fine recent survey, and defence of perdurantism (2001); cf. also Hawley (2001). Hawley and Sider also both discuss the RDA, at pp. 72-90, and 224-236, respectively.

1.1 The RDA

The argument envisages that the perdurantist with her ontology of temporal parts faces the project of defining persistence: since persistence is not identity, she needs to tell us what it is. (This project is called 'analyzing persistence', and 'analyzing or defining the genidentity relation between temporal parts'.) In particular, she needs to define persistence so as to distinguish "ordinary persisting objects" (i.e. the referents of ordinary terms, and elements of ordinary domains of quantification) from the countless other "spacetime worms", i.e. mereological fusions of temporal parts. (Most perdurantists accept unrestricted mereological composition, so that they also accept these worms as genuine objects.) On pain of circularity, the *definiens* is not to presuppose the notion of persistence.

The argument urges that the perdurantist cannot succeed in this project.[1] It is based on two ideas:

(i) *Homogeneous*: In a continuum (i.e. a continuous body whose composing matter entirely fills its volume) that is utterly homogeneous throughout a time-interval containing two times t_0, t_1, a spatial part at the time t_0 is equally qualitatively similar to any spatial part congruent to itself (i.e. of the same size and shape) at the later time t_1. (The properties of the continuum can change over time, but must not vary over space; e.g. the continuum could cool down, but must at each time have the same temperature everywhere.)

(ii) *Follow*: The perdurantist will presumably try to define persistence in terms of suitable relations of qualitative similarity between temporal parts. The obvious tactic is to have the *definiens* "follow" the curves in spacetime that are timelike and track maximum qualitative similarity.

The tactic of *Follow* seems to work well when applied to point-particles moving in a void each with a continuous spacetime trajectory (worldline). For however exactly we define 'maximum qualitative similarity', there will no doubt be, starting at a point-particle at t_0, a unique timelike curve of qualitative similarity passing through it: the worldline of the particle. (Indeed, for this case we could dispense with qualitative similarity, and have the *definiens* refer just to spacetime points' property of being occupied by matter.) Similarly for point-particles moving, not in a void, but in a continuous fluid with suitably different properties—a different "colour", or made of different "stuff", than the point-particle. (Again, we could have the *definiens* refer just to spacetime points' property of being occupied by matter with the "colour", or made of the "stuff", of the given point-particle.)[2]

[1]The RDA arose in recent philosophy in Kripke (unpublished lectures) and Armstrong (1980). Zimmerman (1998) reports how the argument goes back at least to Broad in 1925. Sider (2001, p. 226) notes that Leibniz (1698, sect. 13) deploys essentially the same argument: but Leibniz's target is Descartes' doctrines about matter and motion.

[2]Agreed, one can object that: (i) any such *definiens* is too weak, i.e. not sufficient for persistence, since a god could instantaneously destroy a point-particle and immediately replace it with a qualitative replica—suggesting that the *definiens* must invoke causal notions; and-or that (ii) any such *definiens* is too strong, i.e. not necessary for persistence, since a point-particle could jump about discontinuously.

But *Homogeneous* implies that *Follow*'s strategy stumbles when applied to a homogeneous continuum. There are altogether too many spatial parts at t_1 that are tied-first-equal as regards qualitative similarity to the given spatial part at t_0: any congruent spatial part will do. In other words: the curves of qualitative similarity run "every which way".

This problem is made vivid by urging that the perdurantist cannot distinguish two cases that, the argument alleges, must be distinguished. One main example, on which I will focus, is the case of a perfectly circular and rigid disc of homogeneous matter that is stationary; and a duplicate disc (rigid and congruent to, made of the same homogeneous material as, at the same temperature as *etc.* the first) that is rotating about the axis through its centre. It will be convenient to have labels for two such possibilities: call them '(Stat)' and '(Rot)'.

Hence the argument is nowadays often called the 'rotating discs argument' (RDA). (In some discussions, both discs are rotating, but with different velocities, maybe even in different senses.) But all agree that countless other examples would serve just as well as a disc: e.g. a sphere; or a body of fluid, like a river, that can be either stationary or flowing (or flowing with different speeds, or in different directions).

It seems that the endurantist can easily distinguish the two possibilities, according to whether the very same non-circularly-symmetric part, e.g. a segment, is in the same place at two times. Later (especially Sections 3.3, 5.3), I will pursue the question whether this is really so: can the endurantist legitimately use the notion of being in the same place at two times, i.e. the notion of persisting spatial points? (This question is almost entirely ignored in the metaphysical literature: authors often appeal without further discussion to the idea of "the same place" (e.g. Hawley 2001, p. 85).) But for the moment, I just assume, in order to give the RDA as good a run as possible, that the answer is Yes.

On the other hand, it seems the perdurantist has a problem. Surely she must say that all the relations (and therefore, all her proffered "suitable relations" for analysing persistence) between two temporal parts of the disc (say, second-long parts at noon and 12.01) are the same—whether the disc is rotating or not? And similarly for temporal parts at the two times of any spatial part of the disc, such as a segment.

The rest of this Section clarifies the scope of this argument, and the kinds of reply the perdurantist can give to it. This will yield a statement of a consensus which is widespread in the literature—and an announcement of how the remainder of the paper will argue against that consensus.

I address these objections in Sections 4.1-4.2.1 of my (2004a). In short: as to (i) I am sceptical of the appeal to causation—a topic I will return to in Section 4.1 below; and as to (ii), I suggest we restrict the *definiens* to point-particles assumed to have continuous worldlines. But the details of my replies are not needed for this paper: for they are no help to the perdurantist in facing the trouble made by the RDA.

1.2 Intrinsic properties and the idea of velocity

So far I have expressed the RDA's main idea as the inadequacy, for defining persistence, of qualitative similarity. But in some versions of the argument, the emphasis is instead on the inadequacy of either intrinsic properties or the idea of velocity. Both these topics call for some comments.

1.2.1 The intrinsic-extrinsic distinction

The intrinsic-extrinsic distinction among properties is controversial, but the rough idea is that possession of an intrinsic property implies nothing about the possessor's environment, i.e. about matters of fact beyond the instance. So in some versions of the RDA, the target is a perdurantist who seeks a *definiens* using intrinsic properties of temporal parts. And in some versions, the target is a yet stronger neo-Humean doctrine to the effect that (roughly speaking) *all* facts—not just facts of persistence—are determined by all the various intrinsic properties of all the points of spacetime. The most influential version of this sort of extreme '*pointilliste*' doctrine is *Humean supervenience*, as formulated and defended by Lewis (1986, p. ix-x; 1994, p. 474; 1999).

Fortunately, I will not need to take sides in the ongoing controversy about how to analyse, indeed understand, the intrinsic-extrinsic distinction. (For an introduction, cf. Weatherson (2002, especially Section 3.1), and the symposium, e.g. Lewis (2001), that he cites.) Indeed until much later (Section 4.2 and then Section 7), the distinction will drop out of sight. But I can announce here that even then, my discussion will be based on a much clearer distinction, between what Lewis (1983a, p. 114) dubbed the 'positive extrinsic' properties, and the rest. This goes as follows.

Lewis was criticizing Kim's proposal, to analyze extrinsic properties as those that imply *accompaniment*, where something is accompanied iff it coexists with some wholly distinct contingent object, and so to analyze intrinsic (i.e. not extrinsic) properties as those that are compatible with being unaccompanied, i.e. being the only contingent object in the universe (for short: being *lonely*). Lewis objected that loneliness is itself obviously extrinsic. He also argued that there was little hope of amending Kim's analysis. In particular, you might suggest that to be extrinsic, a property must either imply accompaniment or imply loneliness: so Lewis dubs these disjuncts 'positive extrinsic' and 'negative extrinsic' respectively. But Lewis points out that by disjoining and conjoining properties, we can find countless extrinsic properties that are neither positive extrinsic nor negative extrinsic; (though 'almost any extrinsic property that a sensible person would ever mention is positive extrinsic' (1983a, p. 115)).

This critique of Kim served as a springboard, both for Lewis' own analysis, using a primitive notion of naturalness which did other important work in his metaphysics (Lewis 1983b), and for other, metaphysically less committed, analyses (e.g. Langton and Lewis 1998, Lewis 2001).

But I will not need to pursue these details. I can make do with the notion of positive extrinsicality, i.e. implying accompaniment, and its negation. But in Sections 4.2.2 and 7 I will make some novel proposals about the notion: namely, I will distinguish temporal and spatial extrinsicality, and propose degrees of extrinsicality.

1.2.2 Velocity to the rescue?

On first meeting the RDA, most people make the obvious suggestion that what distinguishes the two cases is the direction of the instantaneous velocity of the disc's (or sphere's, or river's) constituent parts. Thus for the stationary disc, all the disc's parts have zero velocity; while for the rotating disc, the parts have various velocities (and for a perfectly rigid disc, a common angular velocity); and similarly for the sphere or river.

But there is a consensus in the RDA literature against this tactic. The consensus urges that the notion of velocity presupposes the persistence of the object concerned. For average velocity is a quotient of distance and time, whose numerator must be the distance traversed by the given persisting object: otherwise you could give me a superluminal velocity by dividing the distance between me and the Sun by a time less than eight minutes. (This goes with the so-called Russellian theory of motion, also called the 'at-at theory of motion'.) So average velocity's limit, instantaneous velocity, surely also presupposes the notion of persistence. Accordingly, says the RDA, the perdurantist cannot adopt the obvious suggestion, of distinguishing the cases in terms of instantaneous velocity (or angular velocity)—on pain of circularity.

The notion of presupposition, like the intrinsic-extrinsic distinction, is controversial. Besides, Tooley (1988) proposes a heterodox account of instantaneous velocity as an intrinsic property of an object at a time; (and Bigelow and Pargetter (1989, 1990 Section 2.6) propose a similar account). Though these authors are not concerned with the debate over persistence, their account of velocity has been discussed in the context of the RDA. So I shall later return to the idea of appealing to velocity, and to this heterodox account of it (Section 4.2). But for the most part, I will concede the literature's consensus. That is, I will concede that both average and instantaneous velocity presuppose the notion of persistence, and are extrinsic properties. Indeed, they are positive extrinsic in the sense of Section 1.2.1, since they entail the existence at other times of a temporal part of the object. Nevertheless, my favoured reply to the RDA (Section 7) will be that a perdurantist who accepts only non-instantaneous temporal parts (a version of perdurantism which, I contend, is supported by physics) can endorse the obvious suggestion we began with: that is, the perdurantist *can* appeal to velocities to distinguish the two cases.

I should also emphasise at the outset that the orthodox concept of velocity is much subtler (because connected to other concepts in complicated ways) than the above discussion suggests. Even if we consider only classical physics, it is *not* true that velocity is 'just' the quotient of distance traversed and time elapsed, or its limit dx/dt. Similarly, momentum is not just mass times velocity, $m\ dx/dt$. Agreed, the philosophical literature, in particular about the RDA, tends to assume the opposite—that velocity is just the time-derivative of position etc. Besides, until much later (Section 4.2.2.C and Section 7.1.C) my own arguments can go along with this assumption. But it is wrong. We shall see the reasons why in Section 4.2.2.C, building on Sections 2.1 and 2.2. And Section 7.1.C will show the significance of the point.

1.3 "Naturalism"

So far, my description of the perdurantist project of defining persistence, and of the RDA against it, might well be read within the tradition of conceptual analysis. By this I mean that the perdurantist's definition would be both finite in length, and formulated using everyday concepts. But nowadays, the literature also considers a "naturalized" perdurantist project of

(a): providing only a supervenience basis for persistence (i.e. allowing infinitely long definitions), rather than a finite definition or analysis of it; and-or

(b): appealing to technical notions, and contingent bodies of doctrine, in particular the laws of dynamics. Also, some authors combine (b) with use of the Ramsey-Lewis technique for simultaneous functional definition; (in particular, Sider (2001, 224-236)—details in Section 4.4).

Accordingly, the RDA is nowadays sometimes formulated as targeting even: (a) the supervenience of persistence on qualitative similarity among, and-or intrinsic properties of, the perdurantist's temporal parts; where (b) such supervenience may even be contingent, say relative to the laws of a dynamical theory.

This situation prompts two comments: the first relates mostly to (a), the second mostly to (b).

(1): *Non-reductive perdurantism*:— There is also an even more naturalistic conception of perdurantism, which might well avoid the RDA. On this conception, the perdurantist seeks a theory of perdurance and related concepts, that can appeal to scientific technicalities, that can revise rather than describe our concepts—and that does *not* have to define persistence in terms that do not presuppose it. Of course, analogous "non-reductive" conceptions are nowadays commonplace in the philosophical study of many concepts, such as causation, perception and action. So just as a philosophical theory of causation might decline to define causation (even infinitarily, even by Ramsey-Lewis functional definition), a perdurantist might decline to define persistence (even in these liberalized senses), on the grounds that she nevertheless says enough to adequately distinguish "ordinary persisting objects" from other "spacetime worms". I shall return to this modest (because non-reductive) perdurantism in Section 7. But until then I shall consider the more ambitious perdurantist, who aspires to define persistence, and so faces the RDA.

(2): *How many worlds?*:— Once we allow that a perdurantist theory of persistence might appeal to a contingent body of doctrine, such as a physical theory, the discussion of the RDA (or even the whole endurantism-perdurantism debate) is liable to become relative to a theory. There are two aspects to this; the first leads on to the second.

(2.A): The RDA might hold good in one theory, and fail in another. Thus it is a familiar thought that any consistent theory lays out a set of possibilities: in philosophical jargon, possible worlds according to the theory; in physics jargon, a space of solutions. So relative to any consistent theory about matter and rotation (describing them no doubt partially rather than completely—and perhaps falsely), the two cases (Stat) and (Rot) are either two distinct possibilities: or they are not, either because at least one is not possible (since e.g. the theory denies that matter is homogeneous), or because they are the *same* possibility.

This point is independent of whether to accept the notion of a law of nature, not relativized to a specific scientific theory. Authors (on either side of the endurantism-perdurantism debate) who accept this notion can consider contingent theses of reduction or supervenience cast in such terms, e.g. supervenience across a class of possible worlds that each make true all the actual laws of nature. For example, Armstrong and Lewis (to whom I will return in Section 4) are two such authors, and both perdurantists: though they disagree about how to understand laws of nature, and how the perdurantist should respond to the RDA.

On the other hand, authors who reject the notion will construe contingent supervenience theses, and so perhaps their discussion of the RDA (or even the whole endurantism-perdurantism debate), as relative to a given theory.

I myself will not need the notion of a law of nature; (indeed, I am wary of it). And we will later see the RDA holding good, and failing, in different theories. But I will of course allow for evaluation of the RDA which is not wholly relative to a theory. In particular, special interest will of course attach to the case of true theories: or to put it from our epistemic perspective, theories that are our best guess for truth. Such an interest does not presuppose "scientific realism", which concerns whether we should *believe* the theoretical claims of our best theory to be at least approximately true. Any "naturalist", whether or not they are a "scientific realist", will of course be especially interested in whether the RDA holds good in our best theory of matter and rotation.

(I will in fact argue that the RDA fails, not only in general relativity and quantum theory—our best guesses about space, time and gravity, on the one hand, and about matter, on the other—but even in classical mechanics, under an interpretation I favour.)

(2.B): But we should beware of just dismissing the RDA on the ground that according to our best theories, matter is in fact made of atoms and so not homogeneous. For presumably:

(i): A continuous, rigid and utterly homogeneous form of matter could exist and be formed into a disc that either rotates or is stationary. And:

(ii): No philosopher of persistence is "so far gone" in naturalism as to be interested only in how objects persist, given all the contingencies of the actual world.

In what follows, I will agree with these presumptions, so as to give the RDA against perdurantism as good a run as possible. But it is worth drawing attention to them since, as we shall see:

(i'): The sort of continuous and homogeneous matter the RDA needs is a much subtler and more problematic affair than the RDA literature typically recognizes; (cf. Section 2). This leads in to (ii'):—

(ii'): Some perdurantists reply to the RDA by saying that for the possibilities (Stat) and (Rot) to exhibit no difference to which the perdurantist can appeal, the advocate of the RDA needs to "imagine away" so many actual laws, technical and-or everyday, which describe various causes and effects of rotation, that the RDA's possibilities (Stat) and (Rot) are, though logically or metaphysically possible, very arcane. Indeed, they are so arcane that a naturalist perdurantist need feel no shame in being unable to accommodate them.

To put the reply (ii') in the jargon of possible worlds: the perdurantist claims their theory of persistence, though contingent and unable to discriminate the possibilities (Stat) and (Rot), is true in so broad a class of possible worlds that excluding (at least one of) (Stat) and (Rot) is a small price—and worth paying. (Examples of this reply include: Lewis (1986, p.xiii, 1994, p. 475), Callender (2001), and (less explicitly) Sider (2001, 230-236).) This leads to the next Subsection.

1.4 The accompaniments of rotation

Rotation has countless typical causes and effects; or if one is wary of causal talk: countless typical accompaniments. Typically, a rotating object was previously set in motion, say by being pushed by someone, and exhibits distinctive dynamical effects: for example, a solid object tends to become oblate, and a fluid, like water in a whirlpool, develops a concave surface. These accompaniments do not depend on matter being in fact atomistic (or on the laws of physics being relativistic and quantum). So in a possible world that contained continuous and homogeneous matter but was otherwise "like the actual world", these accompaniments—even the "technical" ones, like oblateness and concavity—would occur. In which case, the RDA needs to block the perdurantist appealing to them so as to distinguish the cases.

True to the tradition of conceptual analysis, the literature on the RDA almost entirely sets aside the technical accompaniments, and concentrates on the everyday ones, like having been pushed in the past; and on related everyday counterfactuals, such as 'were I to spray a spot of paint on the disc, I would see it move', or 'were I to grasp the disc, I would feel friction'. More specifically, the literature tends to assume that the RDA can legitimately set aside all the technical accompaniments by just stipulating that the rotating disc is not only solid but perfectly rigid, so that it does not become oblate; (hence Section 1.1's mention of rigidity). The philosophical battle can then be joined on two battlefields familiar to metaphysicians; as follows.

First, there is debate about whether the RDA can legitimately "imagine away" the everyday accompaniments of rotation, so that the perdurantist cannot appeal to them. In particular: if (as usual) the RDA stipulates that the present and "occurrent" everyday accompaniments are absent, can the perdurantist appeal to past or future accompaniments, or perhaps to counterfactuals about them? For example:

(i) Can the perdurantist make the distinction by appealing to a past cause, such as a push, or to a present counterfactual about seeing a paint-spot move?

(ii) Or would appealing to a past cause amount to postulating an unacceptable "temporal action-at-a-distance" (e.g. Robinson 1989 p. 405-406; Hawley 2001 p. 81)?

(iii) And would appealing to a present counterfactual amount to postulating unacceptably "ungrounded" counterfactual truths (Robinson 1989 p. 403; Hawley 2001 p. 74-75)?

Second, there is debate about whether the perdurantist can appeal to differences between (Stat) and (Rot) that are distinctively metaphysical (neither everyday nor technical-physical). For example: Can the perdurantist appeal to:

(i) a special (non-Humean) relation of immanent causation between temporal parts that subvenes (or even yields an analysis of) persistence (Armstrong 1980, 1997, pp. 73-74); or

(ii) special vectorial properties that are numerically equal to, yet different from, velocities (Robinson 1989 pp. 406-408, Lewis 1999: incidentally, this idea echoes Leibniz's proposal against Descartes (1698, sect. 13)); or

(iii) non-causal relations between temporal parts that are not supervenient on the intrinsic natures of the parts that are the relata, and yet are not just spatiotemporal relations (Hawley: 1999, p. 63-66; 2001, p. 85-90)?

For my reply to the RDA, I do not *need* to enter either of these battlefields; (fortunately, since they remain well-populated, despite the crossfire!). As to the first, I can set aside the "everyday accompaniments". For I shall argue (especially in Sections 2 and 5) that the RDA should not just set aside technicalities, in particular the technical accompaniments of rotation; and that in any case, it *cannot* do so just by stipulating perfect rigidity. As to the second, my reply to the RDA (in Section 6) does not need controversial metaphysical proposals like immanent causation, special vectorial properties etc. (of which I am in any case wary). However, I will make some points about these proposals, from the perspective of the philosophy of physics (Section 4).

1.5 Two kinds of reply: Against the consensus

We can sum up "the story so far" in two stages. First, there are two main ways perdurantists can reply (and have replied) to the RDA. They can either:

('Appealing Differences'): argue that there are differences between the discs to which they can appeal; whether everyday (e.g. 'someone pushed it'), technical (e.g. 'it's oblate') or metaphysical (e.g. 'the timelike curves of immanent causation are helical, not straight'); or

('No Difference'): argue that possible worlds in which the discs show no such difference are too arcane to matter: i.e. they do not fall within the scope of their "naturalist" account of persistence.

Second: In the literature on the RDA, considerations of metaphysics, and in particular conceptual analysis, tend to dominate. This dominance has led to a widespread consensus on four points: two in support of the RDA, and two against the perdurantist. Namely:

(I): The RDA *can* legitimately

(a) imagine away the usual accompaniments of rotation: both the everyday ones; and the technical ones such as discs tending to be become oblate (in the latter case, by requiring the discs to be rigid);

(b) assume the intuitive notion of rotation, with its idea of persisting spatial points.

On the other hand:

(II): the perdurantist *cannot* legitimately

(c) appeal to differences of velocity, since velocity presupposes persistence; nor can they

(d) appeal to the atomic, indeed quantum-theoretic, nature of matter, since the topic of debate is our common-sense conception of persistence—which surely allows continuous matter.

Turning to this paper: I shall argue against the consensus (a)-(d). Section 5 argues against (a) and (b); Sections 6 to 8 against (c) and (d). (Sections 2 to 4 will set the stage for these arguments.) The overall effect will be twofold. As to (a) and (b): I will concede that there are sound versions of the RDA. Indeed, the RDA can be formulated more strongly than usual (i.e. than Section 1.1's formulation): for it does not need to imagine away the usual accompaniments of rotation. But as to (c) and (d): a certain sort of perdurantist—roughly speaking, one who accepts only non-instantaneous temporal parts—*can* both appeal to differences of velocity, and garner support for their position from quantum theory.

2 The relevance of physics

So much by way of introducing the RDA. We have already seen that it raises issues in the philosophy of physics as much as in metaphysics. There is of course a spectrum here, from "common sense" doctrines about persistence to "folk physics" to technical physics. And I agree that it is in part a matter of intellectual judgment and-or interest: (i) how far along the spectrum to move; and if one considers technical physics, (ii) which physical theories to consider, classical or quantum, relativistic or non-relativistic. But only in part! I shall argue that the philosophy of persistence needs to go further towards technical physics than the literature on the RDA tends to.

By and large, the RDA literature engages a bit with "folk physics", but not technical physics. There are two connected aspects to this restriction. First, the literature sets aside the fact that matter is in fact made of atoms. Almost all authors maintain that our "common-sense" notions of matter and its persistence are surely compatible with matter's being continuous in its composition; so that a perdurantist seeking an account of these notions faces the RDA.[3] And most authors, especially those closer to traditional conceptual analysis, maintain that these notions form a framework sufficiently widespread, and cognitively central, for such an account to be not parochial, but worthwhile; and worthwhile even if continuous matter is "science fiction physics" (e.g. Robinson 1989, pp. 396-398; Zimmerman 1999, p. 213).

Second, although many authors in this literature discuss velocity, even instantaneous velocity—and several briefly discuss allied concepts from elementary mechanics, like force and momentum—almost all set aside technical physics: not just the modern theories which are our best guesses, viz. relativity theory and quantum theory, but also the details of the classical mechanical description of rotation and of continua (i.e continuous bodies).[4]

I believe these two aspects—taking common sense to encompass continua, and setting aside technical physics—arise from two mutually related, and widespread, assumptions. But these assumptions are in fact *false*—and correcting these assumptions will be the main ingredient in my rebuttal of the RDA. In short, the assumptions are:

(*Straightforward*): The ontology of classical mechanics, including the classical mechanics of continua, is straightforward, i.e. unproblematic.

(*Bracket*): Although the world is in fact relativistic and quantum, we can "bracket" this fact when we investigate persistence. That is: classical mechanics, or at least classical physics as a whole, forms a coherent whole, which can be safely assumed to provide the supervenience basis on which facts about the persistence of macro-objects supervene.

So in the next two Subsections, I shall spell out the errors of these two assumptions, and so urge that the philosophy of physics is relevant to the RDA. That will serve to introduce Section 2.3's Section-by-Section prospectus.[5]

2.1 Classical mechanics is subtle and problematic

(*Straightforward*) says that the ontology of classical mechanics, including the classical mechanics of continua, is unproblematic. More precisely, I think the literature assumes a conception of the ontology of classical mechanics, which I call the *particles-in-motion picture*. This analyses matter into extensionless particles: either point-particles sepa-

[3]I say 'surely compatible' since some authors toy with the view that the RDA shows that the compatibility is an illusion: our notion of matter and its persistence requires atomistic matter. Robinson (1989, p.404, reporting Lewis) portrays this as an example of the traditional "paradox of analysis": roughly, that philosophical analysis can reveal surprising truths.

[4]So far as I know, only one article about the RDA engages with technical physics: viz. Callender (2001), who discusses the classical physics of rotation; I discuss it below. Oppy (2000) surveys various threats from physics, including quantum physics, to Lewis' Humean supervenience; but without focussing on persistence.

[5]For a more detailed discussion of the two aspects above, and these two assumptions, cf. Sections 2.2 and 2.3 of my 2004.

rated from each other by a vacuum, or the extensionless infinitesimal constituents of a continuum (i.e. continuous body), "cheek by jowl" with each other. In either case, the composition and behaviour of matter is analysed in terms of extensionless particles, interacting by particle-to-particle forces such as gravity (with their motions through Euclidean space determined by the forces, according to Newton's second law). Furthermore, the literature assumes that this particles-in-motion picture is unproblematic, as regards *matter*; i.e. once one sets aside the various familiar philosophical problems about space and time (e.g. "absolute" or "relational"?).

This assumption, (*Straightforward*), leads to the first aspect of the RDA literature's restriction, i.e. its taking common sense to encompass continua. For the assumption implies that: (i) philosophical discussions of persistence have no need to tangle with the details of mechanics, either of point-particles or of continua; and (ii) since continua are both countenanced by common sense and unproblematic, an account of persistence needs to allow for matter being continuous, even though matter is in fact made of atoms—so the perdurantist faces the RDA.

But the particles-in-motion picture is wrong. There are in fact considerable conceptual tensions in classical mechanics' description of matter, whether conceived as point-particles or as continua. Besides, classical continua cannot be treated in the "*pointilliste*", i.e. particle-by-particle, way envisaged by the particles-in-motion picture.

Obviously I cannot here enter into details about the foundations of classical mechanics. I will only present two points that bear directly on my concern with the RDA. The first illustrates classical mechanics' subtlety, and will be directly relevant below: in Sections 4.2 and 7 it will give the perdurantist a reply to the RDA. The second illustrates how classical mechanics is problematic, and will lead in to the next Subsection (against assumption (*Bracket*)).[6]

(1): *Against pointillisme*: The first point is that classical mechanics does not in fact describe continua in the *pointilliste* way that the particles-in-motion picture envisages. Instead, the classical mechanics of continua has to be formulated in terms of spatially extended regions and their properties and relations. In particular, one cannot understand the forces operating in continua (whether solids or fluids) as particle-to-particle. Rather, one needs to conceive of a force being exerted on the entirety of an arbitrary finite (i.e. not infinitesimal) portion of matter, and of a force being exerted at the surface of such an portion. In Sections 4.2 and 7, this anti-*pointillisme* will be extended to include *temporal* extension (motivated in part by quantum theory). It will thereby give the perdurantist the right to have only temporally extended, i.e. non-instantaneous, parts: and this will secure a reply to the RDA.

This need to take extended regions as primitives is worth stressing, even apart from

[6]My 2004 gives a more detailed critique of the particles-in-motion picture, especially of its *pointillisme*. For classical mechanics' anti-*pointillisme*, cf. e.g. Truesdell (1991, especially Sections II.2, III.1, III.5). For a philosopher's general introduction to the conceptual tensions in classical mechanics' description of matter, I recommend Wilson's papers, e.g. his (1997) and (2000).

the debate about RDA; for two reasons. First, I admit that *prima facie* the particles-in-motion picture's strategy for analysing continuous matter is more attractive. For the alternative strategy, of describing the states of all the countless overlapping extended sub-regions of a continuum, is highly redundant: each sub-region is described countless times, viz. as a part of the description of a larger region in which it is included. Nevertheless, classical mechanics adopts—and needs to adopt—this alternative strategy. In short: a redundancy worth remarking.

Second, *pointillisme* has been a prevalent theme in recent analytic metaphysics: witness the recent interest in Lewis' *pointilliste* doctrine of Humean supervenience. But classical mechanics's anti-*pointillisme* seems not to have been noticed in metaphysics; though the relevant physics goes back to Euler.

(2): *Problems about point-particles*: Even if we set aside continua and consider only point-particles, i.e. extensionless point-masses, there are conceptual problems. One main group of problems arises once we add to the idea of a point-particle the notion of a field: I will postpone them to Section 2.2. Here, I will just mention two obvious problems, independent of the notion of a field.

The first problem is: how can we describe in terms of point-particles, *contact* between objects? As I see it: this problem divides into two sub-problems—both of them hard. First: how can we reconcile point-particles with solid objects' impenetrability? Even if we postulate, as Boscovitch did, that when point-particles are very close some repulsive force dominates the attractive force of gravity, questions abound. For example: how can we describe the difference between solids and fluids? Second: there is the problem of describing (or else somehow prohibiting!) collisions of point-particles. Such collisions are clearly problematic, not just kinematically but dynamically. In particular, under Newtonian gravity (or any interaction described by an infinite potential well around each particle), two colliding point-particles each have infinite kinetic energy at the instant of collision.

The second problem arises from the fact that, barring collisions, point-particles require that all forces act at a distance. Newton famously "deduced from the phenomena" that gravity acted at a distance. In particular, it acts instantaneously: according to his theory, if the Sun as a whole were now to move by, say, a metre, the direction of its gravitational pull on the Earth would now change, albeit by a minuscule angle. On the other hand, since light takes eight minutes to travel from Sun to Earth, the minuscule change in the visual direction, from our standpoint, of the Sun would take eight minutes to occur. But Newton also agreed that it is 'inconceivable that inanimate brute matter should, without the mediation of something else which is not material, operate upon and affect other matter without mutual contact'; so that he 'contrived no hypotheses' about 'the reason for these properties of gravity'. Though the outstanding successes of Newtonian gravitational theory during the next two centuries accustomed people to action at a distance, the advent of general relativity, in which gravity propagates at the same speed as light, has now revived the natural suspicion of it—which

Newton shared.[7]

In this Subsection, I have argued against the particles-in-motion picture. I end with a conjectural, but humdrum, reason why this wrong picture is so widespread in philosophy. I think it is a result of the educational curriculum's inevitable limitations. In the elementary mechanics that most of us learn in high school, extended bodies are assumed to be small and rigid enough to be treated as point-particles. One never faces the subtleties of classical mechanics' treatment of continua. Philosophers often augment high school mechanics with some seventeenth-century mechanics, through studying such great natural philosophers as Descartes, Hobbes and Leibniz. But there ends most philosophers' acquaintance with mechanics. About 1700, natural philosophy divided into physics and philosophy, so that few philosophers know about mechanics' later development. In particular, as regards the eighteenth century: philosophers read Berkeley, Hume and Kant, not such figures as Euler and Lagrange—whose monumental achievements in developing mechanics, and in particular its treatment of continua, changed the subject out of all recognition.

A fortiori, philosophers also tend not to know about relativity theory and quantum theory. So this conjectural, but humdrum, reason also helps explain the second aspect of the RDA literature's restriction, viz. its setting aside these theories.

But I think there is also another explanation. Namely, the literature tends to make the assumption I labelled (*Bracket*): that classical mechanics, or at least classical physics as a whole, forms a coherent whole, which can be safely assumed to provide the supervenience basis on which facts about the persistence of macro-objects supervenes. In the next Section, I argue that (*Bracket*) is false.

2.2 Classical physics leads to relativity theory and quantum theory

(*Bracket*) says that, although the world is in fact relativistic and quantum, we can "bracket" this fact when we investigate persistence. More precisely: All agree that the everyday macroscopic world "emerges" somehow or other from the relativistic quantum realm; and that in describing that world, classical physics, in particular classical mechanics, is outstandingly successful. This suggests that some enquiries, even some in the foundations of physics or in metaphysics, will be able to take the classical mechanical description of the world as the physical "given", ignoring the fact that it is emergent and approximate. (*Bracket*) proposes that enquiries, physical or metaphysical, about the persistence of macroscopic objects are among them. In more philosophical jargon: the classical mechanical description of the world provides the supervenience basis on

[7]The quotations are from a letter to Bentley of 1693, and the General Scholium added to the *Principia* in 1713: for discussion and references, cf. Torretti 1999, p. 78. I also stress that it is general, not special, relativity, that militates against action at a distance: Lorentz invariance does not prohibit action at a distance, whether along the light cone or across spacelike intervals; (cf. Earman 1989, p. 156, who cites Kerner 1972).

which facts about the persistence of macro-objects supervenes.

The tendency of the metaphysical literature on persistence to invoke "folk physics" and classical mechanics, but to set aside relativity theory and quantum theory, suggests that (*Bracket*) is widespread. But I claim that it is false. Besides, its falsity is central to my own position about the RDA. For the moment, I will just argue that (*Bracket*) is false, in three stages. The first two are brief and general; the third is an illustration. (1): First, I will urge that interpreting classical mechanics leads one to the vast landscape of all of classical physics. (2): Then I will describe how classical physics leads to relativity theory and quantum theory. (3): I will illustrate (2) with the example of self-interaction.

(1): *From classical mechanics to classical physics*
There is vastly more to classical physics than is contained in classical mechanics: for example, thermodynamics, optics and electromagnetism. Furthermore, classical mechanics conceptually depends on these other fields in an open-ended way that is even today not wholly and rigorously mapped out. That is, classical mechanics *cannot* be assumed to have some consistent and unproblematic ontology; (whether along the *pointilliste* lines of Section 2.1's particles-in-motion picture, or in my preferred non-*pointilliste* terms, using extended regions). Even for the special case of point-particles in a void, we saw that one can raise worries, about collisions and the comprehensibility of action-at-a-distance forces. But in any case, the mechanics of continua (even if conceived in a non-*pointilliste* way) leads out into these other fields of physics in so open-ended a way as to raise many questions of ontology, or more generally, of interpretation.

Obviously I cannot go into detail: it must suffice to make one basic point. Energy's role as a grand unifying concept in physics (as discovered in the nineteenth century) means that the classical mechanics of continua needs to be unified with thermodynamics: how else could we understand rigorously such phenomena as the expansion of a (classical!) tarmac road in the heat of the day? For a glimpse of such a unified theory, cf. Truesdell (1991, pp. 79-83, and references therein). But we can hardly stop there. Since the sunlight heats the road, we are led to optics; and thermodynamics leads us to statistical mechanics and the atomic constitution of matter. And so it goes: it would be a brave, nay a foolhardy, person who claimed to descry hereabouts a consistent and unproblematic ontology even for classical mechanics, let alone for all of classical physics.

(2): *From classical physics to relativity and the quantum*
Not only does classical mechanics lead out into the unsurveyably vast landscape of classical physics. Also, that landscape has—as Lord Kelvin famously put it in 1900—clouds on the horizon. Kelvin was in fact referring to the failures of the equipartition theorem in statistical mechanics, and of attempts to detect the motion of the earth through the ether: failures which in due course led to quantum theory, and relativity theory, respectively. But what matters for us is the general point: that classical physics' description of the microscopic structure of matter, and of matter's interaction with

the electromagnetic field, turns out to be embroiled in paradox. This means that the would-be ontologist of classical mechanics faces, not just the problem of open-endedness discussed under (1), but an in-principle difficulty—of paradox. In short, classical mechanics, together with the rest of classical physics, turns out to be a house built on sand.

We know now that it is quantum sand—and that it somehow keeps the house up. But it remains pretty darned mysterious how it does so. By this I do not just mean that the interpretation of quantum theory (especially the resolution of its measurement problem) remains mysterious. Also, some aspects of how "the house manages to stay up" are current research projects in theoretical, not foundational, physics. One obvious example is the physics of decoherence; which also, all agree, will play an important role in solving the measurement problem. But I postpone this example till Section 8, where it will be important in replying to the RDA.

Another example, closely related to the paradoxes of classical physics' description of matter's interaction with the electromagnetic field, is the stability of matter. Classically, atoms would be unstable, since the orbiting electrons would radiate, lose energy and so tumble down to the nucleus. But quantum theory promises to secure stable atoms. The main idea here is the Pauli exclusion principle: it prevents an atom's electrons all tumbling down to be together in the atom's lowest electronic energy levels; (and similarly the principle prevents a cascade down nuclear energy levels). But the details are very complicated; and though they have been attacked successfully, especially in work from the 1960s, they remain an active research area (Levy-Leblond (1995), Lieb (1997)).

(3): *An illustration: self-interaction*

Even apart from atoms, there are paradoxes about the interaction of a classical charged particle with the electromagnetic field. These paradoxes will illustrate (2). They also illustrate the spectrum from conceptual analysis to technical physics, with which I began this Section. For they show that any philosophical theory of persistence (whether endurantist or perdurantist), even one that considered only the apparently straightforward case of point-particles, is liable to get led along this spectrum, even as far as relativity theory and quantum theory. (*A fortiori*, there is good reason to think technical physics is relevant to the more complex case of continua, considered by the RDA.)

The paradoxes arise as soon as we accept that the electromagnetic field carries energy, and that energy is conserved. Here it must suffice to sketch the main idea; there is not space for a proper discussion.[8] Classical electrodynamics says that an accelerating charge emits radiation, and thereby energy; and the conservation of energy then requires that it slow down. If the charge were a point-particle and was the only particle in the universe, the only force present that could cause it to slow down is that

[8]Rohrlich (2000) is a philosophically and historically oriented entry into this large subject. It also covers treatments of charged particles as extended rather than point-like; indeed Lorentz's original statement (1892) of the Lorentz force law assumed an extended charge.

derived from its own electromagnetic field. So it seems that we must take a classical charged point-particle to "feel" its own field, even though in ordinary calculations we do not do so—e.g. in applying the Lorentz force formula $\mathbf{F} = e(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$ we ignore the charge's (infinite!) contribution to $\mathbf{E}$.

This predicament suggests two possible strategies.

(i): To try to formulate a consistent interaction of a charge with its own field which will both (a) give some sensible result for the solitary accelerating charge, and (b) vindicate as approximately correct our usual calculational practice of ignoring each charge's self-interaction. (We need both (a) and (b) since the point-particle can hardly "know" whether it is lonely or not.)

(ii): To revise classical electrodynamics so as to avoid the solitary-charge argument for a self-interaction; e.g. by postulating that energy is radiated only if, later on, something will absorb it.

Each of these strategies has had very distinguished proponents: from Lorentz and Dirac, for (i), to Feynman and Wheeler, for (ii). But the details of their work, and that of others, do not matter here. Anyway, a proper discussion of how to reply to these paradoxes must nowadays include quantum theory's description of matter (and specifically topics like renormalization in quantum electrodynamics): which lies far beyond this paper's scope. Here it is enough to have shown that the concept of a point-particle, which at first seems part of "educated common sense", is in fact problematic: as we saw in Section 2.1, point-particles with action-at-a-distance are problematic, and now we see that problems remain when we combine point-particles with the concept of a field.

2.3 Prospectus

In this Section, I have argued: that classical mechanics is both more subtle, and more problematic, than philosophers generally recognize (Section 2.1); and that in addressing its problems, one is led to the rest of classical physics, and even to relativity theory and quantum theory—though it is still unclear, in various ways, how the everyday macroscopic world "emerges" from the relativistic quantum realm (Section 2.2). I can now describe how these views yield my main claims about the RDA.

My overall position is that the perdurantist can rebut the RDA; but physics also shows how the RDA can be formulated more strongly than it has been. More specifically, I will argue for three main conclusions. The first two are in Section 5, which focusses on the details of physics' description of rotation, especially for continuous matter. (Quantum theory is set aside until Section 8.) The first conclusion is that the RDA can be formulated more strongly than is usually recognized. For it is not necessary to "imagine away" the dynamical effects of rotation (e.g. the tendency of a spinning sphere to be oblate), as advocates of the RDA usually do; (Section 5.5). The second conclusion is that in general relativity, the RDA (even in its stronger formulation) fails, because an (amazing but well-established) physical effect called 'frame-dragging' implies that there are differences between rotation and non-rotation which the perdurantist can appeal to (Section 5.6).[9]

The third conclusion is in Section 6 onwards. It is that even setting aside general relativity, the strong formulation of the RDA can after all be defeated. I argue that the subtleties and problems of classical mechanics (including the way it "emerges" from quantum theory) mean the perdurantist can take objects in classical mechanics (whether point-particles or continuous bodies) to have only temporally extended, i.e. non-instantaneous, temporal parts (stages): which blocks the RDA.

I stress that I will *not* claim that considerations of physics show perdurantism superior to endurantism; though, as I will discuss in Section 5.4, endurantism and perdurantism have traditionally been associated with conceptions of metaphysics as *a priori* conceptual analysis, and as *a posteriori* theory-construction, respectively. I do not even claim this, when one considers quantum theory's description of atomic particles as "wave-like" and evanescent. My reason is that (as I said in Section 2.2) it remains mysterious how the macroscopic world, with its persisting objects "emerges" from the quantum realm—despite impressive recent progress in understanding the physics of decoherence (Section 8). This mystery means that it is, at least *today*, impossible for anyone to state precisely what is the "supervenience basis" for macroscopic objects' persistence. In short, the jury is still out, scientifically as well as philosophically. The most we can now claim is that the RDA fails, and that perdurantism is, so far, tenable.

I will prepare the ground for these three conclusions, by first discussing: (i) the RDA in more detail (Section 3); (ii) some metaphysicians' replies to it (Section 4). Besides: though Sections 3 and 4 are written from the perspective of the philosophy of physics, they will exclude technical physics, especially relativity and quantum theory. (Indeed, so will Sections 5 onwards, to a large extent.)

More specifically, nothing in Sections 3 and 4 contradicts the metaphysicians' prevalent assumption which I labelled (*Bracket*): that classical mechanics, or perhaps instead the whole of classical physics, provides a supervenience basis for persistence. (But of course, nothing I say depends on this assumption, which I reject.) To that extent, these two Sections should be of interest to friends of that assumption. In effect, these Sections report some of the themes and arguments of the RDA literature, from the perspective of the philosophy of physics. So it is only in Sections 5 onwards that the claims of Sections 2.1 and 2.2 come to the fore: in Section 5, I will "re-admit" relativity theory; and in Section 8, I re-admit quantum theory.

Finally, by way of prospectus: it may help to announce what my answers will be to the following questions about rotation and continuous matter, which are obviously

[9] These two conclusions are not original to me. (1): The strengthened formulation of the RDA is due to Paul Mainwood and David Wallace, in an Oxford seminar, autumn 2003; and is hinted at by Zimmerman (1998, p. 268-269). (2): Callender (2001, p. 38) mentions frame-dragging as one of many differences between rotation and non-rotation the perdurantist can appeal to. So to all four, my thanks: my only contribution is to set these conclusions in a broader landscape than did their originators.

relevant to evaluating the RDA. As to rotation, one naturally asks:

(1) How exactly does physics, or more specifically a given physical theory, describe rotation?

(2) Do endurantist and perdurantist have equal rights to that description?

(3) Does that description supply some differences between rotation and non-rotation which the endurantist's RDA has ignored, but which the the perdurantist can appeal to? Or does it strengthen the RDA?

And about continuous matter, one naturally asks:

(4) Must a theory of persistence allow that continuous matter is possible, and so address the RDA's distinction between the two discs? Or could it legitimately set aside continuous matter, and so duck out of discussing the RDA? (As we have seen: the metaphysical literature says Yes to the first question; and tends to explicitly set aside atomism and especially quantum theory.)

My answers to these questions will be broadly as follows.

(1): I will report in Section 5 how physics describes rotation, including some peculiarities of rotation in our best theory of space and time, viz. general relativity.

(2) I will allow in Section 5.4 that endurantist and perdurantist have equal rights to this description; though this is largely for the tactical reason of giving the RDA as good a run as possible.

(3) This description has both a positive and a negative implication for the RDA. The positive implication is that the RDA can be formulated more strongly than is usually recognized; (my first conclusion, Section 5.5). But within general relativity, the RDA fails: frame-dragging implies that there are differences between rotation and non-rotation which the perdurantist can appeal to; (my second conclusion, Section 5.6).

(4) Though I maintain that classical continua are subtler and more problematic than usually recognized, I agree that they are indeed logically possible. And I therefore agree that a philosophical theory of persistence should if possible allow for continuous matter, and so not duck out of discussing the RDA. But as stressed, I will go on to maintain (Section 6 onwards) that in fact a perdurantist theory can reply to the RDA, by endorsing its distinction between the discs.

3 The RDA and kinds of reply—in detail

In this Section, I first present the RDA more fully than in Section 1.1; (Sections 3.1 and 3.2). Then I consider what the RDA implies for endurantism (Section 3.3). Finally, in Section 3.4, I distinguish the two kinds of perdurantist reply to it, more fully than in Section 1.5.

3.1 The argument: keeping track of homogeneous matter

Here are two distinct possibilities for a perfectly circular disc made of homogeneous matter: where 'homogeneous' means that the properties of the matter do not vary across space even on the smallest length scales:

(Stat): that it is stationary, and in particular not rotating about an axis perpendicular to the plane of the disc; (of course this possibility can be subdivided as regards the disc's size, and the properties of its matter, e.g. its mass-density):

(Rot): that it rotates about this axis; (of course this possibility can be further subdivided, apart from the subdivisions in (Stat), viz. as regards the angular velocity of the disc.)

It seems that the endurantist can easily recognize and describe the two possibilities, according to whether the very same non-circularly-symmetric part, e.g. a segment, is in the same place at two times. But I postpone considering the endurantist until Section 3.3. For the moment, consider the perdurantist. It seems she has a problem: surely she must say that all the relations (and therefore, all her proffered "suitable relations" for analysing, or at least subvening, persistence) between two stages (temporal parts) of the disc, say at noon and 12.01, are the same—whether the disc is rotating or not? And similarly for stages at the two times of any spatial part of the disc, such as a segment: surely perdurantism must say that all the relations are the same?

More precisely: the phrase 'any spatial part of the disc, such as a segment' seems to presuppose persistence—which is precisely in question here. So a better way to put the second rhetorical question is to say: Similarly for any spatial part of the disc-at-noon, such as a segment, and *any* congruent subvolume of the disc-at-12.01: surely the perdurantist must say that all the relations are the same, whichever of the many congruent subvolumes of the disc-at-12.01 are chosen?

In the sequel, it will sometimes be useful to have mnemonic labels for the temporal parts being compared. So let me express perdurantism's apparent problem by using some memorably ugly labels, as follows. For *any* four choices of spatially congruent temporal parts of the discs:

a spatial segment of the stationary disc at noon, call it StatNoon;
a congruent spatial segment of the stationary disc at 12:01, call it StatMin;
a congruent spatial segment of the rotating disc at noon, call it RotNoon;
a congruent spatial segment of the rotating disc at 12:01, call it RotMin;

StatNoon and RotNoon match in their properties; as do StatMin and RotMin; and StatNoon bears to StatMin exactly the same relations as RotNoon does to RotMin.

I have phrased this argument so as to allow:

(i) the properties of spatial parts of the discs to vary, provided they vary in a circularly symmetric way, e.g. by each disc being decorated with circles of colour, centred on the centre of the disc;

(ii) the discs' properties to change over time, provided that the two discs always match, e.g. the discs could have a temperature, even a circularly symmetric distribution of tempearture, and could cool down, provided temperatures always match.

3.2 Why continuous and homogeneous matter?

Let us first ask: Why does the RDA use a disc composed of continuous and homogeneous, rather than atomistic, matter? Most of the philosophical discussions do not say why. But the implicit answer is:

> Because if the disc is atomistic (i.e. a swarm of point-particles), the set of spatial points occupied by matter varies over time, or stays constant, according as the disc rotates or not; so that the perdurantist can distinguish rotation from non-rotation by "following" which spatial points are occupied by matter at which times. Similarly, if the disc's matter is continuous but inhomogeneous, the perdurantist can distinguish the cases by following lines of qualitative similarity. But for continuous homogeneous matter, the perdurantist is stuck: she cannot distinguish the cases.

This answer raises three issues. The first is straightforward, independent of the distinction between the discs, and is largely a matter of setting some matters aside. The second and third are important for us, and will need more attention later on.

3.2.1 Tracking matter

The idea of the answer is twofold. First, the answer concedes that the perdurantist can provide an account of persistence (in other jargon: a diachronic criterion of identity) for a point-particle in a void. The criterion is just to follow the continuous curve of the presence of mass (or perhaps of charge; or more generally, of qualitative similarity). The ambient void means that starting from a point-particle at a time, there is a unique way to go forward or backward in time. Similarly for a point-particle moving, not in a void, but in a continuous fluid with suitably different properties—a different "colour", or made of different "stuff", than the point-particle; (cf. the discussion of *Follow* in Section 1.1).

But second: in continuous matter, there is no void—the lines of matter-occupation run "every which way". And it seems that if the matter is also homogeneous, then even the lines of qualitative similarity, however they are exactly defined, run every which way—leading to the argument's challenge to the perdurantist.

This second point will of course preoccupy us in what follows. Here I just make three ancillary remarks about the first point. Though straightforward, they have the merit of showing the scope of the sort of criterion that says "follow the lines of matter-occupation or qualitative similarity". (Recall also from footnote 2 in Section 1.1 that this sort of criterion can be disputed; but that dispute is not directly relevant to the RDA, and I set it aside.)

(i): This sort of criterion will also work for extended objects moving through a void, or through a suitably different continuous fluid—provided it is understood as applying only to such an object as a (spatial) whole. For of course, applying it to the spatial parts of an extended object (e.g. parts of a rigid homogeneous sphere) just resets, on a smaller scale, the problem first posed by the RDA. (So I agree that the perdurantist who considers extended objects will have to add to this sort of criterion some account of the objects' parts.)

(ii): This sort of criterion even works for a homogeneous rotating disc as a whole, if it is not *perfectly* circularly symmetric. Imagine a disc made of Lego—of *rectangular* Lego blocks: it is approximately circular, and may be treated as circular for certain purposes, e.g. if looked at from a sufficient distance, and-or if sufficiently larger than the individual blocks that the edge can be treated as smooth. Now imagine a disc of exactly the same shape, but which is homogeneous (no bricks!). Since the disc's edge is in fact rough, our "follow the lines" sort of criterion works: exactly tracking the lines of matter-occupation or qualitative similarity at the edge reveals whether or not the disc rotates. Similarly of course for all actual rotating objects: they are not perfectly circularly symmetric, and so the spatially varying qualitative features, such as a roulette wheel's numerals, suggest the correct way the "identify" spatial parts across time (i.e. to define persistence)—so that the challenge of the RDA does not arise.

(iii): On the other hand, exact homogeneity is not needed for the RDA. In my version above, I allowed the spatial properties to vary in a circularly symmetric way. If they do, the lines of qualitative similarity will have to be circularly symmetric: but the challenge to the perdurantist will remain, since there nevertheless seems to be an abundance—a continuous infinity—of such lines. How can the perdurantist specify those that define persistence?

3.2.2 The persistence of spatial points

The second issue is that the answer above glosses the distinction between rotation and non-rotation intuitively. It presupposes that there are persisting spatial points, so that it can say: only in the rotating disc do the point-sized bits of matter occupy different spatial points at different times. This prompts the question: What account is to be given of the persistence of spatial points? This question is very important to evaluating the RDA, but is almost entirely ignored in the metaphysical literature: even in the best discussions, authors often appeal without further analysis to the idea of 'the same place' (e.g. Hawley 2001, p. 85). This question will take centre-stage in Section 5, where I leave metaphysics for the philosophy of space and time and the physics of rotation.

3.2.3 The accompaniments of rotation—again

The third issue arises from the last sentence of the answer. That sentence is contentious: and (unlike the assumption of persisting spatial points) it *is* contested in the metaphysical literature—as I reported in Section 1.4. And as I also announced there, my own view will be that:—

(i): the RDA should not just set aside the technical accompaniments (this goes along with the importance of the technical description of rotation, just announced in Section 3.2.2);

(ii): it cannot do so just by stipulating perfect rigidity; and

(iii): the perdurantist can reply to the RDA without resorting to distinctively metaphysical proposals such as immanent causation, or special vectorial properties. (I shall also join some perdurantists such as Sider in accepting appeal to everyday causes, effects and counterfactuals. I discuss Sider's position in Section 4.4; and develop an analogue of his position in Section 6.2.)

So, to sum up this presentation of the RDA:— Its strategy is clear. It needs to "imagine away" enough of the usual accompaniments of rotation (and-or non-rotation) to make it plausible that the perdurantist (or Humean) has trouble making distinquishing the discs. This Subsection has developed the first main example of this strategy: the RDA imagines a perfectly circular and perfectly rigid disc, made of continuous and perfectly homogeneous matter; thereby aiming to block the perdurantist from "tracking" matter through the void, or "following" lines of qualitative similarity.

3.3 Tu quoque?

So far as I know, the RDA literature never considers whether the rotating discs harbour any problems or projects for the endurantist (or more generally, non-Humean). I think this is a mistake. Surely the endurantist owes us a discussion of diachronic criteria of identity for the spatial parts of a piece of homogeneous matter, such as the disc: a discussion that will secure the distinction. Of course, it is not my brief here to develop endurantism. But as a preliminary to considering perdurantist replies to the RDA, it is worth discussing the factors that combine to make us forget that the endurantist owes us such a discussion.

First, we easily slip into relying on intuitive judgments of sameness of place. But as we saw in Section 3.2.2, it is not enough for the endurantist to say just that the difference between the possibilities is a matter of whether the worldlines of the enduring pieces of matter are straight or helical. The intuitive contrast "straight vs. helical" depends on the idea of persisting spatial points. The endurantist owes us an account of this idea, just as much as the perdurantist does. Either this idea must be vindicated, or some other (maybe more technical) notions that describe rigorously the distinction between rotation and non-rotation must be invoked and justified. This is an endeavour which leads into issues in the philosophy of space and time, and the physics of rotation. I will discuss these issues in Section 5. In fact, I will there allow that as regards these issues, the honours are even, or roughly even, between the endurantist and perdurantist. That is, I will allow that both sides have equal right to the notion of persisting spatial points, or to whatever notions are needed to describe rigorously the rotation/non-rotation distinction. I say 'allow', because my reason will be that since I want to give endurantism and the RDA as good a run as possible, I give them the benefit of the doubt about their rights to these notions.

On that assumption, it is tempting to think, as the discussion in Section 3.1 implicitly did, that only the perdurantist "has work to do". More precisely: it is tempting to think that:

(i): the perdurantist needs to say what, in terms of qualitative similarity or causation or whatever, distinguishes the correct worldlines from all the other spacetime worms (mereological fusions of stages) they accept as objects;[10] while

(ii): the endurantist can take the distinction between the correct and incorrect worldlines (straight vs. helical) as "bedrock": no more can be said, and besides, no more needs to be said.

I think this temptation arises from a widespread belief that only for the endurantist does a persisting object remain self-identical over time. This belief leads to the idea that—at least for the spatial parts of a piece of homogeneous matter—diachronic criteria of identity are unnecessary, or even unintelligible: i.e. the idea that the identity over time of such parts is just "good old identity", and is both unanalysable, and in no need of analysis—it is as clear as crystal!

But this belief is *false*. Sider (2001, p. 54-55) exposes the error: also for the perdurantist, the persisting object is genuinely self-identical over time. (Sider seems to forget this insight on p. 226, para 2, when he endorses assumption (i) above, i.e. says the endurantist has an 'easy answer' about how to distinguish the discs.)

So I think a good case can be made that the endurantist also has work to do (even after persisting spatial points, or whichever notions are used to describe the rotation/non-rotation distinction, are in play). I agree that it is unclear exactly what sort of account of matter's identity over time, the endurantist is to give. But in what follows, I shall not go further into this: developing endurantism is not my brief. Suffice it to make three remarks:

(i): I think part of the reason for the obscurity is that it is unclear exactly how to formulate endurantism (Sider 2001, p. 63-68).

(ii): Some endurantists agree that some such account is needed. For example, Zimmerman, after developing a detailed account of immanent causation for the perdurantist (1997, p. 449-456), argues that the endurantist should accept some parts of it; (roughly speaking, for histories of enduring objects: p. 456-459). For more on immanent causation, cf. Section 4.1.

(iii): I think endurantists are likely to see what perdurantists say in order to distinguish the discs as so complex, as to amount to a serious disadvantage for perdurantism. In particular, they are likely to accuse Sider's position (and mine) of this. My response will be, in effect, that endurantists will themselves need them to *say*

[10]How difficult this is, how much work there is to do, will of course depend on their other views. In particular, perdurantists who are Humean about causation, like Lewis, will presumably have more work to do, in distinguishing the discs, than perdurantists who are not, like Armstrong; cf Section 4.1.

much of what the perdurantist says: though for them it may well be collateral information about the distinction between the discs, rather than (as for the perdurantist) "constitutive" of the distinction.

3.4 Kinds of reply

In this last Subsection, I will develop Section 1.5's two kinds of reply to the RDA. This will also bring out a complaint implicit in Section 3.2.2's question about the account of space and rotation. Namely, that as Callender (2001, p.30) puts it: 'analysing RDA is frustrating because the possible worlds described are left so vague'.

A preliminary remark. I admit that my distinction is not exhaustive: there are other possible replies. In particular, Teller (2002, p. 207-208) gives a reply which, though at a glance similar to my first kind, is much more radical. He suggests the perdurantist, or at least the advocate of Humean supervenience, should say that even for a inhomogeneous disc like a roulette wheel, there is nothing objectively right about defining persistence in terms of "tracking" spatially varying qualitative features such as one of the wheel's numerals. Teller agrees that the perdurantist can and should accept that:

(i) it is convenient to "identify" parts across time (i.e. to define persistence) on the basis of such features; and

(ii) this is convenient because of its association with what Teller calls 'rotational phenomena': i.e. what I called 'accompaniments of rotation', e.g. having been pushed by someone, and the tendency of rotating solid objects to become oblate.

But, according to Teller, perdurantists should not accept that any disc, even an inhomogeneous one, ever has any 'literal rotation ... for them there is only rotation by courtesy' (p. 208). (So though the perdurantist might call being pushed, oblateness etc. 'rotational phenomena', she should not call them, as we normally do, 'typical causes and effects of rotation': for that suggests there is literal rotation.)

Teller's reply certainly blocks the RDA: but, by my lights, at *far* too high a price. Its denial that there are any facts of persistence in the countless unproblematic cases (e.g. of inhomogeneous discs), facts which perdurantism must accept, amounts to a sort of nihilism about persistence—which I find incredible: but I will not argue against it here.[11]

Though my distinction between replies is not exhaustive, it is natural. We saw in Section 3.2 that the strategy of the RDA is to imagine away enough of the usual accompaniments of rotation to make it plausible that the perdurantist (or Humean) has trouble distinguishing the discs. So in reply, the perdurantist and Humean can either

(i) say there is no difference: too much has been imagined away for there to be a

[11]Note that it is much more radical than both the non-reductive perdurantism mentioned in (1) of Section 1.3, and the (No Difference) reply discussed below. Both these positions accept the facts of persistence in the countless unproblematic cases.

difference remaining; or

(ii) say that in fact, they have the wherewithal to describe the difference.

These are my two kinds of reply, which I label '(No Difference)' and '(Appealing Differences)'. Of course, a perdurantist can in a sense combine them. For in the back-and-forth of debate, she might move from one reply to the other: 'well, if you imagine away *all of those* accompaniments of rotation, I will then reply that there is after all no difference'. I turn to stating the two replies in more detail.

(No Difference): There is no good reason to distinguish the possibilities (Stat) and (Rot). More precisely: though there is of course a distinction between rotating and non-rotating discs, a distinction manifested in various differences between the discs—recall the usual accompaniments of rotation—the RDA needs to assume that *its* discs, in the possibilities (Stat) and (Rot), do not manifest *any* of these differences. And *then* there is no reason to distinguish the discs.

Note that this reply does *not* need the differences to in some sense "ground" the rotation/non-rotation distinction. It is enough that the differences exist, and so could be mentioned in the perdurantist's prospective definition of persistence in such a way that the definition yields for each disc its correct (straight or helical) lines of persistence/worldlines. That is: this is enough, as regards replying to the RDA. Of course, knowing these differences does not by itself tell us how to frame the definition.

Similar remarks apply, when the RDA's target is not perdurantism, but some other neoHumean doctrine such as Lewis' Humean supervenience (1986, p. ix-x; 1994, p. 474). I will discuss this in more detail in Section 4.3. Here I only note that also with this target, the RDA needs to imagine away any differences between the discs to which the neoHumean could appeal.

So far as I know, Callender (2001) is the main example of this reply; (he focusses on Humean supervenience, rather than perdurantism, but he also uses the label 'no-difference'). Lewis also gives essentially the (No Difference) reply, again taking the RDA to have as its target Humean supervenience not just perdurantism (1986, p.xiii, 1994, p. 475). But he later changed his mind, endorsing a proposal of Robinson (1989). And since I want to discuss that proposal only after discussing velocities, I shall postpone Lewis' views, and the comparison of Lewis with Callender, till then (Section 4.3).

For the moment, I just bring out the flavour of the (No Difference) reply by reporting Callender's analogy between the discs and the up/down distinction. He says the distinction between (Stat) and (Rot) is as spurious as the distinction between

(Up): an arrow in an otherwise empty world pointing up; and

(Down): an arrow in an otherwise empty world pointing down:

which all agree to be a distinction without a difference, since there is no up/down distinction except with reference to some other direction, in particular the direction of the local gravitational force. (At least: nowadays, if not in Aristotle's day, all agree to this.)

Callender makes the analogy between the disc-worlds and the arrow-worlds closer, by:

(i): imagining the discs to be each alone in its world; and

(ii) saying 'Assuming Newtonian spacetime with its absolute standard of rest is not crucial to the argument, a harmless change of coordinates will change our case [viz.: one disc rotating, the other not] into one with one disc rotating clockwise, and the other rotating counter-clockwise [i.e. with equal speeds]' (p. 32).

So: since the clockwise/counter-clockwise distinction depends on a choice of direction (a clock-dial moves counter-clockwise when seen from behind!), this really is a distinction without a difference, just like (Up) vs. (Down).

(Appealing Differences): According to this kind of reply, the perdurantist (or Humean) *can* distinguish the possibilities. That is: even supposing that the RDA stipulates that its discs do not manifest the *usual* differences between rotation and non-rotation—so that the argument seems to get a grip—there are differences the perdurantist (or neoHumean) will find acceptable—even appealing!—and can appeal to. In short: there are more things in the (perdurantist or Humean) heaven and earth than are dreamt of by the RDA's advocates.

This reply is much more common than (No Difference). Indeed, so far as I know, Hawley (1999, p. 55-56; 2001, p. 74-76) is the only author, apart from Callender and Lewis, who considers the (No Difference) reply at any length: (but she believes it defective, and advocates a version of (Appealing Differences)).

I think the reason (Appealing Differences) is more common lies in the facts noted in Section 1.4. Namely:

(i): The metaphysical literature concentrates on the everyday, not technical physical, accompaniments of rotation. And:

(ii): The usual everyday differences that the RDA stipulates to be absent involve present and "occurrent" accompaniments of rotation, such as a roulette wheel's numeral, or a spot of paint, moving relative to the disc's environment.

(iii): This leads the metaphysical literature to focus on whether the perdurantist can legitimately appeal to:

(a): differences in past or future or counterfactual everyday accompaniments of rotation; such as having been pushed in the past; or that if a spot of paint were sprayed on the disc, it would move; and-or

(b): differences that are distinctively metaphysical (neither everyday nor technical physical), such as a special relation of immanent causation, or special vectorial properties that are numerically equal to, yet different from, velocities.

(iv): The issues raised in (a) and (b) are familiar to metaphysicians.

In the next Section, I shall discuss various examples of this reply. But by no means all. I shall concentrate on distinctively metaphysical differences, i.e. (iii) (b). But even there I will omit some views, e.g. Hawley's proposal there are relations between temporal parts that are not supervenient on the intrinsic natures of the parts that are the relata, and yet are not just spatiotemporal relations (the paradigm case of such non-supervenient relations: 1999, p. 60, 63-66; 2001, p. 85-90).

4 Some metaphysical replies

In this Section, I give a survey of some metaphysicians' replies to the RDA, emphasising points that will be important later on (or that I think important in themselves!). For the most part, these replies are examples of (Appealing Differences). I begin with two such examples: appealing to causation (Section 4.1), and appealing to velocities (Section 4.2). I reject the first, but am more sympathetic to the second. This leads me to consider a third example of (Appealing Differences): Lewis' and Robinson's appeal to a quantity analogous to (but different from!) velocity; and Zimmerman's reply to that proposal (Section 4.3). Finally (Section 4.4), I discuss Sider's reply, which combines (Appealing Differences) and (No Difference). I discuss Sider in some detail, since his reply is in effect my "fallback position": if my own reply failed, I would endorse an analogue of his (Section 6.2).

Much of this Section involves the distinction between intrinsic and extrinsic properties—a distinction which I have so far just mentioned. Though intuitively compelling, this distinction is controversial, and in particular hard to analyse. By and large, I will not need contentious claims about it. But I will argue (in Section 4.2.2.C) that to assess the RDA, it is worth distinguishing (though the literature has not done so):

(i): degrees of extrinsicality;

(ii): whether predicating an extrinsic property has implications for other times, or for other places (which I will call 'temporal extrinsicality' and 'spatial extrinsicality' respectively).

(It will also be obvious that proposals (i) and (ii) might also be useful for other problems in metaphysics.)

4.1 Appealing to causation

Much discussion of the RDA as an argument against perdurantism concerns the relation between persistence and causation within the persisting object. I shall note four points, in (a)-(d), and then in (e) express my scepticism about appealing to causation.

(a): *The Idea* Quite apart from the RDA, many philosophers take causation to somehow underpin persistence. For in some puzzle cases, causation seems to be what is needed for persistence: instead of, or in addition to, qualitative similarity. A simple oft-cited example is the imaginary case in which a god destroys an object and immediately replaces it with a qualitative replica: it seems that what is missing in such a case of non-persistence are causal relations between the (states of the) destroyed object and the replica. Some philosophers call such causal relations (perhaps together with special doctrines claimed about them) 'immanent causation". (For details and references, cf. the discussion of Armstrong after (d) below, and e.g. Zimmerman (1997, p. 435-437).)

(b): *An obvious reply?* If so, the obvious reply to RDA is to appeal to whether or not there is (an appropriate sort of) causation between the given stages of spatial parts of the disc. Using the ugly labels of Section 3.1: only if StatMin is chosen so as to comprise the same matter as does StatNoon will there be (the appropriate sort of) causation between them; and similarly for RotMin and RotNoon. In short: the obvious reply is to deny the RDA's claim that for *any* choices of the four stages, StatNoon bears to StatMin exactly the same relations as RotNoon does to RotMin: the causal relations *are* sensitive to the choices.

But this reply is "a bit quick", for two reasons. That is: there are two problems about appealing to causation to subvene, or even yield an analysis of, persistence. The first problem, in (c), is much more often discussed, and so presumably thought more important; but I shall later develop ideas from the second problem, presented in (d).

(c): *Trouble for Humeans* Some perdurantists want to endorse some broadly Humean account of causation. (Indeed, for some, Humeanism is a leading motivation for their perdurantism.) For such perdurantists, the RDA still threatens. For surely, once we restrict attention to properties and relations that are intrinsic (or "qualitative", or "occurrent"—or whatever the Humean regards as characterizing their supervenience basis for causation and so persistence), the properties and relations within the two pairs, {StatNoon,StatMin} and {RotNoon,RotMin}, do match for *any* choices of the four stages—as the RDA alleged. So for a Humean, the causal relations should also match: so the RDA seems to show that perdurantism is incompatible with a broadly Humean account of causation. (For a fuller exposition, cf. Zimmerman's discussion of 'Humean supervenience of the Causal Relation' (called '(HS)'); 1998, p. 271.)

(d): *Causation and motion* The second problem is a threat of circularity, arising from connections between the notions of causation and motion. As Shoemaker (1979, p. 328) puts it: 'it seems very unlikely that we can specify the relevant causal relationships without invoking the notion of motion and with it the notion of cross-temporal identity (i.e. persistence) ... which we are trying to analyse.'

But (as Shoemaker goes on (p. 329-330) to describe) there seems to be a way in which this *can* be done. Namely, one adopts the following two-stage procedure.

(i): One can apply the concept of motion—and its associated quantitative concepts like average and instantaneous velocity or acceleration etc.—to an arbitrary spatiotemporally continuous series of momentary stages.

(ii): Only then does one appeal to causation to underpin persistence. That is: One now assumes that the worldlines or worldtubes of persisting objects are distinguished by the stages of each of them having (maybe: the ancestral of) some suitable relaton of causation (maybe of immanent causation)).

Shoemaker's two-stage procedure is rarely discussed; but (so far as I know) is endorsed by those who do discuss it; for example, Zimmerman (1998, p. 279-280). But Zimmerman goes on to emphasise the first problem, (c) above. That is, in the context of the RDA, with its two pairs of spatial parts of discs, one pair causally related and the other not: the appeal in stage (ii) to causal relations surely requires non-Humeanism about causation.

I myself agree that Shoemaker's stage (i) works. One can certainly apply the concept of motion and its associated quantitative concepts, as made precise by differential geometry, to:

(a) any worldline, or to a foliated worldtube (in the latter case, one would assign the velocity and acceleration vector to, say, the centroid of each of the foliation's leaves); and even to

(b) spacelike curves and tubes (though for these cases, one might resist using the usual language of motion, e.g. calling the tangent vector of a spacelike curve a 'velocity').

Indeed, textbooks of modern spacetime theories contain countless examples of (a) and (b). Agreed, the notions of velocity, acceleration etc., as usually understood, presuppose the notion of persistence; (as I conceded in Section 1.2 and will discuss in Section 4.2). But Shoemaker's procedure does *not* conflict with that understanding. His stage (i) applies such notions, stripped of that presupposition; (how this works will become clearer in Section 4.2.2.C). Then, after stage (ii), notions like the instantaneous velocity of spatial parts of the discs are to be reinstated, "piggy-backing" on the relation of causation. That is: the notions as usually understood are applied just to the worldlines or worldtubes that stage (ii), i.e. causation, picks out.

But on the other hand, turning to Shoemaker's stage (ii): I fear that it may fail, because causation might presuppose persistence in a different way than that Shoemaker alerts us to, i.e. in a way independent of the notion of motion—details below.

(e): *Armstrong, Lewis and a warning* The issues raised in (a)-(d), especially (a)-(c), are illustrated in many perdurantists' discussions of the RDA, e.g. Armstrong's and Lewis'. Armstrong is not a Humean about causation and so endorses the reply in (b): he believes the perdurantist can and should reply to the RDA by appealing to causal relations between stages, and spatial parts of stages (1980, 1997, pp.73-74). More precisely: he thinks that, quite apart from the RDA, the perdurantist should take persistence—the "suitable relations" between stages of a persisting object—to be a matter of what (following Broad and W.E. Johnson) he calls 'immanent causation': 'a form of causality which remains confined to a single particular and that, further, does not proceed by interaction between sub-particulars' and which involves 'the actual *bringing into existence* of later by earlier temporal parts' (1997, pp.73-74). So for Armstrong, the moral of the RDA is simply that immanent causation does *not* supervene on the intrinsic natures of the relata: a conclusion which, as a non-Humean about causation in general, Armstrong is happy to endorse.[12]

On the other hand, Lewis is a Humean about causation. (More precisely: he defends a counterfactual analysis of causation, which makes the truth-values of counterfactuals, and so of causal statements, supervene on the qualitative nature of the world (1979, 1986a, p.22).) But he also agrees with (a) above that causation is crucial to understanding persistence: as he says in his last discussion of the RDA: 'the most important sort of glue that unites the successive stages of a persisting thing is causal glue' (Lewis 1999, p. 210). So Lewis cannot endorse the reply in (b) above, and has to reply to the RDA in another way; cf. Section 4.3.

[12]So far as I know, the fullest account of immanent causation is Zimmerman (1997), which builds on his (1995).

But I myself am wary about appealing to causation to solve a metaphysical problem, since, like many philosophers of science, I think the notion is too problematic to be relied on. (Recent discussion of its problems include Hitchcock 2003, Norton 2003.) More specifically, analytic metaphysicians should take heed when their doctrines, e.g. about persistence, carry contentious commitments about causation. For example: Dowe (2000) argues for a process theory of causation which explicitly assumes the notion of a persisting object. So a metaphysician who appeals to causation to analyse or at least subvene persistence is commited to Dowe's theory being wrong: not a commitment to be entered into lightly! (This warning is not a universal accusation: some metaphysicians are admirably explicit about their commitments about causation; for example Zimmerman (1997, p. 444-449, 464-465).)

4.2 Appealing to velocities

On first meeting the RDA, most people's response is that since the two discs differ in their instantaneous angular velocity (similarly: corresponding spatial parts of them differ in instantaneous velocity), the perdurantist should reply to the argument by attributing instantaneous angular velocity to the stages (or similarly: instantaneous velocity to spatial parts of stages).

But as I said in Section 1.2, there is a consensus in the RDA literature against this tactic. The consensus urges that the notion of velocity presupposes the notion of persistence, so that appealing to velocity brings circularity; and that this is so, both for the usually notion of velocity, and a heterodox notion advocated by Tooley and others.

I shall first report this consensus (Section 4.2.1); and then present three replies to it, in ascending order of importance (Section 4.2.2). The second and third replies will foreshadow Sider's and my own replies to the RDA. And the third reply will develop my denial of *pointillisme* (announced in Section 2.1).

4.2.1 The consensus against velocities

The consensus against appealing to velocities relates to metaphysics rather than technicalities of physics. It uses only "naive" notions of average and instantaneous velocity, thereby implicitly assuming a space of persisting spatial points. So as I did in Section 3.3, I will postpone till Section 5 the question how to describe rigorously the distinction between rotation and non-rotation: whether by invoking a space of persisting spatial points, or by invoking some other notions.

The first, and main, point of the consensus is that if velocity is understood, as usual, in terms of spatial separations of the places occupied at different times by one and the same object, then the notion of velocity *assumes* the idea of persistence. (This goes with the so-called 'Russellian theory of motion', also called the 'at-at theory of motion'.) This is obvious for the elementary definition of average velocity as the quotient of distance traversed and time elapsed. And the notion of instantaneous velocity is usually understood "just" as a limit of such quotients, so that it also assumes the idea of persistence.

Many authors make this point, taking it to show: either that

(i) it would be circular for the perdurantist to reply to the RDA by appealing to velocity; or

(ii) velocity is not an intrinsic property of an object at a time, or of a temporal part; or

(iii) both (i) and (ii).

For example, cf. Shoemaker (1979, p.327), Zimmerman (1998, p.268), Sider (2001, p. 34) and Hawley (2001, p. 77-79).

But perhaps velocity should not be understood as usual. Various authors have sketched a rival, heterodox account of velocity, based on the idea that velocity should be an intrinsic property of an object at a time; for example, Tooley (1988, p. 236f.), Bigelow and Pargetter (1989, especially pp. 290-294; 1990, pp. 62-82) and Arntzenius (2000: pp. 189, 197-201). These proposals seem to be mutually independent: the three later authors do not cite the previous work. But in what follows, I shall concentrate (as the RDA literature does) on Tooley; and so speak of 'Tooleyan velocities'.

Tooley denies the Russellian theory of motion on the grounds just mentioned: that it makes instantaneous velocity extrinsic to the moving object (at the time). He sketches an alternative, which aims to have velocity be an intrinsic property of the object: a property that causes and explains its position at (shortly) later times—whereas the usual notion is a "logical construction" out of the object's positions at those times (and shortly earlier ones). In developing this rival notion, Tooley's strategy is to Ramsify the accepted laws of motion: i.e. to adapt Lewis' (1970) tactic for functional definition of theoretical terms. So, roughly speaking: Tooley says that the velocity of object o at time t is that unique intrinsic property of o at t that is thus-and-thus related to other concepts, as spelled out in the usual formulas of kinematics and dynamics. It follows, in particular, that velocity is equal to the time-derivative of position, only as a matter of physical law, and not as a matter of logic or conceptual analysis.

Similarly, Bigelow and Pargetter (ibid.) propose that velocity should be an intrinsic property that causes and explains later positions: but they develop this idea in terms, not of Ramsification, but of the metaphysics of universals. Finally, Arntzenius' recent survey of three possible answers to Zeno's arrow argument takes one answer to be that the velocity of an object at an instant is an intrinsic property of it: a property that causes and explains change of position, on account of a law of nature (*not* a definition!) stating the value of velocity to be equal to the time-derivative of position (ibid.). (Both Bigelow and Pargetter, and Arntzenius, suggest their view is a descendant of medieval views, in particular impetus theory.)

At first sight, this heterodox view of velocity has an obvious merit and an obvious defect. The merit is that velocity causes and explains later position: which sounds right. The defect is that on this view it is logically, though not nomically, possible that the velocity should point in the "wrong direction". It is logically possible that an object move to the right, while all the while its velocity vector pointed to the left—which sounds wrong!

But to weigh this *pro* and *con*—and other *pros* suggested by Tooley, Bigelow and Pargetter, and *cons* suggested by Arntzenius—would take us too far afield.[13] For present purposes, I need only add to the above sketch that:

(i): In my opinion, the main motivation for this view is to secure a "*pointilliste*" interpretation of mechanics; (as these authors say or hint: e.g. Arntzenius (2000, p. 200)). But there are good reasons against such *pointillisme*; cf. Section 2.1 and my (2004).

(ii): I will return to this view, in both a positive and a negative way, when I state my favoured reply to the RDA (in Sections 7 and 8). Positively: the view will fare better in quantum theory than in the context considered by the RDA, viz. classical mechanics. But negatively: my anti-*pointillisme*, which militates against the view, provides the best reply to the RDA.

But it seems that "Tooleyan velocities" do *not* circumvent the consensus above, that velocity presupposes persistence. For the laws of motion that Tooley Ramsifies make constant use of the notion of persistence. So even though a Tooleyan velocity is an intrinsic property of the object, the *concept* of velocity urged on us by Tooley involves the notion of persistence no less than does the usual Russellian concept. Accordingly, Zimmerman (1998, p. 282-284) reiterates, for Tooleyan velocities, the consensus above; (Hawley (2001, p. 79) makes what is apparently the same point):

> ...the friends of temporal parts cannot appeal to [Tooleyan] velocities as theoretical properties implicitly defined by the laws of motion [to answer the RDA] ... [For it is] part of the definition of instantaneous velocity that it be that property of an object which is such that its possession by an object at each instant of an interval, together with its location at the beginning of an interval and the length of the interval, determines where *that very same object* will be at the end of the interval. [Zimmerman 1998, p. 282. Side-remark: Zimmerman adds a footnote which sets aside forces acting during the interval, and refers to Tooley (1988, p. 238) for discussion of so doing.]

Agreed, this consensus is no worries for Tooley. He is not concerned with the RDA, or in any way with the metaphysics of persistence: his *desideratum* for velocity is only that it should be an intrinsic property that causes and explains later positions.

As to the other advocates of heterodox velocities:—

(1): Arntzenius is also unconcerned with the debate about persistence.

(2): Bigelow and Pargetter briefly discuss the RDA, and deny the consensus above. They claim both that: (i) a portion of matter has a "non-qualitative identity"

[13] For more discussion, cf. e.g.: Zimmerman (1998, pp. 275-278) who adds some discussion of the notion of intrinsicality (277-278); Sider (2001, pp. 35, 39, 228), who cites only Tooley; and Smith (2003) who defends the orthodox account of velocity, mostly against Arntzenius.

across time; and, more directly against the consensus above, (ii) velocity, as understood by them, grounds such identities, and associated causal powers (1989, p. 297; 1990, pp. 72-74). But I shall not try to evaluate these claims, since:

(a): I shall later criticize a more developed version of claim (ii), due to Robinson and Lewis ((4) of Section 4.3.1); and

(b): being no friend of heterodox velocities, I think there are better ways than this to reply to the consensus ...

4.2.2 Against the consensus

I now present three replies to this consensus, in order of what I take to be ascending importance. The first two are objections to the verdict just given, that Tooleyan velocities are no help to a perdurantist who wants to distinguish the discs in terms of velocity. The third is more substantial, and much more important for the sequel: it develops the idea that the presupposition of persistence by velocity (understood either as usual, or *a la* Tooley) is mild and innocuous. All three replies will connect with other positions or topics in the debate—which I will return to.

4.2.2.A Functionally defining rotation? Just as Tooley specifies velocity, in Ramsey-Lewis style, by its functional-causal role, i.e. the collection of its nomological or causal accompaniments, one might claim that the perdurantist should specify rotation (and associated quantitative measures) in terms of *its* functional-causal role, i.e. the accompaniments of rotation. And one might claim that this yields an (Appealing Differences) reply to the RDA.

So the idea is to admit that Tooleyan velocity presupposes persistence: but to urge that rotation etc. can be functionally defined *without* such a presupposition. So roughly speaking: the rotating disc is rotating "in virtue of" having one or other of the accompaniments of rotation.

I think the reply is coherent, but not attractive. (So far as I know, it has not been articulated in the literature; I learnt it from David Wallace in conversation—who also does not advocate it.) I say 'not attractive' because, as an example of the (Appealing Differences) reply, it will have to face the usual trouble for this reply: that an advocate of the RDA will argue that the accompaniments of rotation (i.e. the conjuncts within the functional-causal role) that it invokes can be "imagined away", while the disc nevertheless rotates. Agreed, the reply may well be able to outface this trouble, e.g. by the commonly discussed tactic of appealing to past or future of counterfactual differences between the discs. But I do not think the use of a functional definition adds much to the general strategy of the (Appealing Differences) reply: for two reasons.

(a): However exactly the intrinsic-extrinsic distinction is made precise, it seems that rotation (and its quantitative measures) should be intrinsic to an object; and that it needs to be intrinsic, if we are to answer the RDA, since the RDA can consider discs that are alone in their worlds. But there is no reason to think that when rotation is functionally defined in the proposed way, it will be intrinsic. For in general, a property that is functionally defined by its occupying a certain role need not be intrinsic.[14]

(b): Functionally defining rotation without making a presupposition of persistence runs the risk that rotation, so defined, will not mesh appropriately with one's other doctrines about persistence, be they general philosophical doctrines (even analyses) or physical doctrines (as in the laws of mechanics). For presumably, both endurantist and perdurantist want rotation to involve, as a matter of conceptual analysis (not just scientific law), an object's (the disc's) persisting parts having circular (or approximately circular) orbits in space (on some appropriate account of "space"—cf. Section 5). But if rotation is functionally *defined* by accompaniments none of which presuppose persistence, such as a tendency to oblateness, rotation will have only a nomological connection to persisting parts having circular orbits in space.[15]

4.2.2.B Functionally defining velocity and persistence? One might propose that even though Tooley's own version of Tooleyan velocities presupposes persistence, one could *extend* Tooley's appeal to Ramsey-Lewis style functional definition so as to simultaneously define both velocity *and* persistence. As we shall see, this is very close to Sider's position (Section 4.4); which is my own "fallback position".

For the moment, I note only that since this tactic functionally defines—not rotation alone—but both persistence and velocity, objection (b) at the end of Section 4.2.2.A will *not* apply. For rotation will be defined in the usual way, after velocity and persistence have been defined. So as usual, and as desired, rotation will involve, as a matter of conceptual analysis, an object's persisting parts having circular orbits in space. (Again, to say 'usual' is true but casual: a proper account of space is still needed—cf. Section 5).

4.2.2.C Instantaneous velocity is hardly extrinsic My third reply to the consensus is the most important of the three, for three reasons:

(i): it introduces new ideas about the intrinsic-extrinsic distinction: specifically about the need to subdivide the distinction by admitting degrees of extrinsicality;

(ii): it bears on the reply to the RDA proposed by Robinson and Lewis; which I will discuss in Section 4.3;

(iii): most important, it supports my favoured reply to the RDA (in Section 7).

This Subsection develops the reply's main ideas. The next Subsection adapts these ideas to ascriptions of specific values of velocity, as a preparation for the comparison with Robinson's and Lewis's proposal in Section 4.3.

My leading idea is that the consensus that velocity presupposes persistence is, though correct "in the letter", wrong "in spirit". Although velocity *does* presuppose

[14] So Tooley, keen to have velocity cause and explain (together with forces) the object's later position, needs his functional definition of velocity to require that the role-occupant be intrinsic to the object: intrinsicality does not come for free.

[15] Point (b) brings out that this reply is similar to Teller's (Section 3.4), though more "positive" than Teller's in that it accepts there are facts of rotation. But I will not pursue the comparison.

persistence, the presupposition is milder than the literature allows. For "most" of the content of an ascription of velocity to an object is free of this presupposition: though this "most" is about the object at other times, it does not imply that the object exists at any such times, since it is hypothetical (conditional) in content. This leading idea will also apply to acceleration and higher derivatives of position. In (1) and (2) below, I present two closely related ways of making this idea precise. But I should first make three general points, (A)-(C).

(A): *Temporal intrinsicality and extrinsicality*:— Our topic prompts some terminology. Since here and later, I will be focussing on whether the possession of a property P by an object o at a time implies propositions concerning matters of fact, especially about o, at other times, it will be convenient to use the phrase '*temporally intrinsic* property'. By this I mean "intrinsic as regards time": i.e. roughly, a property whose possession by o at a time implies nothing about matters of fact (especially about o) at other times (though it may imply propositions about other places). Similarly, I shall talk of temporally extrinsic properties; and of spatially intrinsic and extrinsic properties.

Two warnings about this terminology. (1): I agree that my explanation is vague, not least because the general intrinsic-extrinsic distinction on which it rides is itself vague; (indeed probably ambiguous—cf. Humberstone 1996, Weatherson 2002). But my vague explanation will be enough for this paper. (2): Note that a property could be temporally extrinsic for one instance and not for another. Velocity itself provides examples of this. Imagine a non-instantaneous temporal part. That one of the part's constituent pieces of matter o has a certain instantaneous velocity at a time t "within" the part surely corresponds to an intrinsic property of the part. But it is temporally extrinsic for o at the *instant* t. Humberstone (1996, p. 206, 227) notes that a similar phenomenon—extrinsic for one instance, but intrinsic for another—occurs for extrinsicality and intrinsicality *simpliciter*.[16]

(B): *Degrees of extrinsicality*:— Extrinsicality is usually discussed as an all-or-nothing affair. But it is natural to suggest that it comes in degrees (e.g. Lewis 1983a, p. 111).[17] Intuitively, a property is more extrinsic, the more that its ascription implies about the world beyond the property's instance: (compare the philosophy of mind's jargon of 'wide' and 'narrow' mental states—some are wider than others). That is rough speaking; and all the rougher because of controversies about the intrinsic-extrinsic distinction. But I expect that in many sufficiently limited contexts, the idea could be made precise in a natural way. In any case, I shall only consider the temporal extrinsicality at an instant of the properties of position and its time-derivatives (velocity, acceleration etc.), in the classical description of motion. This is certainly a sufficiently limited context for the idea to be made precise.

(C): *Other conceptions of velocity*:— My claims in (1) and (2) below could be

[16]My (2004) further discusses temporal and spatial extrinsicality.

[17]Especially when one considers how many properties are extrinsic—so large a class merits being sub-divided.

carried over, with appropriate changes of wording, to Tooleyan velocities, accelerations etc. But I shall develop my claims only for the orthodox view of velocity as the time-derivative of position, since as I said in Section 4.2.1 I am not convinced by the *pointilliste* motivation for Tooleyan velocities. (Indeed, I am not convinced in good part because of the present idea that orthodox velocity is "almost intrinsic".)

(D): *Velocity as underived?*:— Here I should emphasise that, from the perspective of physics rather than metaphysics, my discussion here is limited; (and will remain so until Section 7). Namely: I here go along with the RDA literature's assumption that, Tooleyan velocities apart, velocity is defined just as the time-derivative of position, so that position is conceptually prior to velocity, and momentum is defined as mass times velocity. But as I announced at the end of Section 1.2.2: even apart from Tooleyan velocities, this assumption is *very* questionable—even within classical mechanics. That is: the concept of velocity is much subtler (because connected to other concepts in complicated ways) than such a definition suggests.

For there are rigorous formulations of classical mechanics (both for point-particles and continua) in which position is not thus privileged. In particular, one can develop classical mechanics by taking momentum as primitive, together with position and mass, and defining velocity as momentum divided by mass. (And in such a presentation, momentum does not need to be "secretly understood" as mass times velocity: one can introduce it abstractly, and without reference to time, as the generator of spatial translations. Thanks to Gerard Emch for stressing this point.)

Furthermore, this point is strengthened when one recalls from Section 2.2 how classical mechanics leads to the open sea of the rest of classical physics, and thereby eventually into paradox. To take a vivid example: the speedometer of a plane measures velocity "directly", i.e. not as the time-derivative of position, viz. by measuring the pressure of the apparent head-wind, i.e. the oncoming air.

Agreed, you could try to rigorously describe the physics of that instrument in a way that privileged position as basic, in the sense that velocity, though apparently measured "directly", was nevertheless defined as the time-derivative of position—indeed, for all the various objects involved, as well as the plane as a whole. And initially at least, you could certainly make progress. You could describe the details of the instrument's interaction with the air, describing the air either with the kinetic theory of gases, or with a continuum model: both kinds of model could privilege position in this sense (and perhaps in various ways). (Technical aside: in particular, continuum models can be given a Lagrangian formulation, which thus privileges position.)

So I agree that *maybe*, for this example, a coherent classical description can indeed be given that both privileges position as basic and is in some strong sense complete. But since in general, classical physical theories are eventually embroiled in paradox, I contend that you could not do this for all such examples. As emphasised in Section 2.2: classical physics is a house built on sand, and there is no reason to think that its best formulation (i.e. the formulation that achieves the best combination of the conflicting virtues of rigour and completeness/coverage) will privilege position as basic, so that velocity is always defined as just the time-derivative of position.

So in (1) and (2) below, I present two closely related ways of making precise the idea that instantaneous velocity is "hardly extrinsic", i.e. hardly temporally extrinsic, since its ascription to an object o at t implies "little" about matters of fact at other times.[18] Both ways are based on the obvious point that the only "categorical" proposition that an ascription of a velocity (or indeed, of a higher derivative of position) to o at t implies about other times is that the o exists for some open interval (a, b) containing t: all the other implications are hypothetical.

(The difference between the two ways will be that according to the first, which is "read off" the calculus, successively higher time-derivatives of position are more extrinsic; while on the second way, which is more logical and less mathematical, velocity acceleration and all higher derivatives are equally—and only mildly—extrinsic.)

In what follows, we can think of o as a point-particle; but it could equally well be a point-sized piece of matter in a continuum, or an extended body small and rigid enough to be treated as a point-particle. It will also be clear that the temporal extrinsicality of average velocity, acceleration etc. is mild for essentially the same reasons as for instantaneous velocity, acceleration etc. But to save space, I will focus on the instantaneous quantities.

(1): *The sequence of time-derivatives*:— The discussion will be tidier if we consider ascriptions, not of specific values of position, velocity, acceleration etc. to o at time t, but of some or other value. Then successive ascriptions are of increasing logical strength: having a velocity implies having a position, having an acceleration implies having a velocity etc.

So consider a sequence of ascriptions to o at time t: viz.

(Pos): an ascription of a position, i.e. a proposition saying that o has some or other position at t;

(Vel): an ascription of an (i.e. some or other) instantaneous velocity at t;

(Acc): an ascription of an instantaneous acceleration at t.

These ascriptions are of course the first three members of an infinite sequence of ascriptions stating the existence of higher time-derivatives of o's position. This gives an obvious sense in which instantaneous velocity is only mildly extrinsic. Each ascription is logically stronger than its predecessor; so (Vel), being almost at the start of the sequence, implies little in comparison with later members.

In more detail: if a real function f has a derivative at a point $t \in \mathbb{R}$, it must be defined on a neighbourhood of t and be continuous at t. So the existence of $f''(t)$ requires the existence of f' in a neighbourhood of t and its (i.e. f''s) continuity at t; and this in turn requires the continuity of f in that *same* neighbourhood of t. And so on. In short: the existence of the nth derivative gives more information about times other than t than does the existence of the $(n-1)$th derivative.

(2): *The "only categorical implication"*:— But there is also another sense in which velocity and the higher derivatives of position are only mildly temporally extrinsic.

[18]It is also hardly temporally extrinsic, on a third construal of that notion discussed in my 2004. Of course none of this is to deny that instantaneous velocity *is* temporally extrinsic at an instant, since it presupposes persistence.

This sense is more directly tied to the basic idea that the only categorical proposition that an ascription of such a quantity to o at t implies about other times is that the o exists for some open interval (a, b) containing t.

In more detail. Let us ask what exactly is implied about other times by the ascriptions in the sequence; starting with (Pos). The metaphysical literature invariably assumes position to be temporally intrinsic: why? The answer seems clear: 'because (Pos), or even an ascription of a specific value 'o is at $\mathbf{x}$ at t', implies nothing about o's position at other times'.[19]

But to be more precise about 'implying nothing' (apart of course from necessary or analytic propositions), we need:

(a) to decide whether to allow that the object o might exist only for an instant; (as many metaphysical discussions of persistence do: true to the tradition of conceptual analysis, they allow all metaphysical or logical possibilities, not just the nomic ones); and

(b) to distinguish categorical from hypothetical propositions.

Although the categorical-hypothetical distinction is vague and contentious (because 'logical form' is), I will not need to be precise or partisan about this: for it will be obvious from the calculus' definition of a limit which propositions implied by ascriptions such as (Pos)-(Acc) to count as hypothetical.

If we allow o to exist only for an instant (if we say 'Yes' in (a)), then indeed (Pos) implies no categorical proposition about o's positions at other times: there may be no such positions! But consider a hypothetical proposition along the lines: 'if o exists at a later time t', and some value (or upper limit) is assumed about its average speed (defined in the usual way as distance traversed divided by time elapsed) over $[t, t']$, then o is at t' within a sphere of a certain radius, centred on $\mathbf{x}$'. Such a hypothetical proposition is of course not analytic; but it follows by just definitions and logic from 'o is at $\mathbf{x}$ at t'.

When we turn to the next member of the sequence, (Vel), we of course get many more implications. o must exist throughout some open interval, maybe tiny, around t; and since differentiability implies continuity, o's position at a time t' in the interval tends, as t' tends to t, to o's position $\mathbf{x}$ at t; and so on. But these implied propositions are, with one exception, hypothetical. The hypothetical propositions include those about average velocity discussed in the previous paragraph, and various others one can spell out by applying the definitions of continuity and differentiability. The exception is of course the categorical proposition that o exists throughout some open interval of times around t; (and, to be precise: *its* analytic consequences, like o's existing at some time t' not equal to t). In particular, (Vel) is compatible with o being anywhere at any other time t', no matter how close t' is to t.[20]

Similarly again, for (Acc). There are again more implications, but they are almost

[19]As discussed e.g. in Section 3.2.2: I here set aside (i) the absolute-relational debate about space, and thereby (ii) possible implications about other objects' positions, at t or other times.

[20]I here assume there is no limiting velocity, as in relativity.

all complicated hypotheticals: the only categorical proposition about other times that the ascription implies is the same one again: that o exists throughout some open interval of times around t. And so on along the infinite sequence of ascriptions.

To sum up this discussion of (1) and (2): the temporal extrinsicality of velocity and higher derivatives of position is mild. For almost all of the implied propositions are hypothetical; and even the temporally intrinsic ascription (Pos) implies countless such propositions. Besides, the categorical propositions implied by an ascription of velocity, or of any higher derivative, are all just consequences of the one proposition that o exists throughout some open interval of times around t. So as regards categorical implications about other times, the temporal extrinsicality gets already at stage (Vel) as "bad" as it ever gets along the sequence: and that, I submit, hardly deserves the name 'bad'—it is mild.[21]

4.2.2.D Instantaneous velocity without presuppositions: "welocity" Finally, I turn to ascriptions of specific values of velocity, acceleration etc. The first point to make is that the discussion above can of course be carried over straightforwardly. For example, an ascription of velocity $\mathbf{v}$ to o at t simply adds to the ascription (Vel) information about what is the limit to which the countless average velocities tend for smaller time-intervals, viz. $\mathbf{v}$; and similarly for acceleration etc.

But for my purposes, it is more important to notice that there is a way of representing my conclusion, that velocity etc. are hardly extrinsic, in terms of a novel vector-valued quantity that is like velocity—but lacks its presupposition of persistence (mild though that presupposition is).

I will call this new-fangled quantity *welocity*, the 'w' being a mnemonic for '(logically) weak' and-or 'without (presuppositions)'. The benefit of introducing welocity will be clear in Section 4.3's comparison of it with Robinson and Lewis' proposed reply to the RDA.

So the idea is that welocity is to reflect, in the way its values are defined, this lack of presupposition. That is: the values are to be defined in such a way that it is impossible to infer from the value of the welocity of the object o at time t that o in fact exists and has a differentiable worldline in some neighbourhood of t: an inference which, as we have just seen, *can* be made from the value of velocity (at least as orthodoxly understood!).

Developing this idea takes us to familiar philosophical territory, viz. rival proposals for the semantics of empty referring terms. In our case, the empty terms will be expressions for o's instantaneous velocity at t; and, as we have seen, they can be empty either because:

[21]This view is reflected in the jargon of mathematics and physics. For example, mathematicians call not only (Pos), but also the ascriptions (Vel) etc., 'local'; and physicists call equations of motion that determine the object's motion at t in terms of its position and some of its derivatives then (but without reference to facts a finite temporal interval from t) 'local in time'. For more discussion, cf. Arntzenius 2000 pp. 192-195, Smith 2003 and my 2004.

(NotEx): o does not exist for an open interval around t, or

(NotDiff): o does exist for an open interval around t, but its position $\mathbf{x}$ is not differentiable at t; (roughly: there is a "sharp corner" in the worldline).

(And similarly for acceleration and higher derivatives; but I shall discuss only velocity—tempting though words like 'wacceleration' are!)

In fact, it will be clearest to lead up to my proposal for welocity by first considering a more familiar one, which is modelled on Frege's proposal that (to prevent truth-value gaps) empty terms should be assigned some "dustbin-referent", such as the empty set $\emptyset$. Thus if one sets out to define a quantity that is like velocity but somehow avoids its presupposition of persistence, one naturally first thinks of a quantity, call it $\mathbf{u}$, defined to be

(a): equal to the (instantaneous) velocity $\mathbf{v}$ for those times t at which o *has* a velocity; and

(b): equal to some dustbin-referent, say the empty set $\emptyset$, at other times t; i.e. times such that either (NotEx): o does not exist for an open interval around t; or (NotDiff): o does exist for an open interval around t, but its position $\mathbf{x}$ is not differentiable at t.

Of course, variations on (b) are possible. One could select different dustbin-referents for the two cases, (NotEx) and (NotDiff), (say, $\emptyset$ and $\{\emptyset\}$) so that $\mathbf{u}$'s value registered the different ways in which an instantaneous velocity could fail to exist. And instead of using a dustbin-referent, one could say that the empty term just has no "semantic value", or "is undefined": (a contrast with dustbin-referents which would presumably show up in truth-value gaps, and logical behaviour in general).

Agreed, this definition is natural. But it does not do the intended job. For this quantity $\mathbf{u}$, whether defined using (b) or using the variations mentioned, does not avoid, in the way intended, the presupposition of persistence. For $\mathbf{u}$'s value (or lack of it, if we take the no-semantic-value option) registers whether or not the presupposed persistence holds true. That is: we *can* infer from the value of $\mathbf{u}$ (or its lack of value) whether (a) o has a velocity in the ordinary sense, or (b) the presupposition has failed in that (NotEx) or (NotDiff) is true. In short: $\mathbf{u}$'s individual values tell us too much.

But there *is* an appropriate way of assigning semantic values to empty terms, i.e. a way of defining a quantity, *welocity*, that is like velocity but avoids its presupposition of persistence, in that welocity's values do not give the game away about whether the presupposition has failed, i.e. about whether (NotEx) or (NotDiff) is true. In order not to give the game away, welocity must obviously take ordinary values, i.e. triples of real numbers, when the presupposition has failed. But how to assign them?

The short answer is: arbitrarily. The long answer is: we can adapt schemes devised by logicians in which a definite description, whose predicate has more than one instance, is assigned as a referent *any one* of the objects in the predicate's extension. (The first such scheme was devised by Hilbert and Bernays; but we will only need the general idea.) Such a scheme applies to our case, because we can write the definition of welocity in such a way that when the presuppositions fail (i.e. (NotEx) or (NotDiff) is true), the predicate (of triples of reals numbers) in the definition is vacuously satisfied by all such triples; so that forming a definite description, and applying semantic rules like Hilbert-Bernays', welocity is assigned an arbitrary triple of real numbers as value. Thus we get the desired result: if you are told that the value of welocity for o at t is some vector in $\mathbb{R}^3$, say (1,10,3) relative to some axes and choice of a time-unit, you cannot tell whether:

(a): (NotEx) and (NotDiff) are both false (i.e. the presuppositions hold), and o has velocity (1,10,3); or

(b): (NotEx) or (NotDiff) is true, the predicate is vacuously satisfied by all triples, and (1,10,3) just happens to be the triple assigned by semantic rules taken from Hilbert-Bernays' (or some similar) scheme.

The details are as follows. (1): Hilbert and Bernays introduced the notation $(\varepsilon x)(Fx)$ for the definite description 'the F', with the rule that if F had more than one instance, then $(\varepsilon x)(Fx)$ was assigned as referent any such instance, i.e. any element of F's extension. (We need not consider their other rules, nor their rules' consequences for the semantics and syntax of singular terms.)

(2): Next, we observe that intuitively the *velocity* of an object o at time t can be defined with a definite description containing a material conditional whose antecedents are the presuppositions of persistence and differentiability. That is: it seems velocity can be defined along the following lines:—

The velocity of o at time t is the triple of real numbers $\mathbf{v}$ such that:

> for some (and so any smaller) open interval I around t:
> $\{[o$ exists throughout $I]$ and $[o$'s position $\mathbf{x}(\mathbf{t})$ is differentiable in $I]\}$ $\supset$
> $[\mathbf{v}$ is the common limit of average velocities for times $t' \in I$, compared with t, as $t' \to t$ from above or below$]$.

This *definiens* uses a material conditional. So it will be vacuously true for all triples $\mathbf{v}$, if the antecedent is false for all open intervals I around t, i.e. if (NotEx) or (NotDiff) is true: in other words, if velocity's presuppositions of continued existence and differentiability fail.

(3): Now we put points (1) and (2) together. Let us abbreviate the displayed *definiens*, i.e. the open sentence with $\mathbf{v}$ as its only free variable, as $F(\mathbf{v})$. Then I propose to define the *welocity* of o at t by the singular term $(\varepsilon\mathbf{v})(F\mathbf{v})$: which is, by Hilbert-Bernays' semantic rule:

(a): equal to the (instantaneous) velocity of o for those times t at which o *has* a velocity; and

(b): equal to some arbitrary triple of real numbers, at other times t; i.e. times such that either (NotEx): o does not exist for an open interval around t; or (NotDiff): o does exist for an open interval around t, but its position $\mathbf{x}$ is not differentiable at t. Welocity, so defined, has the desired features: its values do not give the game away about whether (NotEx) or (NotDiff) is true.

That is all I need to say about welocity, for this paper's purposes; and in particular, for Section 4.3's comparison with Robinson's and Lewis' proposal. But I end this Subsection by noting that there are of course various technical questions hereabouts, even apart from the logical questions about ε (which are of course addressed by the masters, Hilbert and Bernays!).

In a discussion of the RDA and so of continuous matter, a natural question arises from letting o be a point-sized bit of matter in a continuum, and letting the presuppositions of velocity fail for various such point-sized bits of matter: some such bits may fail to exist, and some may have a non-differentiable worldline. One then faces the question: how widely across space, and in how arbitrary and gerry-mandered a spatial distribution, can these bits fail to exist, or have a non-differentiable worldline—i.e. how widely and arbitrarily can the presuppositions of velocity fail—while yet the welocity field might not give the game away, in that the arbitrary values *can* be assigned at all the points where the presuppositions of velocity fail, in such a way as to give a smooth (e.g. continuous or even differentiable) welocity field?

This is in effect a question about the scope and limits of "regularization" of "singularities" in real vector fields: a good question—but not one for this paper!

To sum up this Subsection, i.e. Section 4.2.2: I hope here—and especially in the last two parts, Subsections 4.2.2.C and 4.2.2.D—to have "set the cat among the pigeons", to have "upset the applecart", about the literature's consensus that velocity presupposes persistence.

These scattered pigeons and upset apples will be important for my reply to the RDA in Section 7. But in the meantime, they will not much affect the discussion, except for the next Subsection's comparison of welocity with Robinson's and Lewis' proposal (Section 4.3). So they can be set aside for:

(i) most of this Section's discussion of metaphysical replies to the RDA; and for

(ii) the next Section's discussion of the technical description of rotation, and of what it entails about the RDA.

4.3 Velocities on the cheap? Lewis and Robinson

I turn to Lewis' and Robinson's version of (Appealing Differences). They propose that a moving object has a vectorial property (i.e. a property represented by a vector) which is intrinsic to the object, and whose vector is equal to the velocity vector. But this property is not itself velocity, since velocity presupposes persistence, and this property is to be intrinsic, not merely "almost intrinsic".

I will first present the proposal, in Section 4.3.1. I will emphasize: (i) Lewis' doctrine of Humean supervenience; and (ii) how Lewis came around to this defence of Humean supervenience (ca. 1998), after espousing for a while (ca. 1986-1994) a (No Difference) reply. Then in Section 4.3.2 I will assess the proposal.

4.3.1 The proposal

(1) *Humean supervenience*
We saw in Section 4.1 that Armstrong's appeal to causation, in response to the RDA, is not available to someone like Lewis who advocates both perdurantism, and a Humean view of causation. Indeed, as I mentioned, Lewis advocates a much stronger doctrine, Humean supervenience, which has become the paradigm in contemporary metaphysics for what I have called *pointillisme* (cf. Section 2.1). He holds that *all* truths supervene on truths about matters of local particular fact: where 'matters of local particular fact' is to be understood in terms of Lewis' metaphysics of natural properties, with the properties having spacetime points, or perhaps point-sized bits of matter, as instances. He writes:

> ...all there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another ... We have ... relations of spatio-temporal distance between points ... And at those points we have local qualities ... For short: we have an arrangement of qualities. And that is all. There is no difference without a difference in the arrangement of qualities. All else supervenes on that. (1986, p. ix-x.)

Or in other words: Humean supervenience

> ...says that in a world like ours, the fundamental relations are exactly the spatiotemporal relations: distance relations, both spacelike and timelike, and perhaps also occupancy relations between point-sized things and spacetime points. And it says that in a world like ours, the fundamental properties are local qualities: perfectly natural intrinsic properties of points, or of point-sized occupants of points. Therefore it says that all else supervenes on the spatiotemporal arrangement of local qualities throughout all of history, past and present and future. (1994, p. 474.)

(2) *Lewis' (No Difference) Reply*
So Lewis addresses the RDA as an objection to his Humean supervenience thesis. His reply changed over time; we can distinguish three phases (1986 p.xiii, 1994 p. 475, 1999). At first (1986 p.xiii), he appealed to the fact (clear from the second quotation) that he advocates Humean supervenience as a contingent thesis, true at some worlds (including, he hopes, ours) but not at others. That is, he advocated Humean supervenience for an "inner sphere" consisting of the non-alien worlds—defined (in his quiddistic theory of natural properties) as the worlds where any instantiated natural property is not alien to the actual world. So he replied to the RDA, taken as putting its differing discs (Stat) and (Rot) each in its own world, by saying that one or both of the worlds must be outside the inner sphere.

Of course, essentially the same reply can be given using other definitions of the "inner sphere" across which Humean supervenience is to hold as a contingent supervenience thesis. For example, as I mentioned in Section 1.3: one might claim the supervenience to hold across all the worlds that each make true all the actual laws of nature.

Similarly, Robinson (1989, p.404: crediting Lewis):

(i): toys with replying to the RDA that it shows that the common sense notion of homogeneous matter and its persistence requires atomistic matter; and

(ii): suggests this would be an example of the traditional "paradox of analysis": roughly, that philosophical analysis can reveal surprising truths.

Later, Lewis adjusted this reply; (1994 p. 475—this is the second phase). He agreed that this reply had not given a reason for thinking that enduring objects were different in their fundamental nature from perduring objects, so that one or both of the disc worlds had to be alien; (in response to Haslanger (1994); cf. also Robinson 1989, p. 403-404). But his preferred reply to the RDA remained a version of (No Difference): that one or both of the disc worlds were not "worlds like ours"; i.e. they fell outside the class of worlds (now only vaguely specified) for which Humean supervenience was claimed.

(3) *Comparison with Callender*
It is worth briefly comparing this reply with Callender's (No Difference) reply (cf. Section 3.4). The main difference is that:—

Lewis admits that there are some possible worlds very 'unlike ours' (roughly: outside the inner sphere of possibility) which sustain the distinction between (Stat) and (Rot), in the sense that at least one of these two worlds must be outside the inner sphere.

On the other hand, Callender (at least as I read him) takes a tougher stance. He does not define a limited class of worlds in which there is no difference (i.e. from which the (Stat)/(Rot) distinction is banished). He apparently believes the (Stat)/(Rot) distinction is yet "worse off". For good metaphysical arguments can be given that it is as spurious as the up/down distinction (his Section 2, p. 30-35). And even if these arguments fail, there are methodological reasons (roughly: Occam's razor) to deny the distinction (his Section 3, p. 35-40). Thus he says that the discs that the RDA needs are 'the metaphysical equivalent of fairies, ghosts and vital spirits' (p. 26). By this he means that they must be uncoupled (i.e causally isolated) from any of the fields (electromagnetism, gravity etc.) that exist in our world, and from all the usual causes and effects of rotation. 'Such a disc is no different from a ghost, and is not something Humeans or non-Humeans ought to posit' (p. 37).

(But maybe Callender is closer to Lewis than this summary suggests: perhaps he thinks the (Stat)/(Rot) distinction makes some kind of sense, but is less committed than Lewis to the framework of possible worlds and so to defining some kind of "inner sphere" from which the distinction is banished.)

(4) *Lewis' (Appealing Differences) Reply*
But in a final short paper (replying to Zimmerman 1998), Lewis endorsed (1999, p. 211) a proposal that had been floated by Robinson (1989; p. 405 para 2, p. 406 para 2—p. 408 para 1). Roughly speaking, the proposal is that:

(i) a vectorial property at a point can be an intrinsic property of that point;

(ii) the propagation of continuous matter through spacetime involves such a property at every spacetime point; and

(iii) these properties distinguish the rotating and non-rotating discs, since the vector that represents the property at a point is timelike, and points in the same direction as the instantaneous four-dimensional velocity vector at that point;

(iv) the distribution of these properties, from point to point, determines (subvenes) the relations of qualitative similarity between points, and especially the relations of causal dependence between events at those points; and

(v) the distribution of these properties, by determining the lines of causal dependence, determines the lines of persistence.

Three side-remarks: (a) So this proposal takes causal dependence to underpin persistence: as I noted at the start of Section 4.1, many philosophers endorse this.

(b) In fact, Lewis already agreed to (i) in his (1994, p. 474); but lacking (ii) and (iii), and so also (iv) and (v), he there retained his "not like ours" (No Difference) reply.

(c) Robinson's (i)-(iv) are clearly similar in spirit to Tooley's and Bigelow and Pargetter's heterodox understanding of velocity as an intrinsic property, discussed in Section 4.2.1. Robinson does not refer to their papers which were of course contemporaneous. But Zimmerman (1998, p. 281, p. 284) and Sider (2001, p. 228) both see the similarity to Tooley's proposal (1988). Zimmerman first discusses reading Robinson's proposal as the same as Tooley's (p. 281), and then discusses reading it as just similar (p. 284, note 65). Sider reads the proposals as similar. More specifically, Sider and Zimmerman's second reading both see Robinson's proposal as going with a Russellian "at-at" account of motion. So also (implicitly) does Lewis' discussion.

So the idea of the proposal is that the difference in these properties amounts to a difference in the 'local arrangement of qualities' as demanded by Humean supervenience. Thus Lewis (1999, p. 211) begins by approvingly quoting Robinson, suggesting we should

> ...see the collection of qualities characteristic of the occupation of space by matter as in some sense jointly self-propagating; the fact of matter occupying space is itself causally responsible ... for the matter going on occupying space in the near neighbourhood immediately thereafter. ... [The posited vectors] figure causally in determining the direction of propagation of [themselves as well as] other material properties. (Robinson 1989, p. 406-407.)

Lewis then goes on to formulate the proposal more formally, as a putative law that partially specifies a vector field V. The specification is partial, both in (i) being admitted to be a "first approximation", and (ii) specifying only the direction but not the length of the vector at each point. But (ii) hardly matters: it will be obvious that Robinson and Lewis could frame their proposal entirely in terms of postulating a timelike direction field (i.e. a specification at each point of continuous matter of a timelike direction), rather than a vector field. But I shall follow them and talk of a vector field.

In giving this formulation, Lewis' aim is partly to avoid various objections or limitations. In particular, the formulation should not invoke either persistence or causation, since these are meant to supervene on the local arrangement of qualities, taken of course as including facts about the vector field V. Thus the formulation is to avoid circularity objections that had been urged by Zimmerman (1998) against some related proposals.

So in particular: the vector field V cannot simply be the instantaneous (four-dimensional) velocity (Russellian, not Tooleyan!) of the matter at the point in question. For V is to contribute to an analysis of (or at least to a supervenience basis for) persistence and thereby of velocity.

Similarly, since Lewis agrees that causation is crucial to persistence ('the most important sort of glue that unites the successive stages of a persisting thing is causal glue': 1999, p. 210), causation cannot be invoked in the course of specifying the vector field V.

Lewis proposes that (for a world with continuous space and time), the specification of V 'might go something like this':

> Let p be any spacetime point, and let t be any smooth timelike trajectory through spacetime with p as its final limit point. Let each point of t before p be occupied by matter with its vector [i.e. vector of the vector field V] pointing in the direction of t at that point. [So in the jargon of modern geometry, t is an integral curve of V.] Then, *ceteris paribus*, there will be matter also at p. (1999, p. 211.)

Here, the '*ceteris paribus*' clause is to allow for the fact that the point-sized bit of matter might cease to exist before p, because of 'destructive forces or self-destructive tendencies' (ibid.).

Lewis also stresses that this proposal is to be read as a law of succession, not of causation. This means, I take it, that the 'Then, *ceteris paribus*' is to be read as a material conditional.

4.3.2 Assessment

I think Lewis' proposal fails. After saying why, I will broach the more general (and I think, more important) issue of how plausible is an extreme *pointillisme* like Lewis' Humean supervenience. This will return us to the discussion in Sections 4.2.2.C and 4.2.2.D.

4.3.2.A The vector field remains unspecified I claim Lewis' proposal is too weak: it does not go far enough to specify V. For it only says, of any timelike open curve that is an integral curve of V, that the future end-point p of this curve will, *ceteris paribus*, have matter at it.

But every suitably smooth vector field U defined on a open region R of spacetime has integral curves throughout R; (which are timelike, by definition, if U is). (To be precise: 'suitably smooth' is none too demanding: all we need is that U be C^1, i.e. the partial derivatives of its components exist and are continuous.) So suppose Lewis stipulates, that the field V is to be timelike and C^1 on an open set R which is its domain of definition (say, the spatiotemporal region occupied by continuous matter): which ("giving rope") we can assume to be a legitimate, in particular non-circular, stipulation. Then his proposal says that, *ceteris paribus*, every point $p \in R$ has matter at it.

But that claim hardly helps to distinguish V from the countless other (timelike continuous) vector fields U. For however exactly one interprets '*ceteris paribus*', the claim is surely true of p regardless of the integral curve one considers it as lying on. So the claim about p does not constrain the vector field. Indeed, if Lewis sets out to specify V on the spatiotemporal region occupied by continuous matter, the claim is thereby assumed to be true for all p in the region, regardless of vector fields. So again, we have said nothing to distinguish V from the countless other vector fields U.

Agreed, Lewis puts forward his proposal as a "first approximation" to specifying V. But so far as I can see, his discussion doesn't contain any ingredients which would, for continuous matter, help distinguish V from other vector fields.[22]

Zimmerman (1999) makes a somewhat similar objection to Lewis' proposal. But his exact intent is not clear to me.

He maintains that in some seemingly possible cases of continuous matter, Lewis' proposal does not specify a unique vector field V—indeed hardly constrains V at all. He says (p. 214 para 1 and 2) that in possible worlds with a physics of the sort Descartes might have envisaged, i.e. where there is *nowhere* any vacuum, and only *one* kind of (continuous homogeneous) stuff fills all of space: '*every* vector field will satisfy [Lewis'] law.'

Thus Zimmerman assumes that:

(i): the worlds with which he is concerned are wholly filled with the one kind of stuff; and

(ii): these worlds are thus filled as a matter of law, not happenstance (in the jargon: as a matter of physical or nomic necessity).

He also says (p. 214-5) that he needs to assume (i) and (ii) in order to criticize Lewis' proposal, together with obvious modifications of it which allow for different types ("colours") of continuous matter. That is: Zimmerman thinks Lewis' proposal works, or could be modified to work, for worlds in which:

(i') continuous matter does not fill all of space and-or comes in various types; or

[22]Nor can I guess how I might have misinterpreted Lewis' proposal. The situation is puzzling: and not just because Lewis thought so clearly, and my objection is obvious. Also, the objection is analogous to what Lewis himself says (p. 210) against the naive idea that V should point in the direction of perfect qualitative similarity: viz. that 'in non-particulate homogeneous matter, ... lines of qualitative similarity run every which way'.

(ii') continuous matter of just one type fills all of space, but only as a matter of happenstance.

In view of my own objection, I do not understand why Zimmerman feels he needs to assume (i) and (ii) in order to object to Lewis. He does not explicitly say why he does so. *Maybe* it is to block some Lewisian rejoinder, that would better specify V, by adding constraints of either or both of two kinds:

(i"): constraints about the spatiotemporal relations of the continuous matter in a bounded volume (say, one of our discs) to other matter outside the volume.

(ii"): constraints about the nomic or modal properties of matter.

But it remains unclear how the details of (i") and (ii") might go.

To sum up: For all I can see, my objection, that V is not distinguished from countless other vector fields, applies to Lewis' proposal (and thereby: the spirit of Zimmerman's objection also applies) for the case that Lewis intended it—i.e. the discs of the original RDA.

4.3.2.B What price Humean supervenience? Doubts about intrinsic vectorial properties I announced my denial of *pointillisme*, and so my antipathy to Humean supervenience, already in Section 2.1. And in Sections 4.2.2.C and 4.2.2.D, I developed this by arguing that temporal extrinsicality was after all "not so bad". More specifically, I argued that velocity was almost intrinsic, and that we could even define a quantity, *welocity*, that in a sense avoids velocity's presupposition of persistence.

I am afraid these doctrines would not appeal to Lewis! He would probably be unimpressed by velocity's being almost intrinsic. For Humean supervenience is so central to his metaphysical system that he sets considerable store by intrinsicality. So he would probably say that as regards failing to be intrinsic, a miss is as good (i.e. bad!) as a mile.

Similarly, I am not confident that he would welcome welocity. I agree that he might be "envious" of its being well-defined (*modulo* the freedom to assign referents associated with the ε operator), since his own proposal, the intrinsic vector V, is yet to be successfully defined.

I also agree that in one important respect, welocity fits Lewis' conception of intrinsicality. Namely, on Lewis' conception, intrinsicality is not hyperintensional: that is, necessarily co-extensive properties are alike in being intrinsic, or not. (The reason for this lies in Lewis' proposal for how to analyse intrinsicality. Both his preferred analysis (and a fallback analysis, in (Langton and Lewis 1998)) take an intrinsic property to be one that does not differ between duplicate objects—where duplication is defined, in both analyses, as sharing a certain elite minority of properties. Clearly, any analysis with these features will imply that necessarily co-extensive properties are alike in being intrinsic, or not.)

Now, the welocity of an object o is intuitively (albeit hypothetically!) "about" o's positions at other times; so that someone who construes intrinsicality as hyperintensional may want to argue that welocity is extrinsic, or temporally extrinsic (if they use that notion). Conversely, the idea that welocity is intrinsic goes with a conception of intrinsicality as not hyperintensional—such as Lewis'.

Nevertheless, I am not confident Lewis would welcome welocity, just because there are two general obstacles to connecting it to his framework:—

(a): Lewis talks only of intrinsic and extrinsic properties, not (as I have) of *temporally* and *spatially* intrinsic or extrinsic properties; and

(b): Lewis' proposed analysis of intrinsicality (and the Langton-and-Lewis fall-back proposal) is cast in terms of his very general metaphysical system, using notions like 'natural property' and 'possible world'. This makes it a delicate matter to classify everyday, or even technical scientific, properties in terms of his proposal. So in particular, I am unsure whether my welocity counts as intrinsic for Lewis.

(I add, in Lewis' defence: I think this "gap" between his metaphysical categories and the properties we know explains some of the counterexamples brought against his proposal. But I also add, against him: the "gap" makes considerable trouble for his overall Humean project (Mainwood 2003); and these counterexamples, together with other considerations, also suggest that there is no single intrinsic-extrinsic distinction; (cf. Humberstone (1996) and (broadly following him) Weatherson 2002).)

But it would take us too far afield to further compare my anti-*pointillisme* with Lewis' Humean supervenience, even if we considered only the topic of velocity. I must leave further discussion of these issues to my 2004. To advertise that discussion, and to emphasise that controversy surrounds even basic questions about the intrinsic-extrinsic distinction in application to scientific properties, I end this Subsection by pointing out that the very first claim of the Robinson-Lewis proposal, viz. (i) of Section 4.3.1:

(i): a vectorial property at a point can be an intrinsic property of that point

has been doubted in the metaphysical literature—and even by Robinson and (the earlier) Lewis themselves! (Lewis endorsed (i) in what I called the 'second phase' reply to the RDA; (1994, p. 474).)

I said in Section 4.3.1 that Robinson 'floated' the Robinson-Lewis proposal, precisely because he did not endorse it. His anxiety concerns the directionality of a vector. He writes: 'Direction seems to me an inherently relational matter' (1989,p. 408). He supports this with the following argument, for which he credits Lewis; (so Lewis seems to have come round to believing (i), that vectors can represent intrinsic properties of points, sometime between ca. 1988 and writing his (1994, p. 474)).

The argument has two premises:

(a): A vector quantity could not be instantiated in a zero-dimensional world consisting of a single point; (though since arbitrarily close points define a direction, there is of course no lower limit to the "size" of a world in which a point instantiates a vector quantity). But it also seems that:

(b): Since a point in an extended world that instantiates a vector quantity is indeed a *point*, it could have a duplicate that existed on its own, i.e. was the only object in its world.

Taken together, (a) and (b) imply that duplicate points might differ in their vectorial properties; so that (at least on a Lewisan approach to the intrinsic-extrinsic distinction, according to which intrinsic properties are those shared by duplicates) such properties are extrinsic.

Nor is Robinson alone in worrying that vectors could only represent extrinsic properties of a point. Cf. also: Bricker (1993); Zimmerman (1998, p. 277-278; mentioned in Section 4.2.1's discussion of Tooleyan velocities (footnote 13); and Black (2000, p. 103), who holds that vectors can only represent intrinsic properties in a *flat* manifold, i.e. roughly, a manifold in which there is a unique preferred way to compare vectors located at different points.

To sum up: even among authors squarely within contemporary metaphysics' approach to the intrinsic-extrinsic distinction, step (i) of the Robinson-Lewis proposal remains controversial.

4.4 Functionally defining persistence and laws: Sider

I will describe Sider's reply to the RDA (2001, p. 230-236) in some detail, as it is in effect my "fallback position": if my own reply failed, I would endorse an analogue of his (Section 6.2).

It also combines several of the themes we have introduced. For example, it is close to Section 4.2.2.B's idea of simultaneously defining velocity and persistence. More important, it is an interesting example of combining the two kinds of reply, (Appealing Differences) and (No Difference), in the way mentioned in Section 3.4. First, Sider appeals to non-obvious differences that other perdurantist replies have not appealed to; ('non-obvious' because they are differences in the discs' environments, not in the discs themselves). But second, if these differences are "imagined away", along with the more obvious differences (like oblateness) that the RDA imagines away, then Sider turns to the (No Difference) reply: he "bites the bullet" and says that in such a world, there is no distinction between the discs. This second part of Sider's position is also interesting. For he does not turn to the (No Difference) reply merely as a matter of his philosophical judgment, or "intuition": nor even as a matter of scientific methodology (as Callender argues). Rather it follows from Sider's *theory* of how the perdurantist should go about defining persistence, that in such a world there will be no distinction.

Sider develops his position from the following two independent components.

(i): He notes the "logical circle" of the laws (of dynamics) and persistence. That is: the laws concern persisting objects, and so use the notion of persistence. But for perdurantists, persistence, i.e. the relation between stages of an ordinary persisting object, has a causal or nomic component—and Sider is happy to have it be nomic, so that the notion of persistence presupposes the laws. In the face of this logical circle, Sider proposes the now-familiar tactic: Ramsey-Lewis simultaneous functional definition, so as to simultaneously specify persistence and the laws from a single body of doctrine.

(ii): He adopts the Mill-Ramsey-Lewis best-system theory of laws of nature (Lewis 1973, Section 3.3, p. 72-77).

Given these components, Sider's position follows swiftly. He writes (using 'genidentity', where I have hitherto used 'persistence', for the relation between stages (temporal parts) of an ordinary persisting object—which he calls 'continuants'):

> Consider various ways of grouping stages together into physical continuants. Relative to any such way, there are candidate laws of dynamics. The correct grouping into physical continuants is that grouping that results in the best candidate set of laws of dynamics; the correct laws are the members of this candidate set.
> More carefully. Any law of dynamics is a statement restricted to physical continuants, which may be rewritten in terms of the predicate 'genidentity' as follows: 'for any maximal genidentity-interrelated sum x ...'. Let S be any axiomatization of any candidate set of laws of nature. Let S(genidentity) be the result of rewriting any dynamical laws in S in terms of the genidentity predicate. Where G is any two-pace predicate variable, let $S(G)$ be the result of replacing all occurrences of 'genidentity' in S(genidentity) with G. ... relative to any assignment of a two-place relation $\mathbf{G}$ to the variable G, we can evaluate the strength [JNB: and the simplicity] of the resulting system $S(\mathbf{G})$. We now define the best system and genidentity at once: they are the pair $\langle S(\mathbf{G}), \mathbf{G}\rangle$, where $\mathbf{G}$ is a two-place relation over stages and $S(\mathbf{G})$ is the system that achieves the best combination of strength and simplicity.
> [The idea is that] we must look *globally*, across the entire world, to find what assignment yields the best candidate laws of dynamics. Thus although the states of a spinning disk may qualitatively match those of a stationary disk, what is going on elsewhere in the world may result in differences of rotation. [JNB: 'result in' here means 'imply' not cause] Suppose, for example, that a stationary disk with a small hole is impacted by an object that seamlessly lodges itself in the hole, resulting in a perfectly homoegenous disk ... Suppose further that, in the possible world in question, collisions generally result in transfer of momentum. The best simultaneous assignment of genidentity and laws of dynamics will then be one according to which this disk is spinning, for a pair of a genidentity assignment and set of laws on which the disk does not spin will not contain exceptionless laws governing the transfer of momentum. Now suppose further that, elsewhere in the same world, a disk with an empty niche had initially been spinning, and that a perfectly fitting object moving opposite to the direction of rotation collided with the disk. If the speeds and masses are appropriate, the best assignment of genidentity and laws will have the result that this second disk is stationary after the collision. The present view, therefore, allows the possibility of differences in rotation between homogeneous disks without appealing to non-Humean quantities. (p. 230-231)

So Sider's leading idea is to have both the notion of genidentity and the laws of dynamics "get established" in unproblematic cases, and then "projected" to the problematic cases involving continuous homogeneous matter. As he says:

> it is crucial that the world contain plenty of unproblematic cases *not* involving uniform homogeneous matter. Once a certain candidate pair of laws and genidentity gets its foothold in these unproblematic cases, it can then be projected into the problematic cases involving homogeneous objects, for this projection increases the strength of the candidate laws and does not decrease their simplicity. (p. 233)

So Sider goes on to admit (in effect by way of concession to the argument of Zimmerman (1999), which I discussed in Section 4.3.2.A) that his view cannot

> distinguish states of rotation in cases where there is not enough else going on in the world to give candidate pairs of genidentity and laws a foothold. In a world that contains only a homogeneous disk, the facts will not be sufficiently rich to allow one candidate pair to win out; there will therefore be no unique facts about genidentity, no unique spacetime worm that counts as a given spatial part of the disk, and no fact of the matter whether the disk spins or rotates. (p. 233-234)

Sider then argues (p. 234-236) that he can "bite this bullet". (Though Sider does not explicitly discuss Zimmerman's space-filling homogeneous fluid, he would no doubt also bite the bullet in this case.) That is to say, in terms of Section 3.4's two kinds of reply: for such a world, he adopts the (No Difference) reply; where, as I noted above, this is not just a matter of his philosophical judgment, but follows from his *theory* of how to go about defining persistence—functional definition, and the best-system theory of laws.

(Sider also argues that he can similarly bite another "more general" bullet, that arises from his overall strategy of defining both laws of dynamics and persistence by looking '*globally*, across the entire world'. Namely: the bullet that according to his account, whether or not a disc is rotating is a very extrinsic matter—i.e. it depends on what goes on in spacetime external to the disc. Sider, a good Humean, says he can accept this: indeed, for much the same reasons that a Humean about causation accepts that a singular causal fact, say c causes e, is extrinsic to the two relata c and e.)

In metaphysics, I am an aspiring Humean: to that extent, I like Sider's position. But the endurantist will no doubt reply that Sider's bullet-biting amounts to conceding the force of the RDA: 'even Sider's version of perdurantism, with its sophistication about the account of persistence invoking the laws of mechanics, cannot secure facts of persistence in the troublesome cases considered by the RDA'. In other words: Sider's (No Difference) verdict suggests that after all, there is at best a stalemate.

From Section 6 onwards, I will argue that the perdurantist can do better than this stalemate. But before turning to that, we need to consider ...

5 Describing rotation

So much, for the moment, for metaphysics! I now return to Section 3.2.2's demand that the advocate of the RDA (indeed all parties to the dispute) should state and justify their claims about spatiotemporal structure—i.e. the claims they need to make, in order that statements of rotation *make sense*. I begin by stressing the need for precision (Section 5.1). Then I report how physics rigorously describes states of rotation (Sections 5.2 and 5.3), and review how these technicalities bear on the endurantism-perdurantism debate (Section 5.4). This yields two of the paper's three main conclusions:

(i): the RDA can be formulated more strongly than is usually recognized: it is not necessary to "imagine away" the dynamical effects of rotation (Section 5.5); but

(ii): in general relativity, the RDA fails (even in the strengthened version), because of frame-dragging (Section 5.6).

5.1 The need for precision

As I argued in Section 3.2.2: to get a grip on the two possibilities that the RDA urges on us, it is certainly not enough to just draw or visually imagine the contrasting diagrams, with straight and helical worldlines. For such diagrams implicitly assume that the rotation/non-rotation distinction is defined in terms of a space of persisting spatial points; and the question arises what account either party, endurantist or perdurantist, can give of such points—or of whatever (maybe more technical) notions they need, or choose, to use so as to describe rotation.

Besides, this question is also brought out by Callender's (No Difference) reply in Section 3.4. Callender's claim that the (Stat)/(Rot) distinction is as spurious as that between (Up) and (Down) is essentially the claim that, pending some further account, the straight/helical contrast for a diagram's worldlines can be dismissed as an artefact of the diagram: I can change coordinate system to make what I drew as straight (helical) be now drawn as helical (straight), just as I can change coordinates to make an arrow drawn pointing upward get drawn as downward.

The general point here is that diagrams can carry implicit assumptions or connotations that a certain distinction makes sense (aka: 'is physically significant/real')—and that one can propose, or hope to have, a theory of motion in which that distinction is in fact denied.

This is a familiar point in the philosophy of geometry. A standard simple example, much like the up/down one, is the description of 3-dimensional Euclidean space with cartesian coordinates, i.e. as $\mathbb{R}^3$. The diagram of the three axes suggests a distinguished point, and three distinguished directions: a connotation we immediately do away with by emphasising how we can equally well choose coordinate systems with other origins and-or axis-directions.[23]

[23]This leads into a large mathematical subject, which goes back to Klein: articulating the geometric

Indeed, this sort of rectilinear example is very relevant to the RDA. For the RDA can be—and sometimes has been—developed using, instead of discs (or spheres, cylinders etc.) and rotation: rivers of homogeneous continuous matter undergoing an homogeneous steady flow, i.e. with the velocities of all the point-sized bits of matter being the same as each other, and constant in time.

Thus the argument against perdurantism would be that the perdurantist apparently cannot distinguish between the river being stationary and flowing steadily. (But most authors in the RDA literature who mention rivers do not confine themselves to steady homogeneous flow: they gesture at the endless variety of possible flows, with all sorts of eddies, which allegedly all "look the same" to the perdurantist or Humean.

And the argument prompts the now-familiar two kinds of reply. (Appealing Differences): Can the perdurantist distinguish the cases by appealing to, for example, motion relative to the river bank? And if not, say because the river is the only thing in the world (say, filling all space), can she appeal to instantaneous velocity or causation? On the other hand, (No Difference): can the perdurantist deny that there is a distinction?

So in fact our topic in this Section is, not just how is rotation rigorously described, but: how is all motion, even rectilinear motion, rigorously described? But I shall emphasise rotation, since:

(i) the RDA literature does so, and:

(ii) nowadays, the rejection of absolute space makes an argument, based on the stationary vs. irrotationally steadily flowing river, look weak. That is: if the river is "lonely", the only thing in the world, then the (No Difference) reply seems convincing. So rotation seems to give the endurantist their best chance of making trouble for perdurantism.

The rigorous description of motion, and especially rotation, in modern geometry and physics is a very large and subtle subject. But to assess the RDA we can fortunately make do with some simple points. I start in Section 5.2, simply and traditionally, by discussing how Newton argued for persisting spatial points, i.e. an absolute space, by appealing to the dynamical effects of rotation. This will lead to Section 5.3's summary of some aspects of the modern *kinematical* description of rotation.

5.2 Motion needs a connection

In his bucket and globes thought-experiments, Newton appealed to the dynamical effects of rotation to argue that the theory of motion needed to postulate an absolute space of persisting spatial points. (At least this is the usual reading: but for subtleties and controversy, cf. e.g. Rynasiewicz 1995, Mainwood 2004.) So at first sight, it seems that both the endurantist and perdurantist might hope to appeal to, or adapt, Newton's argument so as to give an account of the persistence of spatial points.

(Here I assume that for the advocate of the RDA, this does not conflict with the

structure of a space by singling out a class of coordinate systems that gives its structure an especially simple expression, and stating the group structure of this class.

fact that the RDA imagines away such dynamical effects. The idea is that the advocate follows Newton in arguing for the *actual* existence of absolute space; but then says that for the purposes of the argument, the dynamical effects can be imagined away—and that this is not so "unlike the actual world" as to let the perdurantist off the hook of having to distinguish the cases of (Stat) and (Rot).)

But Newton's arguments (and their ilk) can be resisted. There are two points here, of which the second is more important for us.

(i): Those inclined to relationism about space and time (like Leibniz and Mach) will say that the correct account of space must be based on relations between material bodies—and that therefore for a "lonely" disc, i.e. a disc alone in the universe, there can be no distinction between rotation and non-rotation. In effect, Leibniz and Mach hoped to develop a mechanics in which Newton's arguments would fail, because the mechanics would contain a law that vetoes Newton's putative possibilities in which the total material content of the universe rotates: the law would require that the total angular momentum of the universe be zero. Such a relational mechanics has now been developed, especially by Barbour et al.; (for discussion and references, cf. Earman 1989, p. 27-30, 92-96, Belot 2000, p. 570-574, 580-582, Pooley and Brown 2002, Butterfield 2002 296-311). But I set these theories aside in what follows.

(ii) Nowadays, it is clear that, even apart from alternative relationist mechanics, Newton's arguments fail in one precise sense. That is: all now agree that:

(a) Though (relationism apart) Newton was justified in inferring from the dynamical effects of rotation that acceleration had an absolute (i.e. coordinate-independent) physical significance;

(b) And though Newton was justified, within the mathematics of his time, in inferring that absolute acceleration could only make sense if there was also absolute velocity (since acceleration seems to be "just" the time-derivative of velocity), and thereby also absolute position (since velocity seems to be "just" the time-derivative of position);

(c) Nevertheless, modern mathematics enables us to make sense of absolute acceleration (and its quantitative measures), and so of the contrast between straight and helical worldlines, *without* an absolute space (*and* without having a notion of absolute velocity).

The idea in (c) is mathematically subtle: it only became clear in the 1920s (in the work of Weyl, Cartan etc.) after relativity theory prompted physicists to think in terms of spacetime concepts. But I will not need to develop it in detail (cf. e.g. Sklar 1974 pp. 202-206, Earman 1989 p.33). Here it suffices to say that we postulate a geometric structure on spacetime called an *affine connection* (for short: connection), which essentially defines a notion of straightness, and thereby notions of amounts of curvature, for curves in spacetime. Applied to timelike curves, these are notions of unacceleratedness, and amounts of acceleration. A spacetime that is non-relativistic (has a notion of absolute simultaneity) and is equipped with such a connection—but is not equipped with a notion of absolute space, that induces the connection—is called *neo-Newtonian* or *Galilean*.

So to sum up (ii): we *can* make sense of absolute acceleration without absolute rest or absolute velocity. Although a connection *can* be legitimately defined by a notion of absolute rest, as Newton in effect did, it is a logically weaker idea than a notion of absolute rest, and so can be postulated directly—without the rest. Besides, relativistic theories (both special and general) also have a connection in just this way (without absolute rest): they differ in that they *also* lack absolute simultaneity.

5.3 Connections, metric and rotation

So let us ask: how is motion, and in particular rotation, described using a connection? I shall summarize the answer in three Subsections. The first introduces the ingredients needed for describing motion; the second gives more details about the description of rotation; and the third reports some subtleties of general relativity.

5.3.1 Common ingredients

The first thing to say is that most (but not all!) of the ingredients for describing motion are *the same* in most spacetime theories: both non-relativistic (with and without absolute space: Newtonian and neo-Newtonian) and relativistic (special and general). (Again, I set aside the relational theories of Barbour et al.) But we will see in Section 5.3.3 that general relativity has some very special features.

The foremost "common ingredient" is that all these theories describe rotation by invoking two types of mathematical structure, which mesh in an appropriate way.

The first type is relatively familiar: it is metrical structure, which we can think of as primarily assigning a length to curves in spacetime. In relativistic theories, there is a single notion of length for all curves: a spatiotemporal metric. In non-relativistic theories, there are two notions of length—spatial length for spacelike curves, and temporal length for timelike curves: so there is a spatial metric and a temporal metric. For both kinds of theory, I will speak of 'a spatial metric and a temporal metric'.

The second type of structure is the connection, which gives a standard of straightness, and numerical degrees of curvature, for an arbitrary curve in spacetime, and so in particular for the worldline of a point-particle, or point-sized bit of matter in a continuous body.

The meshing required between the two types of structure is called *compatibility*. (In fact, in relativistic theories (whether special or general) any spatiotemporal metric has a unique compatible connection; but in non-relativistic theories, the two metrics (spatial and temporal) do not fix a unique compatible connection.)

So to sum up: Only once we have in hand a spatial metric, temporal metric and a compatible connection, does the judgment that a disc is rotating—that its matter's worldlines are "helical rather than straight"—even *make sense*.[24]

5.3.2 Details: the rotation tensor

This Subsection and the next spell out some details about how the metrics and connection give a framework for describing rotation. This Subsection makes two points which are in common between the theories; the next makes points which are specific to general relativity.

(a) *Acceleration of a single particle*:
For a single worldline, i.e. the worldline of a single point-particle, the connection defines at each point along the worldline a (four-dimensional) acceleration of the point-particle. Using the metrics, one can also define the more familiar three-dimensional acceleration. This point holds good in both non-relativistic and relativistic theories.

(b) *Rotation, local and non-local*:
Though one can define in these theories the rotation of one point-particle relative to another, this notion is not usually treated in the textbooks: (and general relativity holds some surprise about it—cf. (b) of Section 5.3.3). Nor is the notion of a swarm of point-particles rotating about another particle (or about a spatial point) treated in the textbooks. In fact, they concentrate on the case of most relevance to the RDA: the case where we are given a *congruence* of timelike curves, i.e. a continuously infinite collection of worldlines whose points of intersection with a (possibly finite) spacelike slice completely fill the slice. (So the worldlines might be given as the integral curves of the 4-velocity vector field of some continuous matter.) And for this case, the textbooks define a *local* notion of rotation.

That is: the metrics and compatible connection together define at each point in the congruence a *rotation tensor*, usually symbolized as ω, which gives a quantitative measure of the speed and direction of rotation (of the congruence) in an arbitrarily small neighbourhood of that point. Roughly speaking, ω at a point in spacetime encodes how an observer located there sees the limitingly close worldlines of the congruence swirling around her. For us, this construction is important in two main ways.

(i): The construction of ω proceeds in much the same way in the different theories; (for more details, cf. e.g. Misner et al. 1973, p. 566; Dixon 1978, p. 121-128, 140-145, 163-166; Wald 1984, p. 216-218).

(ii): The construction is a *robust* local limit of other *non-local* definitions of rotation. By this, I mean the following; (I thank David Malament for explaining this). There are various intuitively compelling (and experimentally realizable) criteria for whether an extended object, such as a disc, is rotating; but as one considers smaller and smaller discs, the verdicts of these various criteria as to whether a given disc is rotating *converge* on the verdict given by the rotation tensor (i.e. by whether or not

[24] Or rather, this is true once we set aside relational mechanics. More precisely: only with these structures can one make sense of the judgment that the disc is rotating, irrespective of its relations to other bodies—and in particular, if it is lonely.

$\omega = \mathbf{0}$). So the local notion given by the rotation tensor is a common "robust" limit of the other criteria. Besides, this is so in all the different theories.

To give an example: one such criterion supposes that an observer at the centre of the disc bolts a telescope to a water-bucket and then continually observes a light source fixed on the edge of the disc: the disc is judged to be rotating iff the water-surface is concave. Another criterion supposes that a light source fixed on the edge of the disc sends light-signals right around the edge of the disc, in both directions, and asks whether the two signals arrive back simultaneously: the disc is judged to be rotating iff there is a difference.

In (c) of Section 5.3.3, I will discuss how in general relativity, these criteria (and others) can *disagree* in their verdicts about whether an extended disc is rotating. But for the moment, I just make the more "positive" point that as the disc shrinks in size, all these criteria must (in *all* the theories) tend towards agreeing with each other—and with the mathematical condition that the rotation tensor ω at the centre of the disc is non-zero.[25]

5.3.3 Rotation in general relativity

I turn to report three points which indicate the subtlety of rotation in general relativity. The first point is standard material in the physics textbooks: but worth reporting since, as we shall see, it implies that the RDA fails in general relativity. The second and third points are specialist knowledge: striking results by Malament (2002, 2003).

(a) *Frame-dragging*: According to general relativity, there is an (amazing) physical effect of rotation, understood in Section 5.3.2's sense that $\omega \neq 0$), on spacetime itself. Namely, a rotating body distorts its nearby spacetime geometry; or as it is more vividly put, the rotating body "drags" the inertial frames in its vicinity (hence the name 'frame-dragging'). That is: test particles falling freely under gravity near a body move differently, according to whether the body is rotating (and in what sense, and how fast)—they "feel" not just the mass of the body, but also its state of rotation. (Cf. Misner et al. 1973, p. 699, 879, 1117.)

The theory of this effect goes back to 1918 (by Thirring and Lense). The effect is numerically minuscule, even when the rotating body is very massive, e.g. the earth. Yet the dragging of frames by the rotating earth may soon be detected.[26]

[25]By the way: to define, not the rotation tensor, but merely the qualitative distinction, rotating vs. non-rotating, one does not need all of Section 5.3.1's ingredients, metrics and compatible connection. One needs only a *conformal structure*: which is, roughly speaking, a structure in which angles are meaningful but lengths are not. A conformal structure can be encoded by an equivalence class of metrics, with equivalence classes $[g_0] := \{g : g = \Omega g_0\}$; where Ω is a positive smooth $\mathbb{R}$-valued function on spacetime, and where this structure is to be again compatible with the connection (where 'compatible' is spelt out by adapting the usual relativistic and non-relativistic conditions for a given metric by an existential quantifier over the equivalence class).

[26]Namely, by tiny supercooled gyroscopes in an orbiting satellite, recently launched. Some numbers make vivid how ambitious, and delicate, is this experiment (called 'Gravity Probe B'). After a year in orbit, the drag on a gyroscope will be 42 milliarc-seconds, which is the angle subtended by a metre-

(b) *Relative rotation of two particles*
In this and the next point, I report two much less well-known peculiarities—indeed surprises—of rotation in general relativity. But they are only needed briefly later (in (B) of Section 5.6); so the reader can skip to the summary of this Subsection.

For a pair of worldlines, X and Y say, in either a non-relativistic or a relativistic theory, one can define a "direction from X to Y" (and *vice versa*), and its "rate of change", and thereby define the "angular velocity of Y relative to X". Besides, the physical ideas behind these definitions are natural, and similar, in non-relativistic and relativistic theories: e.g. in relativity theory, the direction from X to Y is given by the direction of the tube of a telescope held by an observer on X who continually observes Y. (And one can extend these definitions so as to talk about a collection of worldlines (particles) $Y_1, Y_2, \ldots$ rotating relative to a given particle X.)

But even with just two worldlines, general relativity surprises us. In non-relativistic theories, the defined notions have the expected properties: in particular, the angular velocities of Y relative to X, call it ω_{XY}, and of X relative to Y, ω_{YX}, are equal. But this is *not* so in general relativity. In this theory, Y can be non-rotating relative to X, i.e. $\omega_{XY} = 0$, while X rotates relative to Y, i.e. $\omega_{YX} \neq 0$; and this can be so while the distance between X and Y (in any reasonable sense of 'distance') remains constant, and is as small as you care to demand! (For details, cf. Malament 2003.)

(c) *Conflicting criteria of rotation*
Finally, general relativity also holds considerable surprises about the RDA's case: the rotation of a disc (or a sphere or hoop). One surprise is that different intuitively compelling (and experimentally realizable) criteria for whether a disc is rotating can give different verdicts—not in all spacetimes, but in some. Thus recall the two examples from (b) of Section 5.3.2. The first asks if the water-surface in the bucket at the centre of the disc is concave; the second asks if light-signals circumnavigating the disc in opposite directions arrive back at different times. These criteria will match in their verdicts for any disc in a non-relativistic spacetime, or in the Minkowski spacetime of special relativity. Besides, in any general relativistic spacetime, they must tend to agreement with each other, and with whether the rotation tensor is non-zero, for smaller and smaller discs (as discussed in (b):(ii) of Section 5.3.2). But for a disc of given size, there are general relativistic spacetimes in which the verdicts will *differ*; e.g. Kerr spacetime (Malament 2002).

Indeed, more is true: *any* criterion of rotation for a disc must violate *some* intuitively compelling condition in *some* general relativistic spacetime! More precisely: Malament (2002) shows that any criterion of rotation (in the very weak sense of a binary classification, for any disc in any state of motion, as to whether it qualifies as rotating), that agrees with the water-surface criterion (and so with the rotation tensor criterion: $\omega \neq 0$?) in the limit of smaller and smaller discs, must violate another

stick at a distance of 3000 miles, or the thickness of a sheet of paper at a distance of a mile. To prevent this minuscule effect being masked by random thermal motions, the gyroscope must be cooled to very close to absolute zero; and then one has to measure the effect by radio contact with the satellite a year after its launch. No wonder the experiment has been designed over some thirty years!

compelling condition, when it is applied to a spacetime like the Kerr spacetime. (This other condition is roughly: if a disc d_1 is not rotating, and d_2 is rigidly attached to d_1 in the sense that the distance between any two point-sized bits of matter in d_1 and d_2 is constant over time, then d_2 is also not rotating.)

To sum up Sections 5.2 and 5.3:— To make sense of rotation, it is by no means enough to draw straight vs. helical worldlines. One needs a considerable body of theory: specifically, spatial and temporal metrical structure, and a compatible connection (whether or not induced *a la* Newton by a notion of absolute rest). With this equipment, one can define (in much the same way in the different theories) a robust local notion of rotation, expressed by the rotation tensor. But in general relativity, rotation has complex and even counter-intuitive features, especially as regards the rotation of extended bodies—like a disc.

I believe this technical material yields two significant conclusions about the RDA, which I will develop in Sections 5.5 and 5.6. But first (Section 5.4), I need to connect this material to the endurantism-perdurantism debate in general, by stating some familiar general assumptions about the bearing of physical theories on metaphysical theses.

5.4 The endurantism-perdurantism debate in the light of physics

I began this Section by recalling Section 3.2.2's demand that both endurantist and perdurantist should state and justify the claims they need to make about spatiotemporal structure. We have now seen that these claims are technical; and that physics always formulates them in terms of equipping a manifold of spacetime points with various mathematical structures. So even apart from the RDA, the question arises whether the endurantist and perdurantist have "equal rights" to these claims.

This is a large question. I will lay out some of its aspects, but not pursue them in detail. My reason is that I want to give endurantism some rope. That is: since I want to give the RDA against perdurantism as good a run as possible, I will give endurantism the benefit of the doubt about its right to these claims.

(i) *Traditional associations*:
Our question has two traditional associations:

(a): Perdurantists have traditionally argued that their position fits much better than does endurantism with the description of matter, space and time in modern physics; and in particular, with the description in spacetime theories like relativity theory. On the other hand, endurantists often distinguished the conceptual schemes of physics and everyday thought, and took their position to be about the latter.

(b): The endurantism-perdurantism debate is also traditionally aligned with the debate whether there is objective "temporal becoming", as against the "tenseless" or "block universe" theory of time being true. Again, modern physics, especially relativity theory, has been taken to support the tenseless view, and thereby perdurantism.

(ii) *Today's debate*:
But nowadays, endurantism's traditional associations, as sketched in (a) and (b) of (i), are broken.

As regards (a), many endurantists are "scientific realists", and even substantivalists about spacetime. They believe that successful scientific theories like relativity theory, literally construed, are approximately true; and even that spacetime points are *bona fide* objects bearing the properties and relations represented by mathematical structures like metrics and connection.

As regards (b), the tenseless view is nowadays often called 'eternalism'—and many endurantists endorse it. (On the other hand, the currently most popular version of becoming seems to be presentism, the doctrine that only the present exists—which is no doubt at least as hard to reconcile with relativity's denial of absolute simultaneity, as are other versions of temporal becoming.)

I think the breaking of these associations reflects both: the rise of philosophical naturalism (cf. Section 1.3); and (more contentiously!), the difficulty of defending (or even making sense of!) the idea of temporal becoming. In any case, the upshot is that nowadays, the endurantist is likely to claim "full rights" to the technical claims of modern spacetime theories, just as much as perdurantist does. (For more discussion of the current standing of both traditional associations, (a) and (b), cf. Butterfield 2004 and Sider 2001 pp. 75-76, 110-119.)

(iii) *Three questions*:
Accordingly, I think that our large question breaks down, at least nowadays, into the following three questions, (A) to (C). The first two questions, I propose to set aside, since they are independent of the endurantism vs. perdurantism debate.

(A): The first pertains to general philosophy of science. It is the question: should one be (a) a scientific realist about the theoretical claims of modern spacetime theories, especially general relativity, or (b) some sort of instrumentalist (maybe constructive empiricist) about them? So in setting this question aside, I shall in effect speak like a scientific realist: which is anyway the widespread practice of much current discussion of endurantism and perdurantism—cf. (ii) above.

(B): The second question pertains to the philosophy of (chrono)geometry. Even if we are scientific realists, and even substantivalists, there is a further question about how we should interpret spacetime points' properties and relations as represented by e.g. metrics and connection. One view is that they are in some strong sense independent of the physics of matter (and radiation), at least in theories where the metrics and connection are not dynamical. (I think this is the dominant view among substantivalists.) An alternative view is that these properties and relations *are* dependent on the physics of matter: for they are a way of compendiously representing some features, especially invariances, of the dynamical equations governing matter. (This is the view—at least as I read them!—of Brown and Pooley; cf. Brown and Pooley 2001, 2004.) Again, I shall not pursue this question; so I shall in effect speak like a substantivalist—which is anyway widespread in current discussion.

(C): So: setting (A) and (B) set aside, and assuming substantivalism, and (as in (i)) that the perdurantist thereby has "full rights" to the technical claims of modern spacetime theories, our question becomes: does an endurantist have equal rights to them?

Note that even with these assumptions in place, one can envisage two versions of endurantism. The first version is committed to spacetime points and sets of them (and their properties and relations), but does not accept spacetime regions as spatiotemporally located objects (say as mereological fusions of points). Rather, regions are to be treated as sets of points; and sets are "abstract" in at least the sense that they are not located in spacetime—and therefore in no sense persist. Since such regions, taken to be spatiotemporal objects, would surely persist by perduring, not enduring, this version's denial that regions are spatiotemporal objects enables it to hold, not only that ordinary material objects endure, but also that *no* spatiotemporal object perdures.

On the other hand, a second version of endurantism accepts spacetime regions as perduring objects, and so is what I will call a *mixed view*: some objects endure, but others perdure. (These others include at least spacetime regions, but maybe also other objects which one might call 'events', like wars or meals; (for more discussion, cf. Butterfield 2004).)

So our question is whether either of these versions of endurantism has as much right to the technical claims of modern spacetime theories as the perdurantist does.

A proper answer to this question would have to investigate two main topics:

[i]: whether there are problems about the mixed view (i.e. the mixed view for spacetime points—nevermind wars and meals); and

[ii]: whether relativity theory makes problems for endurantism (as it certainly does for temporal becoming);

and then decide whether any such problems could be solved.

As I announced above, here I want to give the RDA against perdurantism as good a run as possible, and so I will simply *assume* that (setting aside the RDA) there are no such problems—that the answer to both [i] and [ii] is 'No'.

This assumption can be partly defended by appealing to a formal equivalence between the ways that endurantism and perdurantism describe the motions of point-particles and continua (in both non-relativistic and relativistic spacetimes). The idea of the equivalence is that:

(a): an endurantist will represent the motion of a point-particle, or a point-sized bit of matter in a continuum, by a single function $q : t \mapsto q(t) \in \mathcal{M}$, mapping times at which it exists to locations in a manifold $\mathcal{M}$ (either space or spacetime); while

(b): the perdurantist will use a collection of functions, labelled by time-intervals that together cover the object's lifetime; for example, if it exists throughout the closed time-interval $[a, b]$, there might be a function $q_{[a,b]} : t \in [a, b] \mapsto q_{[a,b]}(t) \in \mathcal{M}$.

I develop this equivalence (including extending it to spatially extended objects), and relate it to both [i] and [ii] in Butterfield 2004 and 2004a. But I should also note that this equivalence gives only a partial defence of the assumption, that the answer to both [i] and [ii] is 'No'. For the equivalence is formal; and formal equivalences are liable to be broken by philosophical considerations. (For more discussion, cf. e.g. Balashov 1999, 2000 for [ii]; and Sider 2001 p. 110-119 for [i], and p. 79-87 for [ii].)

5.5 Dynamical effects revisited

So much by way of general connections between the physics of rotation and the endurantism-perdurantism debate. I now return to the RDA, and to arguing, in this Subsection and the next, for two main conclusions.

In this Subsection, I return to the accompaniments of rotation, especially dynamical effects like oblateness. Since Section 1.4 (and especially since Section 3.4) I have assumed, along with the metaphysical literature, that the RDA's advocates need to justify "imagining away" any accompaniments that the perdurantist might latch on to as marking the distinction between the discs, (Stat) and (Rot).

The physics of rotation—the material in Sections 5.2 and 5.3—yields three main points about this assumption, which I develop in the next three Subsections. In short:—

(i): One main theme of Sections 5.2 and 5.3 supports the practice by the RDA's advocates, of ignoring such accompaniments (Section 5.5.1).

(ii): But the advocates are lucky—it is an undeserved victory—since their *avowed* reasons for ignoring such accompaniments, especially dynamical effects, are *worse* than what these Subsections provide (Section 5.5.2).

(iii): But in any case, the RDA can be developed very effectively, *without* imagining away all such accompaniments (Section 5.5.3).

5.5.1 Rotation is kinematic

We saw in Section 5.3.2 that rotation—and its quantitative measures, given by the rotation tensor locally, and by various criteria non-locally—is definable in a wholly *kinematic* way: i.e. without mention of dynamics. In less abstract terms, it is definable in terms of acceleration, without mention of forces (or more generally, the causes and effects of motion).

Agreed, it was perhaps Newton's greatest insight to couple acceleration and force, viz. in his second law of motion $\mathbf{F} = m\mathbf{a}$. But that is a nomic, not logical connection. Force could instead be coupled to velocity, i.e. the first derivative of position (an "Aristotelian mechanics"), or to a higher derivative than the second: such alternative schemes change physical behaviour enormously, but are logically coherent.

(Indeed, in a framework in which force is coupled to velocity, but which is otherwise as close to classical mechanics as possible, a body's future motion would be determined by its position, and the force acting on it. This would imply, I take it, that:—

(a): Metaphysicians like Tooley, Bigelow and Pargetter would feel no temptation to introduce a heterodox intrinsic notion of velocity to act as cause and *explanans* of future positions.

(b): More importantly for us: the RDA would have much less bite, at least for a "naturalistic" perdurantist, who is willing to let her account of perdurance depend on the actual laws. For now ingredients that the RDA agrees to be available to the perdurantist (more generally, the Humean), viz. position and forces, *would be* enough to determine future positions. I will return to this in the context of quantum theory (Section 8.1.1).

More radically, rotation makes sense without any forces at all—nevermind how force couples to kinematic quantities. To talk in terms of possible worlds: there are worlds with a spacetime manifold, spatial and temporal metrics and compatible connection, and a congruence of timelike curves representing continuous matter—again, nevermind the forces. A pair of these worlds can match in countless ways and yet differ as to whether the matter is rotating, in say the usual local sense, i.e. at some given point in their common spacetime. Just suppose that in one world the rotation tensor is zero at the point, while in the other it is non-zero.

I take this as evidence that perdurantism should strive to accommodate the distinction between these possibilities.

I do not claim that it is conclusive evidence. Some perdurantists such as Callender (Section 3.4) will still prefer the 'No Difference' reply to the RDA. That is: they will say that worlds with no dynamics are so unlike the actual world, that perdurantists have no responsibility to distinguish rotation and non-rotation within them (cf. Callender 2001, p. 38).

But I do not need to resolve this dispute between myself and fellow-perdurantists. For all perdurantists can agree to the more important conclusions in the following Subsections.

5.5.2 Beware of rigidity

On the other hand, I think that advocates of the RDA have often had worse reasons than than that just given, for insisting that the perdurantist should distinguish (Stat) and (Rot) even without any of the usual accompaniments of rotation. I will not try to catalogue people's errors, but will focus on one prevalent reason. (Parts of this Subsection's critique will carry over to versions of the RDA that use a homogeneous fluid, rather than a rigid solid.)

This reason is the belief that it is entirely straightforward to "imagine away" the accompaniments, since one only needs to stipulate that the discs are perfectly rigid. This implies in particular that the rotating disc will not be oblate—and so the RDA will be posed, to the consternation of the perdurantist.

This reason is defective in two ways. First: to say these two words 'perfectly rigid', so "trippingly off the tongue", is to forget that within the theories of classical continuum physics, perfect rigidity is a very strong idealization—it violates central principles of these theories.

To take our example: what in fact would happen when a (classical, continuous, homogeneous) stationary disc is given a push at its edge to make it rotate, is very complicated. A disturbance would travel outward (at the speed of sound for the disc's material) from the place where the push is applied, leading to a complex process that settled down so that the whole disc rotated approximately uniformly, with internal cohesive forces exerting the required centripetal forces on parts of the disc. (In the actual quantum world, this description is a very good approximation for solid discs, the cohesive forces being electromagnetic forces between atoms. But I am here just assuming a classical continuum treatment.) Without going into further details, this is enough to bring out that assuming perfect rigidity requires that the disc's cohesive forces should respond "infinitely quickly" to distorting influences. More precisely, it amounts to vetoing any account of how the whole disc is set in motion as a consequence of the motions of the parts. (In physics jargon: it vetoes any constitutive theory.)[27]

Second: it is *not* true that perfect rigidity gets rid of all the actual technical accompaniments of rotation. For not all such accompaniments are kinematically manifested, i.e. associated with changes in shape or size, like oblateness. There are also forces and energies that *would* be present in a perfectly rigid rotating disc. (In physics jargon: some dynamical effects of rotation involve stress rather than strain.) There will be cohesive forces throughout the disc's interior which would be absent if the disc were stationary: besides, the disc's energy is greater—which means in relativity that its *mass* is greater. Though such accompaniments are more technical, less commonsensical, than being oblate, that is no reason to think the perdurantist is less able to appeal to them, so as to distinguish (Stat) and (Rot).[28] So it seems the RDA will also need to imagine away these "kinematically hidden" accompaniments.

Finally, I note that this critique of just assuming perfect rigidity leads us back to Section 2.1's theme, that classical mechanics is more subtle and problematic than philosophers usually recognize.

More specifically, I think that a traditional philosophical view, that forces are unobservable, underlies the second defect above, i.e. the allegation that the perdurantist can appeal only to accompaniments of rotation that are kinematically manifested. I cannot here go into details about why this view is wrong. Suffice it to say that I think it mainly arises from either or both of:

(a): an overly strong empiricism, that the only physical quantities to which we have empirical access are some small handful, no doubt including length, time, mass

[27]Two incidental remarks about rigidity. (1): There is also the worry that perfect rigidity violates relativity's prohibition on faster-than-light signals. But in fact, relativistic theories allow generalized notions of rigidity: for a philosopher's introduction, cf. Earman (1989, Chapter 5.5, pp. 98-101). (2): Among Bigelow and Pargetter's arguments for their heterodox account of instantaneous velocity, as not always a limit of average velocities, is a thought-experiment involving perfectly rigid spheres (1989, pp. 292-293, 1990, pp. 67-68). As it happens, I disagree with their argument, but I will not go into details: as I have said (starting in Section 1.2), I am not convinced by such heterodox accounts of velocity—and my reply to the RDA does not need them.

[28]At least: it is only a reason if we take the endurantism-perdurantism debate as entirely a matter of analyzing everyday concepts. In particular, the RDA cannot just consider an oblate rotating disc and a non-rotating one moulded so as to be congruent to it (as proposed by Hawley 2001, p. 83-84).

and charge—but excluding force;

(b): a distortion of Hertz' research program in the foundations of classical mechanics. Thus Hertz proposed to explain forces in terms of cyclic microscopic variables; (Lanczos (1986, Section V.5, p. 130-132) explains the idea). But had he succeeded, forces would *not* have been rendered unobservable.

5.5.3 An improved RDA—allowing dynamical effects

I said just now that it seems the RDA will need to imagine away accompaniments involving stress, as well as those involving strain. But in fact, not so: it only seems so. More precisely: the RDA can be developed, and be a powerful argument against perdurantism, *without* imagining away any accompaniments of rotation. We only have to change the example a bit, so that two possibilities, apparently distinct on account of worldlines, match exactly in such accompaniments.[29]

Thus the endurantist challenges the perdurantist to distinguish the possibilities:—

(Same): Two perfectly circular discs, d_1 and d_2, both made of continuous homogeneous matter and lying in the same spatial plane—but otherwise as different as you please from one another—spin in the same sense (i.e. both clockwise as seen from one side of the plane, and so anti-clockwise as seen from the other side).

(Different): Two discs, d'_1 and d'_2, match d_1 and d_2 *respectively* in all respects (at all times); except that d'_1 and d'_2 spin in opposite senses relative to one another.

The idea is that all the usual accompaniments (stress as well as strain: forces and energies as well as distortion) match between d_1 and d'_1; and similarly between d_2 and d'_2. So there is no need to imagine them away, in order to challenge the perdurantist.

Nor is there any need for discs *within* one of the possible worlds to match in any respect, except being perfectly circular, made of continuous homogeneous matter, lying in the same spatial plane—and for (Same), spinning with the same sense.

Four comments, in descending order of importance, by way of clarifying this formulation of the RDA:—

(i): Intuitively, (Different) describes equally well two distinct possibilities: one in which d'_1 spins in the same sense as both d_1 and d_2; and the other in which instead, d'_2 shares their common sense of rotation. This contrast of course depends on there being a fiducial spatial direction in common between the possibilities. I agree that this idea is perfectly coherent: though I emphasise, as Callender did with his pseudo-distinction between the arrow's states (Up) and (Down) (Section 3.4), that the direction needs

[29] Paul Mainwood and David Wallace devised the following formulation in a seminar in autumn 2003. The idea of exploiting the distinction between two senses of rotation, so as to avoid having to imagine away the usual accompaniments, had already been briefly advocated by Dean Zimmerman (1998, p. 268-269), crediting an anonymous referee. But beware: Zimmerman's discussion can be read as placing each disc in a separate possible world—in which case it fails, as explained in (ii) below. Zimmerman kindly points out (personal communication) that this was not his intention; so that his formulation of the RDA is essentially the same as that invented by Mainwood and Wallace. For novelty and precision, I present theirs. My thanks to them and Zimmerman.

to be specified by something salient in the environment, such as a local gravitational field giving one an up-down distinction, on pain of its being a distinction without a difference, i.e. a spurious distinction—an artefact of a diagram, or of our visual imagination. So: given such a specification, (Different) indeed represents two possibilities. No matter: to challenge the perdurantist, the RDA can simply consider either one of them.

(ii): (This follows on from (i).) The danger of making a distinction without a difference also crops up in another way. As mentioned in footnote 29, a formulation of the RDA in terms of distinguishing two senses of rotation (and thereby keeping the usual accompaniments) has been urged before, by Zimmerman (1998, p. 268-9). But Zimmerman's brief discussion can be read as challenging the perdurantist to distinguish between a disc rotating clockwise, alone in its possible world, and a duplicate disc rotating counterclockwise at the same rate, alone in *its* world. And this formulation fails for the reason emphasised in (i): the clockwise-counterclockwise distinction assumes a fiducial spatial direction in common between the possibilities, which for these "lonely" discs is a spurious distinction. (Callender (2001, p. 32, 36-7) seems to read, and object to, Zimmerman in this way.) Our formulation above avoids this difficulty by considering two discs in each possible world, so that we need only *intra*-world comparisons of the sense of rotation.

(iii): The possibilities can be modified in various ways. In particular, to secure the needed intra-world comparisons of sense of rotation, we do not need two discs. (Same) could instead contain just one disc, rotating in the same sense as a curved arrow drawn on a sheet of paper lying beside it; (Different) would then similarly contain a single disc rotating contrary to the sense of another curved arrow drawn on an adjacent sheet of paper.

(iv): As in the original RDA, at the end of Section 3.1: we can also allow the discs' properties to change over time, and to vary in a circularly symmetric way—provided of course that they do so in a suitably matching way.

Finally, a comment about how the perdurantist should reply to this version of the RDA. I shall develop my own reply in the next Subsection and subsequent Sections. Here I just report my guess about how Sider (Section 4.4) would reply to this version of the RDA; (which of course, he does not discuss).

I think Sider would bite the bullet, just as he did in the "lonely disc" worlds he considered. That is: he would say that in a sufficiently simple two-disc world, there need be no unique facts about persistence, and so no fact of the matter about whether the two discs' senses of rotation match; (and similarly for the analogous world with one disc and a curved arrow drawn on paper).

5.6 The RDA fails in general relativity

So much by way of expounding some implications of the physics of rotation—the material in Sections 5.2 and 5.3—for the RDA literature's usual assumption that the RDA needs to imagine away the actual accompaniments of rotation.

But beware: the last Subsection's punchline—that this assumption is unnecessary, that the RDA can keep all the usual accompaniments—is *fragile*. This improved RDA, and the original version, both fail in the context of general relativity, because of the dragging of inertial frames around rotating bodies (cf. (a) of Section 5.3.3).

That is: in general relativity, the trajectory of a test-particle falling towards a massive body depends on whether (and how) the body is rotating: the rotating mass "drags", albeit very slightly, the inertial frames in its vicinity (Misner et al. 1973 pp. 699, 879, 1117). This frame-dragging means that the RDA fails in the sense that, in the usual version, the inertial frames (the worldlines of test particles) are dragged around the rotating disc (Rot), but not around (Stat); and in Section 5.5.3's version, there cannot be the perfect match in rotation's accompaniments both between d_1 and d'_1 and between d_2 and d'_2, since the dragging of inertial frames around a rotating body is different, for different senses of rotation. In short: the RDA fails because frame-dragging represents an appealing difference, to which a "sufficiently naturalist" perdurantist can appeal so as to answer the challenge of distinguishing the possibilities.[30]

Before asking how the advocate of the RDA might respond, it is worth making two comments.

(A): First it is worth listing—as a partial review of the story so far—the five main ideas that have led to this conclusion. This "cast, in order of appearance" is:

(i): the idea that since a (consistent and precise) physical theory specifies a set of solutions (in philosophers' jargon: possible worlds), the RDA could hold in one such theory and fail in another; (cf. (2A) in Section 1.3);

(ii): the idea that classical mechanics is subtle and problematic, and leads to relativity theory and quantum theory; so that there is good reason to consider general relativity as the setting of the RDA (even apart from its being our best guess about space, time and matter); (cf. especially the qualms about action-at-a-distance in Newtonian gravity, in Section 2.1);

(iii): the idea that the perdurantist can reply to the RDA by finding differences between the possibilities, (Stat) and (Rot), that she can appeal to; (Appealing Differences) in Section 3.4;

(iv): the dragging of inertial frames around rotating bodies in general relativity (cf. (a) of Section 5.3.3);

(v): the idea that the endurantist will want to accept, as much as the perdurantist, the technical claims of general relativity's description of spacetime (presumably by being a scientific realist, maybe even some form of substantivalist); and this will involve a largely literal (though perhaps not a substantivalist) construal of general relativity's ascription of a dynamical geometry to otherwise empty spacetime; (Section 5.4).

(B): The RDA failing in general relativity does *not* mean there is no more to say about the endurantism-perdurantism debate in the context of general relativity. As always in philosophy, there is plenty to explore! In particular, the subtleties of rotation

[30]This argument against the RDA, in its usual version, is due to Callender (2001, p. 38); it is part of his 'No Difference' reply.

in general relativity (witness Malament's results in (b) and (c) of Section 5.3.3) return us to question [ii] at end of Section 5.4. That is: can endurantism and perdurantism really make equally good sense of all these subtleties?

If not, so much the worse for whichever party cannot make sense of them. For once you have gone beyond traditional conceptual analysis to the extent of considering general relativity, it would surely be *ad hoc* to rule out of court whichever of the general relativistic spacetimes, such as the Kerr spacetime, you have trouble making sense of. That is, you cannot just declare that the spacetime represents a world which is "so unlike ours" as to make considerations based on it irrelevant to the endurantism-perdurantism debate. (In any case, the spacetime in question might not be "exotic": assuming scientific realism, it might describe, or approximately describe, our world.)

I turn to the question how the advocate of the RDA can respond. Could she improve the argument's thought-experiment so as to allow for frame-dragging, in the kind of way that (Different) and (Same) improve on (Stat) and (Rot) by allowing for the usual accompaniments of rotation? Perhaps, but I do not see how.

On the other hand, the endurantist has two lines of reply, even if she cannot thus improve the thought-experiment. Both return us to some questions raised before.

First, she might emphasise that in developing the RDA for general relativity (in the usual, or Section 5.5.3's, version) she can stipulate that the discs are "lonely", i.e. that there are to be no test-particles travelling the dragged worldlines. Does this stipulation make the difference to which the perdurantist appeals—viz. whether the frames are dragged, and if so, how—counterfactual? The answer depends on the interpretation of general relativity. Roughly speaking, a substantivalist will answer 'No', since they take the metrical structure of spacetime to be real and occurrent: it is not just an encoding of how suitable bodies would behave. But the endurantist may argue that she can accept general relativity, and so develop the RDA for it, without being a substantivalist in this sense; (cf. Section 5.4). On the other hand, even if we accept that the difference is counterfactual, perhaps the perdurantist can still appeal to it: (cf. Section 1.4).

The second reply is the obvious one about philosophical method. Surely no philosophical account of persistence should be "so far gone" in naturalism as to depend on general relativity: it should be able to accommodate continuous matter in classical and special relativistic spacetimes (cf. (2.B) in Section 1.3). And for these cases, the RDA remains unrefuted, at least in Section 5.5.3's improved version.

I think the second reply has force. But in Sections 7 and 8, I will argue that the perdurantist can meet the challenge of defeating the RDA even outside general relativity: in short, by accepting only non-instantaneous temporal parts. Besides, this version of perdurantism is supported by some heterodox proposals about the intrinsic-extrinsic distinction among properties: proposals which are themselves supported by some features of classical and quantum physics.

6 Replying to the RDA

6.1 Two replies

We have seen in Section 5 how the RDA fails in general relativity—but, so far, looks good in classical mechanics. But only 'so far'! From now on, I will develop two replies to the RDA: the first in this Section (Section 6.2), and the second in Sections 7 and 8.

The first reply is an analogue of Sider's (Section 4.4); the main difference being that it is less metaphysically committed and closer to the detail of empirical enquiry. But like Sider's reply, it will be a combination of (Appealing Differences) and (No Difference). In particular, it bites the bullet as Sider does, in that it denies the distinction between the discs, in sufficiently simple worlds. The endurantist advocate of the RDA will of course see this bullet-biting as conceding victory to the RDA, or at best as forcing a stalemate.

This situation will prompt the second reply, which is my preferred reply. It is a version of (Appealing Differences), not (No Difference), given by a modest version of perdurantism which accepts only non-instantaneous temporal parts.

6.2 Some details of persistence within classical mechanics

6.2.1 Comparison with Sider

I can present this reply to the RDA most clearly, by first stating the similarities and differences between it and Sider's reply. There are three similarities.

(i) Like him, I envisage that the perdurantist appeals to a wide "web of belief" to yield a perdurantist definition of persistence.

(ii) Like him, I allow this web to involve technicalities, so that the perdurantist account of persistence is "naturalistic" (Section 1.3): in particular, the account is not a conceptual analysis of the sort traditionally sought by metaphysicians.

So the idea is that the perdurantist defines persistence by appealing to the various relations that the notion has to other notions, including technical ones. Like Sider, I will discuss these relations only for classical mechanics; (in particular, I will not need to distinguish between using a Newtonian and a special relativistic spacetime).

(iii) Like Sider, this reply will bite the bullet in that it denies the distinction between the discs, for cases using sufficiently simple possible worlds, such as worlds with lonely homogeneous discs or with space-filling homogeneous fluids.

On the other hand, there are two main differences from Sider.

(i) I will give more details about the theories of mechanics. For example, while Sider talks of 'the laws of dynamics' (or 'laws of nature'), I will be more specific, e.g. distinguishing point-particles and continua.

(ii) I will be less metaphysically committed. In particular:

(a) I will not be committed to the Mill-Ramsey-Lewis best-system theory of laws; nor to any other specific way of selecting the true "laws of dynamics" from a list of rival candidates.

(b) Nor will I be committed to the use of Ramsey-Lewis simultaneous functional definition; i.e. to the assumption that the body of doctrine selected by the method in (a)—the doctrine dubbed $S(\mathbf{G})$ in Sider's notation—is logically strong enough to uniquely specify $\mathbf{G}$.[31]

So the broad idea of this position is that by exploiting details about mechanics, the perdurantist can claim to define persistence, without having to be committed to Sider's philosophical methods (a) and (b).

A side-remark. One can of course take the details of this reply as "filling in" Sider's position, e.g. as giving details about how the best-system theory of laws applies to mechanics, rather than as providing an alternative to Sider's position. That is, in terms of Sider's notation (cf. Section 4.4): Sider could endorse the details in the next Subsection as exactly *what makes* the system $S(\mathbf{G})$ 'the system that achieves the best combination of strength and simplicity' (his p. 231).

6.2.2 Persistence and the web of belief

So let us join Sider in imagining a world governed by classical mechanics: a world that is not too simple, but has the sort of variety and complexity of motions of objects that we see in the actual macroscopic world.

So here, we are to set aside: (i) the fact that the actual world is quantum; and (ii) Section 2's misgivings about how problematic the ontology of classical mechanics taken on its own is. (There is no reason to think (i) and (ii) prevent a classical mechanical world having a variety and complexity of motions similar to that of the actual macroscopic world.)

We are also to set aside the question how in this imagined world the laws of mechanics earn the name of laws: in particular, it need not be (though it could be) by the best-system analysis of lawhood.

My task is to sketch (in more detail than Sider does) the "functional role" of persistence, the web of belief in which it is embedded. To do so, I shall proceed in three stages.

(1) *Kinds of Object*: First, I shall be more specific about the various kinds of object that are described by classical mechanics: I distinguish four kinds.

(2) *Persistence*: Then I discuss the persistence of these objects. This is a matter of applying familiar factors, qualitative similarity and causation, to the four kinds of objects.

(3) *Establishing the laws*: Then I sketch how the behaviour of these persisting objects could underpin the laws of mechanics, both as true generalizations and as laws:

[31] I think this debatable assumption of the Ramsey-Lewis technique tends to be forgotten: though not by Sider, nor of course by Lewis. Indeed, Lewis recognized that here lurk deep difficulties for his theory of natural properties; cf. his (2004).

even without using Ramsey-Lewis simultaneous definition.[32]

But I stress at the outset that, as is now familiar from Quine's "web" metaphor: ideas and propositions about each of these three stages of course influence, in various complex ways, ideas and propositions about the others. We do *not* first fix the objects, then discover or decide their conditions of persistence (diachronic criteria of identity), and finally establish what laws they obey. Rather, what counts as an object is influenced by the convenience of having different putative criteria of identity agree in their verdicts. And the laws of mechanics (or candidate laws) can contribute to determining persistence. For example, we might judge that o at t is the same persisting object as o' at t', despite some contrary evidence (e.g. insufficient qualitative similarity), just because the laws of mechanics prescribe for o at t (together with its velocity) a future trajectory that at t' passes through where o' then is. (This mutual influence between (1), (2) and (3) of course illustrates my similarities to Sider: both of us appeal naturalistically to a complex web of belief.)

(1) *Kinds of Object*:
As mentioned in Section 2, the main distinction among objects which classical mechanics makes is the distinction between:

(a): point-particles, i.e. extensionless point-masses moving through empty space (and so interacting by action-at-a-distance forces);

(b): continua, i.e. bodies whose entire volume is filled with matter.

Mathematically, this difference is in the first place one of finitude vs. infinity:—

According to (a), a system consists of a finite number of point-particles, so that the system's state is given by finitely many real numbers. (In fact, one needs six for each point-particle: three for its position in space, given by, say, coordinates in a cartesian coordinate system; and three for the components of its momentum.) So (a) conceives an extended macroscopic body, whether solid, liquid or gas—a brick, or a sample of water or air—as a swarm of a gigantic number of point-particles.

On the other hand, according to (b), a system—even a single small rigid body like a marble—consists of continuum-many point-sized bits of matter, one at each spatial point in the volume occupied by the body: so these bits of matter are truly "cheek by jowl" to one another! So we expect the system to be described by continuously many real numbers: indeed, "six times continuously many", to specify the position and momentum of each point-sized bit of matter. (I say 'we expect', because this is a simplification, albeit a harmless one in the present discussion. That is, as I stressed in (1) of Section 2.1: the *pointilliste* particles-in-motion picture is wrong. Classical mechanics in fact describes continua not point-by-point but in terms of the states of the countless arbitrary (in general, overlapping) sub-regions of the body.)

Accordingly, the systems treated *à la* (a) and (b) are often called, respectively, 'finite-dimensional' and 'infinite-dimensional' systems: or for short, 'finite' and 'infinite' systems. Broadly speaking, finite systems are in principle simpler since they

[32] I will not need to distinguish the various formulations of classical mechanics, in particular Newtonian, Lagrangian and Hamiltonian: one can think throughout just of Newton's second law $\mathbf{F} = m\mathbf{a}$.

are described by ordinary differential equations, while infinite systems require us to use partial differential equations, which are considerably more subtle and complicated, both in theory and in practice.

But even finite systems can be very complicated—in various senses, which I will not need to distinguish. All I need to say here is that even for a finite system, i.e. a swarm of point-particles, the number of real numbers needed to specify the state (called the number of *degrees of freedom*) might well be, though finite, intractably large. But fortunately, mechanics has various strategies for reducing such daunting numbers to something manageable.

The paradigm example of such a strategy is to assume that a body is *rigid*. Indeed, it is a strategy that applies both to finite systems and continua—in both cases, enormously reducing the number of degrees of freedom one needs to consider. The idea of rigidity is not just the everyday vague idea of being solid, like a brick: it is the precise assumption that all the distances between the body's smallest constituents—whether they are point-particles in a swarm, or point-sized bits of matter "cheek by jowl" filling a continuum—are constant in time.[33]

Putting together the finite vs. infinite contrast and the rigid vs. flexible contrast, we get a distinction between four kinds of object described by classical mechanics:

(i) a point-particle, i.e. an extensionless point-mass;

(ii) an extended object (in physics jargon: body) that is small and rigid enough that both its internal structure (whether a swarm of point-particles or a continuum) and its orientation can be ignored, so that it can be successfully modelled as a point-particle;

(iii): an object that, though extended, is rigid enough that its internal structure (whether a swarm of point-particles or a continuum) can be ignored, so that it can be successfully modelled as a rigid body; (if it is *also* small enough that its orientation can be ignored, so that it can be modelled as a point-particle, we revert to case (ii));

(iv): an extended object that is both large and flexible enough (especially: a fluid) that its internal structure (whether a swarm of point-particles or a continuum) *cannot* be ignored, and it cannot be modelled as a rigid body.

To sum up: objects of kinds (i)-(iii) either are, or can be modelled as, finite systems. But objects of kind (iv) cannot be, and are thereby in general the hardest objects to model successfully using classical mechanics.

(2): *Persistence*

In saying these objects are 'point-particles', or 'successfully modelled as point-particles', 'successfully modelled as rigid bodies' etc., I have implicitly assumed that they persist. But what ingredients should enter into the definition of persistence? Or less ambitiously: into its supervenience basis, or its functional role?

[33]This assumption implies that the positions of all the point-particles, or point-sized bits of matter, is fixed once we fix the position of just *three* of them. For imagine: if the tips of three of your fingers were placed at three given positions within a rigid brick, and someone specified the exact positions of the finger-tips, then they would have implicitly specified the positions of all the brick's constituent parts. Similarly, rigidity reduces enormously how many momenta one needs to specify, in order to specify a state, i.e. in order to implicitly specify all the momenta.

We have already briefly discussed the two main factors that the philosophical literature (especially in the tradition of conceptual analyis) considers. Namely:

[i] qualitative similarity (cf. *Follow* in Section 1.1);

[ii] causation (cf. Section 4.1).

Of course, how these factors might figure in a definition, or the functional role, of persistence is a large and controversial subject. It is even controversial if, *pace* my denials in Sections 2.1 and 2.2, we make the assumptions (*Straightforward*) and (*Bracket*), i.e. we assume that the interpretation of classical mechanics, or more generally classical physics, is straightforward and does not lead in to the relativity and quantum theories. As discussed in Section 2, that is what the philosophical literature about persistence usually assumes; and in the present context, i.e. for the sort of classical mechanical possible world that we are presently (following Sider) envisaging, I of course agree that it is fair enough.

I will not review, let alone try to settle, this controversy. Indeed, even if the philosophical literature settled this controversy to its own satisfaction, work would remain for me (and Sider): since for us the contribution of the laws of mechanics to the definition (or supervenience basis, or functional role) of persistence would remain to be spelt out. So here I will confine myself to sketching in just a bit more detail, the factors [i] and [ii], and how they apply to the objects of classical mechanics. (I discuss the controversy, also from an endurantist perspective, more fully elsewhere: 2004, 2004a).

I think many, even most, philosophers on both sides of the endurantism-perdurantism debate agree that for most objects, the definition of persistence (i.e. of perdurance as a relation between temporal parts, or for endurantists, of objects' criteria of identity) will invoke one or both of the factors, [i] and [ii] (which also might well overlap).

[i]: Qualitative similarity concerns whether the object at the two times (or in perdurantist terms: the two stages) has suitably similar qualitative properties. Here, 'suitably similar' is to be read flexibly. It is to allow for:

(i) only a tiny minority of properties counting in the comparison;

(ii) considerable change in the object's properties, provided the change is "continuous"; i.e. provided the object goes through some kind of chain of small changes.

[ii]: Causation concerns whether the state of the object at the later time (or the later stage) is suitably causally related by the earlier state or stage. Here again 'suitably causally related' is to be read flexibly. It is to allow for:

(i) various rival doctrines about causation—including even the special variety, 'immanent causation', that some philosophers believe underpins persistence (Section 4.1);

(ii) a suitable chain of states or stages linked by causation.

It is notoriously difficult to go beyond this vague consensus to give a precise definition of persistence (a precise criterion of identity): even if we allow the definition/criterion to vary from one sort of object to another.

Agreed, in *practice*, we have little difficulty with the macroscopic objects of everyday life (Austin's 'medium-sized dry goods', and analogous 'wet goods', such as organisms, rivers, etc.), for the simple reason that for the vast majority of such objects, various relatively simple definitions of persistence or criteria of identity which one might propose, based on the ideas of [i] and [ii], agree in their verdicts. The different proposed criteria are "convergent". In other words, such an object typically has many observable qualitative properties, and the changes in these properties are slow and-or rare enough, and-or linked sufficiently systematically (causally) to other events, that the various proposals based on [i] and [ii] yield the very same judgments of persistence over time.

So it takes strange cases to tease apart the proposals' verdicts. Hence the tradition within conceptual analysis of considering puzzle cases, as a tactic to help us formulate a definition/criterion that covers all (logically or metaphysically) possible cases.

The philosophy of personal identity provides the most obvious examples: viz. puzzle cases where the verdicts of proposals based on bodily properties, and those based on psychological properties, differ. (This is so even if we consider only one of [i] and [ii]. For [i], the trajectories determined by "tracking" bodily properties (albeit slowly changing) and by "tracking" psychological properties (albeit slowly changing) diverge. For [ii], the causal chain of bodily states diverges from that for psychological states.)

As I said, I will here duck out of the project of trying to go beyond the vague consensus above. But by way of justifying my doing so, I note two points. First, I believe this project is independent (at least, to a large extent) both of the endurantism-perdurantism debate, and of whether classical mechanics is true. (I think this claim is uncontroversial: by and large, the literature addressing this project sets aside these two issues.)

Second, recall (from the start of this Subsection) that my present task is to sketch the functional role of persistence in a classical mechanical world with the sort of variety and complexity of motions of objects that we see in the actual macroscopic world. And for that task, it seems legitimate to assume that the actual fact just mentioned—that in the actual world, most macroscopic objects change their observable qualitative properties in a slow and-or rare and-or orderly enough way that various putative criteria of identity agree—"carries over" to the envisaged classical mechanical world. In particular, I see nothing in my denials of (*Straightforward*) and (*Bracket*) (Sections 2.1 and 2.2) to prevent such a widespread agreement of criteria of identity in a classical mechanical world.

Assuming this widespread agreement of criteria of identity, it is straightforward to sketch how the ideas [i] and [ii] would apply in *practice* to the four kinds of object distinguished in (1) above. In other words, we can see how the practice of physics in the envisaged world would be able to ignore, at least in large measure, puzzle cases and conundrums about persistence (including the RDA), just as it does in the actual world. Being myself wary of appealing to causation (cf. end of Section 4.1), I will only consider applying [i], i.e. qualitative similarity. (For some more discussion of causation's role in the definition of persistence, cf. my (2004a).)

As discussed in Section 1.1, qualitative similarity works well when applied to bodies of kind (i): point-particles each with a continuous spacetime trajectory (worldline), moving either in a void or in a continuous fluid with suitably different properties—a different "colour", or made of different "stuff", than the point-particle. For however exactly we define 'maximum qualitative similarity', there will no doubt be, starting at a point-particle at t_0, a unique timelike curve of qualitative similarity passing through it: the worldline of the particle. (Indeed, for the case of a void we could dispense with qualitative similarity, and have the *definiens* refer just to spacetime points' property of being occupied by matter.)

Similarly for the other kinds (ii), (iii) and (iv). Again, qualitative similarity will in practice work well, at least for most cases.

For an object of kind (ii) is small and rigid enough to be modelled as a point-particle: i.e. a successful physical description of it does not need to keep track of its spatial parts.

And though a successful physical description of an object of kind (iii) *does* need to keep track of the object's spatial parts, the assumption of rigidity makes this a vastly easier task than it otherwise would be. In particular, qualitative similarity will again work well, provided there is some property or other (such as colour, density, temperature ...) that (a) varies sufficiently across the object's different spatial parts, and (b) for each such part changes over time slowly/rarely/systematically enough, to enable "tracking" of the spatial part. Broadly speaking, qualitative similarity will only fail in the limiting case of continuous matter that is utterly homogeneous as regards all properties: i.e. the case of the RDA.

For kind (iv), objects large and flexible enough that they must be treated as non-rigid, the assumption of rigidity is unavailable, and tracking the parts of objects will be correspondingly harder. But again, we can expect qualitative similarity to work well, at least in practice, for objects with properties that vary spatially, and change over time in an orderly enough way: for cases unlike that of the RDA.

(Of course, for all four kinds, there might be no *single* definition of persistence (criterion of identity) in terms of qualitative similarity for the whole kind: the kind might be divided into subsets, each with their own definition/criterion.)

To sum up this discussion:— I have argued it is legitimate to assume that in the envisaged classical mechanical world:

(i) the account of persistence, for each of our four kinds of object, will appeal to the same factors, qualitative similarity and causation, that most philosophers actually appeal to; and

(ii) objects change properties slowly and/or regularly enough that in *practice*, various proposed criteria of identity agree, and conundrums about persistence like the RDA do not arise.

(3): *Obeying the laws of mechanics*

Finally, I discuss what it means in the envisaged classical mechanical world, for our four kinds of persisting object to 'obey the laws of mechanics'. I shall discuss in order,

(a) 'obeys' and (b) 'laws', urging that for my purposes both can be left vague.

(a): That a kind of object obeys a certain mechanical generalization (in particular Newton's second law, $\mathbf{F} = m\mathbf{a}$)[34] should not mean merely that for each object in the kind there is some possible schedule of forces exerted on the object, such that were they exerted, the object's motion would satisfy the generalization. That would be far too weak: in particular Newton's second law could be obeyed in a spurious and *ad hoc* way by each object having a schedule of forces tailor-made to describe its motion, no matter how peculiar it might be.

Rather, it is to mean, roughly, that there is some overall assignment of the forces exerted at each time on each object (and for an object of kind (iii) or (iv): its spatial parts) that

(i) is derived from some general principles or formulas applying to all objects of the kind (or at least all of a broad sub-kind, e.g. among point-particles, the electrically charged ones), and

(ii) makes the generalization satisfied by the object's motion.

But for present purposes, we do not need to be more precise than (i) and (ii). In particular, the principles or formulas in (i) surely need not be require using only forces familiar from the actual practice, and macroscopic success, of classical mechanics: e.g. gravitational forces taken as fixed by Newton's inverse-square law. I think it would also be too much to require the forces to have more abstract features familiar from actual classical mechanics, such as being two-body, rather than many-body, in nature.

(b): So much by way of sketching how the laws of mechanics could be *true* in the envisaged world (with (2) giving an account of the persistence of (1)'s four kinds of object). I turn to their being *laws*.

Though as an aspiring Humean, I am attracted to the best-system analysis of the notion of a law of nature, it is clear that the discussion above does not need the notion, or this analysis of it. We can make do with the theory-relative notion of a law *of mechanics* (or more generally, of a given physical theory); and though this notion might be explicated by some theory-relative version of the best-system analysis, it need not be.

Indeed, I think that even if you are sceptical of any general explication of law, even a theory-relative one, you are likely to accept that in the envisaged world, the laws of mechanics earn the name of 'law' if anything does. After all, recall requirements (i) and (ii) in (a) above, that there be a principled overall assignment of the forces exerted on objects that their various motions satisfy: what else need you require of laws of mechanics?

To sum up my stages (1) to (3):— We have seen how a possible classical mechanical world could contain various kinds of object, and sustain a notion of persistence for them such that they satisfy classical mechanical laws. Besides, this need not involve specifying first the objects, then the account of their persistence, then the laws. Rather,

[34]Again, I do not need to distinguish the various formulations of classical mechanics; cf. footnote 32.

the three stages can influence each other: in particular, the account of persistence can invoke the laws (cf. comments just before (1)). Nor need it involve Ramsey-Lewis simultaneous definition or the best-system analysis of laws.

Coda: Biting the bullet
Finally, I admit that that my stages (1)-(3) lead to the same bullet-biting which Sider admits he must do for the case of a lonely homogeneous disc; and which he must also do for my preferred version of the RDA, using two discs or a disc and a sheet of paper, and for Zimmerman's space-filling homogeneous fluid. That is, stages (1)-(3) lead to saying that in such cases, there is (No Difference) between the two putative cases; (cf. the discussion at the end of Section 4.4).

This means the endurantist will reply to me, as they did to Sider, that this amounts to conceding the force of the RDA: 'even this version of perdurantism, with its sophisticated appeal to the web of belief, cannot secure facts of persistence in the troublesome cases considered by the RDA'. This suggests that again, there is after all at best a stalemate between the endurantist and this sort of perdurantist.

But I think the perdurantist *can* do better than this. They can secure facts of persistence in the troublesome cases such as lonely discs and space-filling fluids—by adopting the position in the next two Sections ...

7 Perdurantism without tears: the classical case

I turn to my second, and favoured, reply to the RDA. It meshes with Section 2's rejection of the widespread assumptions (*Straightforward*) and (*Bracket*). That is: it fits my claims that:
(i) classical mechanics is subtle and problematic and
(ii) classical mechanics leads to relativity and the quantum.

More specifically:— As to claim (i), this reply uses that claim's rejection of *pointillisme* to say that the perdurantist can take objects to have only temporally extended i.e. non-instantaneous temporal parts. As we shall see, this makes the perdurantist's account of persistence non-reductive: it uses notions which presuppose persistence (cf. (1) in Section 1.3). But for reasons already discussed (especially Section 4.2.2.C), the account is only "slightly" non-reductive: the presupposition of persistence is "mild" in the way that Section 4.2.2.C maintained velocity's presupposition of persistence was mild. In any case, the perdurantist who accepts only non-instantaneous temporal parts has an (Appealing Differences) reply to the RDA: that is, she can appeal to differences between the two discs. Furthermore, I maintain that non-instantaneous temporal parts can do the various jobs, within the endurantism-perdurantism debate, that the perdurantist demands of temporal parts.

All this, I will argue in this Section. Section 8 will pick up on claim (ii) above. It will support this non-*pointilliste* version of perdurantism by considering how classical mechanical objects "emerge" from quantum theory. (This argument will also suggest augmenting discussion of the intrinsic-extrinsic distinction with a new idea: relativizing the distinction to bodies of doctrine, such as scientific theories.)

7.1 Rejecting instantaneous temporal parts

At the end of Section 1.2, I said I would take it that both average and instantaneous velocity presuppose the notion of persistence, and are extrinsic properties. But when we consider a non-instantaneous temporal part, the second point needs to be qualified.

For one of the part's constituent pieces of matter having a certain worldline segment within the part is surely an intrinsic property of the part. And similarly for lesser, i.e. logically weaker, information than the entire worldline segment. For example, that a constituent piece of matter has a certain average velocity over a time-interval "within" the temporal part is intrinsic to the part: notwithstanding the fact that average velocity presupposes the notion of persistence. Similarly for instantaneous velocity at a time "within" the temporal part.

At least, these properties are intrinsic to the part, *modulo* the topic I set aside in Section 5.2, viz. how to justify the appeal to persisting spatial points, and a spatial metric, that is needed for the idea of the distance traversed by the persisting object.

This situation returns us to the terminology of *temporally intrinsic* properties which I introduced in (A) of Section 4.2.2.C. Roughly speaking, these are properties whose possession by an object o at a time implies nothing about matters of fact (especially about o) at other times (though it may imply propositions about other places). Thus the fact that one of a non-instantaneous temporal part's constituent pieces of matter, o, has a certain instantaneous velocity at a time t "within" the part corresponds to a temporally intrinsic property of the part, though the velocity is temporally extrinsic for o at the *instant* t.

The above points are of course independent of whether matter is atomic or continuous. The piece of matter can be a point-particle or a point-sized bit of matter in a continuum. (Indeed, the qualification could be stated in the very same words for an extended piece of matter, provided it was small enough for us to model it as point-like, i.e. having a worldline, and a single velocity: but I can focus on unextended pieces of matter.)

To sum up: a non-instantaneous temporal part has a rich set of intrinsic, or at least temporally intrinsic, properties concerning the worldline-segments and average and instantaneous velocities, during the part, of its constituent pieces of matter.

Now consider a version of perdurantism that accepts only non-instantaneous temporal parts. (I will not discuss the pre-history of this proposal in authors like Whitehead: for details cf. Grattan-Guinness (2002). But I will soon discuss whether it should accept all such parts, i.e. parts with an arbitrarily short, though non-zero, temporal extent.)

Since such parts have a rich set of intrinsic properties, the prospects for the perdurantist project of defining persistence (or providing a supervenience-basis for it, or at least some non-reductive account of it) look a great deal better than for a *pointilliste* version of perdurantism accepting only instantaneous parts (or accepting also extended parts, yet requiring persistence to supervene on the intrinsic properties of instantaneous parts, as in Lewis' Humean supervenience). For with these rich sets of properties, there are so many more ingredients which one could use in the *definiens* of persistence (or more generally, in the account of persistence). More precisely: the perdurantist's prospects are a great deal better, provided their definition or account of persistence can legitimately refer to these intrinsic properties of non-instantaneous temporal parts.

In the rest of this paper, I will endorse this version of perdurantism, both in general and as a reply to the RDA (both the usual formulation and Section 5.5.3's stronger one).

The reply it affords to the RDA is as follows. The worldline segments, average velocities and instantaneous velocities of point-sized bits of matter within a homogeneous disc provide intrinsic properties of the disc's temporal parts. Assuming that the perdurantist can appeal to these intrinsic properties—an assumption I will discuss in Section 7.2—she can certainly distinguish the discs. Indeed, with these intrinsic properties to hand, she may well have no more of a problem about her project of defining persistence, for the parts of a perfectly circular homogeneous disc, than for the parts of an inhomogeneous one. There are two aspects to this, which we can call 'kinematical' and 'dynamical'.

7.1.A "Kinematics" First, the perdurantist can appeal to the mathematical fact that every suitably smooth vector field U defined on a open region R of spacetime has integral curves throughout R: curves which are timelike, by definition, if U is timelike. (I mentioned this when discussing Lewis' proposal in Section 4.3.2.A. To be precise: 'suitably smooth' requires only that U be C^1, i.e. the partial derivatives of its components exist and are continuous.) So the idea is that the intrinsic properties of a non-instantaneous temporal part of a classical continuum specify the vector field U, of instantaneous velocities (to be precise: 4-velocities) of the point-sized bits of matter, on the spacetime region R of the part. U then specifies integral curves, i.e. the worldlines within R of the bits of matter. Besides, by considering a set of such non-instantaneous parts that "cover" the entire period for which a given bit of matter exists, its entire worldline can be reconstructed.

There are two points to make about this proposal; of which the second will lead us to "dynamics".

(1): Agreed, this proposal seems at first sight a cheat, a case of theft over honest toil. But I am for the moment just *assuming* that the perdurantist can appeal to intrinsic properties of non-instantaneous parts, even though some of them involve the notion of persistence: postponing discussion to Section 7.2. And rest assured, I will there admit that this assumption makes this kind of perdurantism "non-reductive". (This assumption also marks the difference from Lewis' proposal in Paragraph 4.3.2.A:

lacking the assumption, Lewis had trouble specifying the vector field U.)

(2): The idea of reconstructing an object's entire worldline by concatenating segments (each lying in one of a "covering" set of non-instantaneous temporal parts) returns us to the formal equivalence I mentioned at the end of Section 5.4. That equivalence had the perdurantist represent the location in spacetime $\mathcal{M}$ of a point-particle, or a point-sized bit of matter in a continuum, by a collection of functions, labelled by time-intervals that together cover the object's lifetime; for example, if it exists throughout the closed time-interval $[a, b]$, there might be a function $q_{[a,b]} : t \in [a, b] \mapsto q_{[a,b]}(t) \in \mathcal{M}$. Indeed, one can show how to reconstruct worldlines from such functions, even for a point-sized bit of matter in an utterly homogeneous continuum, provided the functions' domains are non-degenerate time-intervals, i.e. *not* singleton sets of times. (For details, cf. Butterfield 2004a, Section 3.)

This reconstruction of worldlines from a collection of functions raises two points. First, I admit again that it seems at first sight a case of theft over honest toil: the perdurantist reconstructs worldlines from functions that involve the notion of persistence. Here I again refer to Section 7.2's discussion.

Second, this reconstruction of worldlines is "kinematical". It uses no information about the properties of the moving matter, in particular the causes of its motion ("dynamics"): it simply invokes a set of functions that immediately specify worldline-segments. So it is natural to ask whether our kind of perdurantist can give an account of persistence that in some way appeals to (i) the properties of the moving matter, or (ii) the causes of its motion. I already reviewed in (2) of Section 6.2.2 how appealing to (i) would work in practice for inhomogeneous matter in a classical mechanical world: and the rejection of instantaneous temporal parts obviously does not affect that appeal. But our perdurantist can also appeal to (ii), at least if she is a "naturalist". This leads to "dynamics".[35]

7.1.B "Dynamics" Our perdurantist can indeed appeal to dynamics. That is: if she is sufficiently "naturalist" that she is willing to appeal to the laws of motion, then in a classical mechanical world, the definition of persistence can "piggy-back" on the determinism of those laws. (Cf. my endorsement of Quine's "web" metaphor just before (1) of Section 6.2.2: the laws of mechanics can contribute to determining persistence.)

That is: in common cases, the classical laws (above all, Newton's second law, that Force = mass $\times$ acceleration) fully determine the motion of a point-particle, or a point-sized piece of matter in a continuum, over an interval of time $[t_1, t_2]$, in terms of its initial position and velocity at t_1 and the regime of forces on it during $[t_1, t_2]$: all of which the perdurantist can take to be given by intrinsic properties of a temporal part

[35]This "kinematics-dynamics" contrast exemplifies two more general contrasts in the philosophy of identity (discussed in in my 2004a, Section 4.1) which I call (i) 'ontic-epistemic' and (ii) 'conceptual-empirical'. (i) concerns whether the criterion or account of identity specifies the "constitutive facts" of persistence, or our grounds—everyday or technical, occasional or systematic—for judgments of persistence. (ii) concerns whether the criterion or account eschews the concepts and results of empirical theories, e.g. physical theories, or is willing to invoke them.

that begins before t_1 and ends after t_2.

Agreed, that is rough speaking: hence my 'in common cases'. For accuracy, I should note some of the subtleties, in particular the threat to determinism from solutions in which some quantities become infinite within a finite period of time after the initial time t_1. For point-particles, such solutions are known to exist even if we veto collisions (cf. (2) of Section 2.1); for a popular account of this, cf. Diacu and Holmes (1996, Chapter 3). For continua, whether there are such solutions is a deep open question: witness the fact that one of the Clay Institute's million-dollar Millennium Prizes is for a proof or disproof of the rigorous existence for all times of solutions of the equations that govern a classical fluid, i.e. the Navier-Stokes equations.[36]

But for present purposes, I can discount these subtleties: here it is enough to suggest that a naturalist perdurantist can go about defining persistence in terms of integrating the equations of motion.

7.1.C An 'anti-*pointilliste*' objection; and reply You can object that the reply as so far developed fails, if the perdurantist accepts spatially extended parts. (Thanks to Frank Arntzenius, John Hawthorne and Dean Zimmerman for this objection.) That is: suppose the perdurantist accepts non-instantaneous temporal parts that are spatially extended. She could accept these either (i) 'right off', or (ii) as fusions of spatially extensionless (but temporally extended) temporal parts (since most perdurantists accept unrestricted fusions of parts they accept). Then again the RDA threatens.

Indeed, we can make the point without the complexities of rotation. Imagine a homogeneous continuum of stationary matter, so that the worldlines of the point-sized bits of matter are all vertical. Draw a congruence of timelike straight lines, all mutually parallel, oblique to the given worldlines, say 'going up towards the right'.

The objector of course agrees with me that no fusion of any set of non-instantaneous segments of the given set of worldlines is a line in this congruence. That is, in different words, the heart of my reply to the RDA as so far developed: (especially in (2) of Section 7.1.A).

But, says the objector, consider one of the parallelograms formed by two parallel worldlines, and two parallel lines of the oblique congruence. Our perdurantist should surely accept as an object the matter in that parallelogram, either (i) 'right off', since it is both spatially and temporally extended—and so surely kosher for an anti-*pointilliste*, or (ii) as the fusion of the uncountably many vertical segments of worldlines it contains.

And now, says the objector, consider a collection of such parallelograms, all congruent, laid out in a straight track, marching up towards the right: surely our perdurantist should accept the fusion of this collection as an object. But this is a 'rogue' object. That is, the perdurantist faces, as in the RDA, an *embarras de richesse* of persisting objects.

In reply, the perdurantist could of course restrict mereological composition. But this

[36]For a popular account, cf. Devlin (2002, Chapter 4); for a monograph discussion of what is known about the simpler case of a perfect fluid (Euler's equations), cf. Section 4.4 and Example 5.5.8 of Abraham and Marsden (1978)—thanks to Gordon Belot for this reference.

seems *ad hoc*: how to make the restriction so as to prohibit all 'rogue fusions'? I think a much better reply lies in naturalism about persistence; and in particular, in the view that in classical mechanics, and classical physics, velocity should not always be taken as just position's time-derivative, and momentum as just mass times velocity ((D) of Section 4.2.2.C, based on Sections 2.1 and 2.2). There is 'access', both empirical and conceptual, to quantities like velocity and momentum that does not go *via* position. Applying this view to the objection's straight track of parallelograms, marching up towards the right: our naturalist perdurantist just needs to:

(i): note that there is no momentum in the direction of the track;

(ii): have her account of persistence require that a persisting object have momentum that is parallel to its worldline.

Two supplementary remarks about this reply.

(a): I am not committed to it being momentum, rather than some other quantity such as energy, that is appealed to so as to prohibit the track. Also the perdurantist will probably also need to appeal to various different quantities for various different examples.

(b): I am of course not committed to the perdurantist denying that the track counts as an object, in the wide 'spacetime worm' sense. It is important only that she deny that it is a ordinary persisting object; for it is the business of an account of persistence to distinguish such objects from the countless spacetime worms. (And in the wide, spacetime worm sense of object, she would then allow that the track has a velocity in the mere sense of time-derivative of position.)

So much by way of replying to the RDA. But I need to defend this version of perdurantism, especially the assumption that the perdurantist *can* appeal to the non-instantaneous parts' intrinsic properties. I will defend this perdurantism in four stages. The first two stages are metaphysical: I expound them in the next two Subsections. The third and fourth stages will return us to the philosophy of physics, and will each involve a proposal about the intrinsic-extrinsic distinction among properties. The third stage (Section 7.4) just appeals to what Section 4.2.2 already argued for, concerning the classical mechanical description of motion: that velocity is hardly extrinsic. The fourth stage, in Section 8, concerns quantum theory.

7.2 Intrinsic properties of non-instantaneous temporal parts

Intrinsic properties of non-instantaneous temporal parts raise three issues; which I address in three Subsections.

7.2.1 Can the perdurantist appeal to them?

I claim that the perdurantist can legitimately appeal to these parts' intrinsic properties, even though some of them involve the notion of persistence. Does this mean that my sort of perdurantist just gives up on the project of defining persistence (or at least providing a supervenience basis for it) in terms that do not presuppose it? Agreed, giving up need not spell defeat for perdurantism. For a non-reductive perdurantism of the sort mentioned in (1) of Section 1.3 might have various merits—and merits that are not undermined by accepting only non-instantaneous temporal parts. (I will support this in Section 7.3.) But *does* my sort of perdurantist give up?

Yes and No! Yes, in that she aims to give *some* account of persistence, yet is willing to have the account invoke notions that presuppose persistence; in particular, instantaneous velocity.

But also, No: for reasons hinted at in Section 7.1.B's discussion of persistence "piggy-backing" on the laws of motion. That is: my sort of perdurantist need not assume persistence as a primitive—or that persistence is somehow satisfactorily defined (or accounted for, say with a supervenience thesis)—for some specific set of parts: say, a set that covers the lifetime of the persisting object in question, or a set containing all those temporal parts with a temporal extent (lifetime) less than some bound. She can perfectly well pursue the project of defining, or accounting for, persistence as a relation between *any* two non-instantaneous parts (including any two sub-parts of any given non-instantaneous part).

And even if the perdurantist accepts all such parts, so that there are parts with arbitrarily short, though non-zero, temporal extents, I maintain that this need not involve a vicious regress of endlessly deferred definitions or accounts of persistence. For the account may, for time-intervals less than some amount, become suitably "uniform", i.e. with no substantive variations for shorter times. In short: it can be "turtles all the way down", provided that below a certain level, the turtles are all the same. Of course, this is in effect what happens in an account of persistence that piggy-backs on the classical deterministic laws of motion, determining future and past positions in terms of present position and instantaneous velocity (or momentum).

7.2.2 Temporal intrinsicality at an instant is rare

I turn to a general point about the sorts of property invoked in an account of persistence: a point that applies to both endurantist and perdurantist, and to accounts of criteria of identity for specific kinds of object, e.g. persons, where there are issues, e.g. about the weighing of diverse factors such as bodily and psychological similarity, absent from the highly general endurantism-perdurantism debate.

The point is simply that almost no properties are temporally intrinsic to their instance *at an instant*. That is: almost all properties require features of their instance not only at a single instant, but also at other (albeit perhaps close) times. So an account of persistence, or a criterion of identity for a specific kind of object, needs must appeal to temporally extrinsic properties; (though the other times involved may be close to the given one).

Unfortunately, this fact is obscured in most philosophical discussion of persistence (at least in the tradition of conceptual analysis). This discussion focusses on the idea of giving an account of, or criterion for, o at time t being the same persisting object (maybe of a specific kind, e.g. person) as o' at t', that invokes everyday properties. As discussed in (2) *Persistence*, in Section 6.2.2, the idea is almost always that the object(s) (in perdurantist terms: the two temporal parts) need to be:

[i] suitably similar as to these properties: where 'suitably similar' allows considerable change provided there is some kind of chain of small changes; and-or

[ii] suitably causally related, with the properties being the causally relevant ones (in other jargon: part of the specification of the object's causal state); where again there can be a suitable chain of stages or states linked by causation.

So far, so good: I have no objection to searching for this sort of account or criterion, nor to its invoking everyday properties in ways [i] and-or [ii]. But the locution 'at time t', and the focus on everyday properties, makes philosophers often choose as their examples observational properties, i.e. properties which can be ascribed "at a glance": be they "everyday-taxonomic" like 'is a rock/leaf/chair' or "purely sensory" like 'is red/hot'. And since they can be ascribed at a glance, philosophers are tempted to think they are temporally intrinsic in the strong sense of requiring something of their instance only for a instant.[37]

And *that* is false. We are very gross creatures: our perceptual apparatus is insensitive to such properties. Rather, the process of perception "averages", in myriadly complex (and often adaptive) ways, over the instant-by-instant properties of not only the object but also the medium, and our perceptual apparatus itself. So any observational property is temporally extrinsic at an instant: it demands features of its instance over a time-interval of at least about one twentieth of a second—and in general a very complex, open-ended and vague array of features, to boot.

When we set aside conceptual analysis and everyday properties, and consider the properties of technical science, in particular physical theories, the same conclusion holds good: most properties are temporally extrinsic at an instant (though as emphasised, they may well be intrinsic to a non-instantaneous temporal part). Thus most of the hundred-odd physical quantities that get an entry in a physics dictionary are clearly temporally extrinsic at an instant. I have already mentioned velocity: obviously momentum, angular momentum and kinetic energy are temporally extrinsic for the same reason. Many other quantities, such as temperature, conductivity (thermal and electrical), permeability and permittivity, depend for their definition (as well as their value) on collective phenomena that require a process or situation to last longer than an instant (though perhaps much less than a second).

I admit that within classical physics, three familiar quantities *are* good candidates for being temporally intrinsic even to an instant: viz. position, mass and electric charge. Besides, for a point-particle: these also seem to be spatially intrinsic at a spatial point, not just for an extended spatial region. At least, this is so *modulo* the topic I set aside in Section 5.2, about the basis of spatial geometry: that is to say, a "relationist" about spatial geometry would no doubt object to the claim that the

[37]All parties can agree that among *non*-observational everyday properties, most are temporally extrinsic; indeed they often require features at other times of objects other than their instance: for example, being married requires a spouse at a past wedding, and no intervening divorce or death.

position of a point-particle is spatially intrinsic to a point.[38]

I also admit that this trio seeming to be intrinsic—taken together with the great success of classical physics in reducing much of the behaviour of large complex objects to the classical mechanics and electrodynamics of postulated tiny components, whether point-particles or point-sized bits of matter in a continuum ("micro-reductionism")—has undoubtedly been one strong reason, perhaps the main reason, for the prevalence in philosophy of *pointilliste* doctrines like Lewis' Humean supervenience.

Of course, the RDA is precisely an argument that such doctrines come to grief on the topic of persistence.[39] And my present point is that the rarity of temporal intrinsicality at an instant supports my proposal to be perdurantist without being *pointilliste*—and so to block the RDA.

7.2.3 A better reason for temporal intrinsicality

Finally, an incidental point. Philosophers discussing persistence have another reason to focus on temporally intrinsic properties, in addition to the erroneous tendency to think observational properties are temporally intrinsic to an instant. I admit that it is a better reason. But it is a reason only for properties temporally intrinsic for shortish intervals, up to about a second: not for the stronger notion of temporal intrinsicality at an instant—which is the target of my anti-*pointilliste* campaign. In short, the reason is that a property that is temporally intrinsic for a longish interval is liable to be useless in a criterion of identity.

In detail: All parties (both endurantists and perdurantists) can agree that an account of persistence, or a criterion of identity, had better not invoke a property that requires some feature of its instance within a period of time similar to the time-scale over which the account or criterion is to be applied. For doing so is liable to make the criterion hard or even impossible to apply. Thus suppose an account of the conditions under which o at time t is the same persisting object (maybe of a specific kind, e.g. person) as o' at t', invokes a property P: requiring, say, that o at t must be P and so must o' at t'. (The argument works equally well with other requirements, e.g. that only one of the two need be P, but that change as regards P is suitably continuous, with some kind of chain of small changes.) Then if being P at t requires a feature ϕ at a time close to t', it may well be hard to apply the account: having to ascertain that ϕ holds close to t' might entangle one in ascertaining whether the persistence claim for o and o' holds.

[38]Beware! For a point-sized bit of matter in a continuum, the trio of position, mass-density and charge-density *seem* to be not only temporally intrinsic, but also spatially intrinsic—provided we can interpret the densities (i) as defining mass and charge through integration, rather than (ii) being themselves defined from the masses and charges of finite volumes, by taking the limit of smaller and smaller volumes. But in fact, we cannot interpret the densities like this: (i) fails, and we need (ii)—another mark against *pointillisme*, in my view (2004).

[39]Philosophers tend to forget that they also have trouble in physics. The classical mechanics and electrodynamics of point-particles and continua have considerable conceptual tensions, some of which are aggravated by a *pointilliste* picture; cf. Section 2.1.

7.3 Non-instantaneous parts can do the jobs

I turn to the second stage of my defence of perdurantism without instantaneous temporal parts. I claim that, by and large, non-instantaneous temporal parts do the various jobs, within the endurantism-perdurantism debate, that the perdurantist demands of temporal parts, just as well as instantaneous temporal parts. More precisely: this is so once the perdurantist "just says No" to the siren-calls of *pointillisme*. Of course, I cannot here discuss all these jobs: I will make do with three short comments. The first comment is general, and will be illustrated by the second and third, which concern particular jobs temporal parts are invoked to do.

7.3.A Humean supervenience revisited The first comment is an offer of a peace-pipe to the neo-Humean. She envisages the world as "loose and separate", a succession of "distinct existences": "just one darned thing after another". My version of perdurantism can agree, in that it might well accept *all* non-instantaneous temporal parts, no matter how short-lived: my veto is only against utterly instantaneous parts.

Besides, my perdurantist can echo Lewis' Humean supervenience, by making some claim along the lines that all the facts supervene on the temporally local facts; i.e. the facts specified by the intrinsic (if you like: temporally and spatially intrinsic) properties of all the non-instantaneous temporal parts. To state this echo more precisely: she can claim that for any covering of spacetime $\mathcal{M}$ by a family $\mathcal{F}$ of non-instantaneous temporal parts (no matter how short-lived some or all of the parts may be), all the facts supervene on the intrinsic properties of elements of $\mathcal{F}$. (Here, 'covering' is understood in mathematicians' usual sense: a set $\mathcal{M}$ is covered by a family $\mathcal{F}$ of sets iff $\mathcal{M} \subseteq \cup\mathcal{F}$; and similarly if $\mathcal{M}$ and the elements of $\mathcal{F}$ are treated not as sets, but as say mereological fusions.)

So the only aspect of Lewis' Humean supervenience that my perdurantist needs to deny is the *pointilliste* idea that all the facts supervene on the intrinsic properties of spacetime points (or of spatially extended instants of time, i.e. spacelike surfaces). I think neo-Humeans should find this a price worth paying: having all the facts supervene on the intrinsic properties of all the non-instantaneous temporal parts should be enough to satisfy a Humean's ambition to have the "global" supervene on the "local".[40]

7.3.B The problem of change The second comment concerns the so-called 'problem of change'. Perdurantists argue that o's changing in respect of a property P is best understood in terms of one temporal part having P and another having $\neg P$. In particular, they argue that the endurantist has to understand P (and $\neg P$) as a relation

[40] Agreed: since these parts in general overlap, the "fundamental description of the world", given by the infinite conjunction of all (the ascriptions of) the intrinsic properties of all such parts, is highly redundant. But I say: no worries. After all, the exact spatial analogue occurs in continuum classical mechanics: to describe a continuum, this theory needs—*not* the infinite point-by-point conjunction of all the properties of points—but the highly redundant infinite region-by-region conjunction of all properties of all regions; cf. Section 2.1.

to a time, and that for the case of an intrinsic property P this is surely wrong. Hence the problem is also called the 'problem of temporary intrinsics'; (cf. e.g. Sider 2001 pp. 92-98, Lewis 2002).

So far as I can tell, almost all the arguments for the perdurantist understanding of change carry over, so as to support my version of perdurantism, i.e. perdurantism without instantaneous temporal parts. (Admitted: as do almost all the arguments *against* the perdurantist understanding of change.) The main reason is of course that if within a single non-instantaneous part o there is change in respect of P, the perdurantist will understand the change in terms of one shorter-lived part of o having P, and another not—and this need not involve any regress (Section 7.2.1). Besides: since temporal intrinsicality at an instant is rare (Section 7.2.2), the perdurantist's argument that endurantism has trouble with temporary intrinsics is more persuasive as an argument for non-instantaneous temporal parts.

But there is one objection; (my thanks to Oliver Pooley). Suppose that a temporary intrinsic property such as shape changes continuously over time, so that an object o is square for merely an instant: to secure an instance of squareness *simpliciter* in this scenario, the perdurantist surely needs an instantaneous temporal part.

Reply: Given the supposition, this is certainly right. Here I can only bite the bullet, by any or all of:

(i) dropping the problem of change from the list of jobs my non-instantaneous temporal parts are to do; or

(ii) urging that since temporal intrinsicality at an instant is rare (Section 7.2.2) my temporal parts can solve the problem of change for the vast majority of temporary intrinsic properties; and besides, urging that succeeding with this vast majority should satisfy the neo-Humean (cf. the first comment above); or

(iii) adopting a "mixed" view, more congenial to *pointillisme*, that admits instantaneous parts as well as non-instantaneous ones, but then argues that it is legitimate to account for persistence (and so answer the RDA) by invoking only the non-instantaneous ones, as I have.

Of these options, I on the whole prefer reply (ii). But I will not in this paper try to choose between these replies: in particular, I will not refer again to the mixed view, though I agree it is tenable.

7.3.C Puzzles of coincidence Thirdly, the situation as regards the debate over 'puzzles of coincidence' is similar to that for the problem of change. The puzzles (reviewed by Sider 2001, p. 5-10, 141-152) concern such cases as the statue and the clay, or the fission and fusion of objects such as amoebae—or even persons. For example, after an artist makes on Tuesday a statue out of a lump of clay, the statue and clay seem to be the very same object. But they seem to differ in their temporally extrinsic properties (often in this debate called 'historical properties', e.g. by Sider 2001, p. 5, 142): the statue but not the lump was created on Tuesday, the lump but not the statue existed on Monday. Perdurantists argue that these puzzles are best understood in terms of distinct objects sharing temporal parts, just as objects can share spatial parts (such as two roads having a stretch in common).

Again: so far as I can tell, almost all the arguments for the perdurantist understanding of these puzzles carry over, so as to support my perdurantism without instantaneous temporal parts. (As do, I admit, the arguments against!). For example, almost all the arguments in Sider's critique of endurantist approaches (2001, p. 154-188), and in his advocacy of perdurantism (2001, p. 152-153, p. 188-208), carry over.

I said 'almost all the arguments' carry over. For there are two wrinkles. First, Pooley puts the analogue of his objection in Section 7.3.B. Suppose that two objects fuse for merely an instant: here the perdurantist surely needs an instantaneous temporal part. I reply: I think this objection is weaker than its analogue in Section 7.3.B, because its supposition is more of an idealization, more a merely logical or metaphysical possibility, rather than part of the content of classical mechanics. That is: classical mechanics does describe deformable objects changing shape continuously, as the objection in Section 7.3.B requires. But it does *not* describe instantaneous fusions. Indeed as mentioned in Section 2.1, classical mechanics finds collisions, even of point-particles, problematic—let alone fusions and fissions. (There is of course no problem about the spatial analogue of instantaneous fusions, i.e. two 3-dimensional objects sharing a 2-dimensional part: think of two semi-detached houses!)

The second wrinkle is that the issue whether to accept instantaneous temporal parts *does* bear on one significant division *within* the perdurantist camp. This distinction concerns how the perdurantist treats temporal language. The traditional perdurantist view is that an object of ordinary ontology—i.e. a referent of an ordinary term, a subject of ordinary predications, an element of ordinary domains of quantification—is the whole four-dimensional object, the "maximal spacetime worm"; (Sider calls this the 'worm view'). But both Sider (2001, p. 188-208) and Hawley (2001, pp. 30-32, 41-64) defend the rival 'stage view', that the referents of our ordinary terms, subjects of ordinary predications etc. *are* the temporal parts.

This is not the place to assess their arguments for this proposal. They concern, for example, counting: the stage view says that at each time before an amoeba splits into two, there is one amoeba (the stage), a verdict which matches everyday thought and language; but since there are then two maximal spacetime worms, the worm view has to say that there are *stricto sensu* two amoebae, and explain away everyday thought and language by invoking some conventions about counting.[41]

For my purposes here, it suffices to comment on Sider's position that the stages he claims to be the referents of ordinary terms are indeed instantaneous—and so do not persist: 'no person lasts more than an instant' (2001, p. 193)! Sider of course agrees that everyday thought and language take: (i) ordinary objects to persist, as in 'Ted was once a boy'; and (ii) most of their properties to be temporally extrinsic at an instant,

[41]For this line of argument, cf. Sider 2001, pp 152-153, 188-193. But Sider has to admit that sometimes we count by maximal spacetime worms, not by stages, as in 'Fewer than two trillion people have set foot in North America throughout history'. He writes (2001, p. 197): 'if 'person' refers to person stages, this sentence will turn out false, since more than two trillion (indeed, infinitely many if time is dense) person stages have set foot in North America throughout history'.

as in 'Ted believes perdurantism is true' (Section 7.2.2). So he goes on to argue that he can accommodate (i) and (ii) with a temporal analogue of Lewis' counterpart theory (2001, pp 111-113, 193-198).

My comment on Sider's position is now obvious. While I admit that temporal counterpart theory is coherent and powerful enough to cope with (i) and (ii)—the stage view does not have to be so *pointilliste* as Sider! That is: one could combine my perdurantism, the rejection of instantaneous temporal parts, with the stage view. Not only do most arguments for a perdurantist understanding of the puzzles of coincidence carry over and support my perdurantism (as I said above). Also, one could combine it with some arguments specifically for the stage view: e.g. a version of my perdurantism that denies overlapping parts could retain Sider's counting argument for favouring the stage view over the worm view ... But I leave developing this topic for another occasion.

This concludes my metaphysical defence of my version of perdurantism. I hope to have made it plausible, quite apart from its blocking the RDA. But the philosophy of physics has some more support to offer it. In the next Subsection, the support comes from the classical description of motion. In Section 8, the support comes from quantum theory. But these two pieces of support are not "just technical": each of them involves a novel proposal about the intrinsic-extrinsic distinction among properties.

7.4 Velocity revisited

My version of perdurantism, without instantaneous temporal parts, meshes well with Section 4.2.2's arguments that:

(i) it is natural to sub-divide the vast class of extrinsic properties—and in particular, temporally extrinsic properties—in terms of degrees of extrinsicality; and

(ii) in the classical mechanical description of motion, velocity is hardly extrinsic.

I will not rehearse again the details of those arguments. I only need to recall the main idea: that the "only proposition going beyond the instance" that is implied by an ascription of velocity (or of other derivatives of position) is the proposition that the instance o exists throughout some open interval of times, perhaps very short, around the time t. This proposition corresponds to an intrinsic property of any non-instantaneous temporal part containing t, no matter how short: a property that is thereby hardly extrinsic to t.

Obviously, this idea meshes with two points in previous Subsections of this Section:—

(a): A perdurantist who rejects instantaneous temporal parts can account for persistence: either by fusing segments, perhaps arbitrarily short, of worldlines ("kinematics"; Section 7.1.A); or (more naturalistically) by "piggy-backing" on solving the deterministic classical laws of motion, given o's initial position and velocity, and the forces on it; ("dynamics"; Section 7.1.B).

(b): A perdurantism without instantaneous temporal parts can accept all *non*-instantaneous parts, no matter how small their temporal extent. Besides, if one accepts all such parts one can add a claim that all facts supervene on the "temporally local" facts, in a strong enough sense to satisfy all but the most *pointilliste* neo-Humeans; (cf. Section 7.3.A).

8 Support from decoherence in quantum theory

8.1 Classical and quantum: relativizing the intrinsic-extrinsic distinction

As I said in Section 1.3, I am not so far gone in naturalism as to just dismiss the RDA on the grounds that matter is in fact atomic. I agree: a classical mechanical continuum could exist—prompting the RDA, *modulo* the above replies. My argument in this Section will instead be that the way in which classical mechanical objects (both particles and continua) are in fact emergent from the quantum realm provides further support for Section 7's perdurantism without tears, i.e. without instantaneous temporal parts.

This argument will use two new assumptions: one about philosophical method, the other about the intrinsic-extrinsic distinction.

(1): I will now assume that the interpretation of classical mechanics—in particular, our conception of how its objects (both particles and continua) persist—should be sensitive to how classical mechanical objects in fact "emerge from the quantum". I agree that this assumption is controversial: why not just interpret each theory on its own, as best you can? After all, there is no lack of work: as I have stressed, classical mechanics is interpretatively subtle and problematic, even without considering the dreaded quantum. But I am not alone in endorsing this assumption, even as regards the interpretation of a classical theory being sensitive to an "adjacent" quantum theory. Thus for Belot (1998, p. 550-554), it is the main moral of his examination of classical electromagnetism and the Aharonov-Bohm effect.

(2): My second assumption is that it is legitimate to relativize the intrinsic-extrinsic distinction among properties to a body of doctrine. The distinction is of course usually discussed in terms of logical or metaphysical possibility: the literature discusses taking a property P to be intrinsic iff it is logically or metaphysically possible for an object o to have P "while lonely", or "whatever the rest of the world is like", or ... But I now assume that it is legitimate to relativize the modality to a body of doctrine, such as a scientific theory T. (I will not need the metaphysically more ambitious idea of relativizing to the "laws of nature", or to the laws of nature of some possible world.) Therefore I shall talk, for any such body of doctrine or theory T, of *nomic* intrinsicality and extrinsicality.

Unless T is logically or metaphysically necessary—a case I need not consider—the relativized modality will be a restricted one. That is: not all logically or metaphysically possible worlds make T true. In general, this will strengthen the notion of intrinsicality, and correspondingly weaken the notion of extrinsicality—however exactly we understand the original intrinsic-extrinsic distinction. That is: nomic intrinsicality will imply intrinsicality *simpliciter*, and extrinsicality *simpliciter* will imply nomic extrinsicality. For intrinsicality is a matter of "not implying propositions about the instance's environment"; and once we assume a theory T is true, any proposition in T can be an implicit premise in an implication—yielding more implications. So in general, once we assume T, more properties will be classified as extrinsic. So extrinsicality *simpliciter* implies nomic extrinsicality; and *vice versa* for intrinsicality. (Similar remarks apply to my notions of temporal, and spatial, intrinsicality and extrinsicality; and to the case where we consider two theories T_1 and T_2, one implying the other.)

In fact, this idea of relativized intrinsicality has surfaced in the literature (Humberstone 1996, p. 238); but so far as I know, it has not been pursued. I agree that many a metaphysician will at first sight doubt its value, though they will probably accept it as coherent. Thus Humberstone writes, after floating the idea of relativizing intrinsicality to a class of possible worlds that match in their laws of nature: 'From a suitably elevated position [i.e. suitably general philosophical stance], this has an element of arbitrariness about it: why not restrict attention to worlds—not with the same laws as ours, but—with the same tourism statistics for Naples as ours?' (ibid.).

But I submit that relativization to (our best guess for) the laws of physics has some interest! In any case, I can at least show that in the present context, it has the interest of being *surprising*. For in Section 8.2 I will argue that the *position*, and even the *existence*, at a time of an emergent classical object (whether a particle or a point-sized piece of matter in a continuum) is *extrinsic*, relative to the laws of quantum theory.[42]

But before arguing for this, I should briefly set aside another way in which quantum theory bears on persistence, and apparently on the RDA.

8.1.1 Unitarity: momentum as temporally intrinsic

Quantum theory violates an assumption that the RDA depends on, viz. that velocity is not part of the instantaneous state of an object. (This assumption, first registered in Section 1.2, led to discussing Tooley's heterodox proposal that velocity *should* be part of the instantaneous state.) This assumption is often endorsed in the metaphysical literature about space, time and motion, even apart from the RDA: for example, Sider (2001, p. 39) says 'fixing the properties and relations of present objects will not fix their velocities' (cf. also his p. 34-35).

The assumption tends to be associated with the fact that in classical mechanics, in order to determine an object's future (and past) motion, you need not only its present position and the forces acting on it (in the time-interval concerned), but also its present velocity; i.e. the fact that classical mechanics' equations of motion are second-order

[42] Besides, the extrinsicality has nothing to do with the possible involvement of other objects in defining position, as urged by a relational conception of space (set aside since Section 5.2). The extrinsicality is what I have called *temporal* extrinsicality, rather than spatial; and it arises from decoherence.

in time. For in a theory in which position and forces were enough to determine the motion (a theory that is first-order in time), it would be more tempting to say that velocity is part of the present instantaneous state. At least, it would be as tempting to say this, as that the whole future (and past) history of the system is part of the present instantaneous state (because of the determinism). Certainly, in such a theory the RDA itself would have much less sting for a "naturalistic" perdurantist, who is willing to let her account of perdurance depend on the actual laws. For in such a case, ingredients that the RDA's advocate presumably agrees to be available to the perdurantist, viz. position and forces, *are* enough to determine future positions.

But quantum theory violates this assumption.[43] It *is* first-order in time. It combines the position and velocity (better: momentum) aspects into a single instantaneous state of a system which, together with the forces acting on the system, determines its future (and past) states (setting aside controversy about whether there is a "collapse of the wave-packet" on measurement).[44]

So it is tempting to say that in quantum theory, velocity and momentum are just as intrinsic (or temporally intrinsic) to the system at a time, as is position; (Arntzenius (2003, p. 282) says this). A bit more precisely: once we are willing to relativize the intrinsic-extrinsic distinction to a physical theory (as proposed in (2) above), it is tempting to say this.

Furthermore, just as Section 7.1 proposed that in a classical setting, a perdurantist accepting only non-instantaneous parts could have their account of persistence "piggy-back" on integrating the classical equations of motion: so in quantum theory, the perdurantist's account of persistence could appeal to integrating the quantum equations of motion. (But as the weasel-word 'system' hints, it is controversial how to relate persisting objects to quantum systems, even if you know the systems' complete histories: cf. the next Subsection).

So be it, say I. But again: I am not so far gone in naturalism about persistence—I am loath to just dismiss the RDA on the grounds that quantum theory is first-order in time. A theory of persistence should accommodate classical continua, and this Subsection's points do not bear directly on how it can do so. However, I will now argue that quantum theory has *other* light to shed on our topic—once we ask the interpretation of classical mechanics to take note of how classical mechanical objects emerge through decoherence.

[43]As readers who are *cognoscenti* of quantum theory will have long ago noticed: at least by the time that Section 7.1 proposed we could have perdurantism without tears, by letting the perdurantist "have" velocity, and even have their account of persistence "piggy-back" on integrating the classical equations of motion. Apologies for the delay!

[44]Agreed, the Hamiltonian formulation of classical mechanics also combines position and momentum in its conception of state, and so is first-order in time. But there is a crucial disanalogy: neither of the pair, position and momentum, determines the other. (Indeed, the formulation is equivalent to the Lagrangian or Newtonian formulation, under certain conditions, in particular taking the phase space to be the cotangent bundle of a configuration space.) But in quantum theory, the position and momentum representations each determine the other.

8.2 Position and existence as nomically extrinsic

So let us adopt the idea in (2) of Section 8.1, of nomic intrinsicality and extrinsicality. The intrinsic-extrinsic distinction among properties is to be relativized to bodies of doctrine—in particular, to quantum theory.

Warning: Choosing logically strong bodies of doctrine can yield odd-sounding verdicts of extrinsicality. Given our interest in temporal extrinsicality, the obvious example of this is provided by a deterministic theory. Thus suppose you choose to relativize, not just to the deterministic theory itself, but to the conjunction of the theory and the regime of forces imposed on a system in some time-interval (a, b). This yields the verdict that every instantaneous state[45] is temporally very extrinsic: indeed, about as extrinsic as it could be. For given the laws of the theory and the forces imposed, any instantaneous state of a system determines the system's states during (a, b). But it sounds wrong to say that every instantaneous state is temporally very extrinsic.

The solution of course is to exercise some judgment about what is a natural or useful body of doctrine to which to relativize. In our example, the theory is presumably such a body of doctrine, but its conjunction with a specified regime of forces is not: that is too particular (logically strong). More generally, we should allow some distinction between "central" and "peripheral" statements (or more generally; features) of an ambient body of doctrine, and relativize the intrinsic-extrinsic distinction only to (the conjunction of) the central ones. That is, only the central ones are held fixed in all the nomic possibilities, and so by nomic intrinsicality and extrinsicality. Then you may say in the example that (maybe part of) the specification of the forces is not central, so that instantaneous states are not so very temporally extrinsic.

Let us now apply this sort of relativization to how classical mechanical objects emerge through decoherence. Fortunately for us, although the quantum measurement problem remains controversial and there remain many open technical questions in the physics of decoherence, we need not address these controversies and questions. We can sidestep the measurement problem, and manage with only the most basic and best-established features of decoherence.[46]

Classical mechanical objects (both particles and continua) are in fact transient and approximate patterns in the quantum state of an underlying quantum system. They are patterns that emerge from an ubiquitous, continuous and very efficient process of decoherence, which continues throughout the lifetime of the classical object. Roughly speaking, decoherence is diffusion (spreading) in to the quantum system's environment of coherence, i.e. of the puzzling interference effects in the probability distributions that are the system's state.

[45]Since for some philosophers, a state is not a property, it is better to say: every property that specifies such a state.

[46]Bacciagaluppi (2003) is an excellent introduction to decoherence for philosophers; for more technical details, Guilini et al. (2003), Schlosshauer (2003) are also excellent. By the way, all these sources endorse the consensus that decoherence cannot by itself provide the solution of the measurement problem, but is an important ingredient in any such solution.

To keep things simple, I shall discuss this in terms of the elementary quantum theory of particles, not quantum field theory. But I should note that:

(i): quantum particles are themselves transient and approximate patterns in the quantum state of an underlying quantum field or fields; for discussion of this, cf. Wallace (2004, especially Section 5.2);

(ii): decoherence also happens within quantum field theory; for a review, cf. Guilini et al. (2003, Chapter 4).

Here are some details about a well-studied model of a quantum particle immersed in an environment (called 'quantum Brownian motion'). Take as the initial quantum state of a tiny dust-particle (radius 10^{-3} cm) in air, a superposition of two positions for the centre of mass of the particle, with the two positions just 10^{-4} cm apart (i.e. a tenth of the particle's radius), and with (say) the two positions not moving relative to one another. The bombardment of the particle by air molecules is *very* efficient in diffusing the coherence in to the environment: the superposition's interference effects converge to zero like $\exp(t/10^{-36}$ sec) and remain small for a very long time (10^{10} years)!

This means that *very* soon the probabilities for any quantity on the particle you care to measure are as if there is an even chance of the (centre of mass of the) particle being in the two positions; (i.e. probabilities for quantities other than position are also given by a 50-50 mixture corresponding to the two positions). Similarly for other initial states: if the initial superposition had the two positions separating from each other at say x cm sec^{-1}, then after a second, the probabilities would be as if there is an even chance of the (centre of mass of the) particle being in two positions $x + 10^{-4}$ cm apart. Indeed, more generally: it is even possible to deduce the approximate validity of the deterministic classical mechanical equations of motion of a dust-particle from the underlying equations for the quantum system, together with a description of the decoherence process.

So the classical object, "the dust-particle we see", corresponds to one of these two decohered possibilities (in my example: possibilities for the position of the centre of mass). It is a pattern in a quantum state, which also contains another pattern corresponding to the other possibility. If the quantum state were sufficiently different, not only would the classical object not have the position and momentum we see: it would not *exist*. In particular, if the decoherence process did not occur, it would never exist; and if the decoherence process did not continue, it would cease to exist. That is: the quantum system would continue to exist, but the classical dust-particle would not: it would "disappear into a quantum fog".[47]

I propose that we take these propositions, about how classical objects are in fact patterns in a quantum state that are formed because of an ongoing process of decoherence, as what I called 'central'. After all, they are crucial to how such objects are in fact constituted. That is: I propose they are to be held fixed in assessing whether

[47]For more discussion of the idea of classical objects as patterns in quantum objects, cf. Wallace (2003).

a property is nomically intrinsic or extrinsic. So they are to be available as implicit premises for implications from ascriptions of a property to propositions about the world beyond the property's instance.

It follows that an ascription to a classical object such as a dust-particle, of a position at t (to be precise: for its centre of mass, say), is nomically *extrinsic*. (I would say: temporally extrinsic, since the implications are about facts at times other than t). For the ascription (together with the implicit premises) implies the (categorical) proposition that the object has a position at all other times in a (very short but non-zero!) interval of times around t. Here, the length of the interval is determined by the decoherence process' time-scale.

Similarly, a statement that the object exists at a time is nomically *extrinsic*. For it implies that the object exists at all other times in an interval about as long as the decoherence time-scale.[48]

So far I have only discussed the emergence of a classical particle, such as a dust-particle. But the discussion just given carries over to continua, as regards both physics and philosophy.

Admittedly, there are more technical questions about decoherence in quantum fluids that are still open than about quantum Brownian motion, which is by now very well-studied. But there is already a good understanding of decoherence in quantum fluids, and so of the emergence of classical continua. In short: recent work shows that even in a quantum fluid, where there is no clear distinction between system and environment, decoherence selects certain quantities (roughly, hydrodynamic variables) as "behaving classically". Again, one can deduce the approximate validity of the classical equations of motion for a fluid. (For details, cf. Halliwell (1999) and references given there.)

As regards philosophy: I said above that the fact that classical mechanical objects (both particles and continua) are in fact emergent from the quantum realm should be reflected in the interpretation of classical mechanics, and so in a naturalistic theory of persistence. One way to do this is now clear. Namely: take the nomic extrinsicality of position at a time, and even existence at a time, as favouring the denial of instantaneous temporal parts. Thus decoherence supports the perdurantism without the tears of *pointillisme* which I defended in Section 7: a naturalistic perdurantist can interpret classical mechanics in terms of temporally extended temporal parts—and thereby block the RDA.

[48]A point of clarification for quantum *aficionados*. You might object that since

(i) the reduced state density matrix of the dust-particle (strictly: of its centre of mass degree of freedom) is nearly diagonal (upto some desired level of approximation) in position, *at an instant*;

it surely follows that:

(ii) the position and existence of the classical particle is *not* nomically temporally extrinsic.

I reply: (i) is of course true, but does not imply (ii). For I am taking as "central", not just the formalism of reduced states etc., but also the physical fact of a decoherence process over time.

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