Reconsidering the interpretation of the Lorentz transformations

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The Lorentz transformations form the mathematical core of the 1905 theory of Special Relativity as well as the earlier version of relativity created by Lorentz himself, originally in 1895 but developed further in the ensuing years. These two theories interpret the physical significance of the transformations quite differently, but in ways that are generally not considered to be empirically distinguishable. It is widely believed today that Einstein's Special Relativity presents the superior interpretation. A number of lines of evidence, however, from cosmology, quantum theory and nuclear physics present substantial evidence against the Special Relativity interpretation of the Lorentz transformations, challenging this traditional view. I review this evidence and suggest that we are now at a point where the sum of the evidence weighs against the Special Relativity interpretation of the transformations and in favor of a Lorentzian or neo-Lorentzian approach instead.

1. Introduction

I'm sitting in a public square in Athens, Greece, biding my time as I write these words. The battery on my phone ran out as I was trying to navigate to my lodgings on my first night in this historic city, forcing me to stop and charge my phone for a little while. I'm waiting for the passage of time.

The nature of time has been debated vigorously since at least the age of Heraclitus and Parmenides in ancient Greece. "All things flow," said Heraclitus. "Nothing flows," said Parmenides as a counter-intuitive rejoinder, suggesting that all appearances of change are an illusion. How could Parmenides make the case that nothing flows, nothing changes? It would seem, from easy inspection of the world around us that indeed all things do flow, all things are always changing. So what was Parmenides talking about?

Parmenides' arguments illustrate well the rationalist approach that Plato was later to more famously advocate, against the empiricist or "sensationist" approach that Heraclitus and Aristotle too would champion as a contrary approach. Parmenides and Plato saw reason as the path toward truth and they were not afraid to allow reason to contradict what seemed to be obvious sensory-based features of the world. Apparent empirical/sensory facts can deceive and, for these men, Parmenides, Plato and their followers, reason alone was the arbiter of truth. Wisdom entailed using reason to see through the world's illusions to the deeper reality.

Heraclitus and Aristotle, to the contrary, stressed the need to be empirical in our science and philosophy (science and philosophy were the same endeavor in the era of classical Greece). Reason was of course a major tool in the philosopher's toolbox for these men too, but it seems that reason unmoored from evidence should not be used to trump the obvious facts of the world. The Aristotelian approach is to find a pragmatic balance between empirical facts and reason in attempting to discern the true contours of reality.

Einstein was firmly in the camp of Parmenides and Plato (Popper, et al. 1998). He famously considered the passage of time, the distinction between past, present and future, to be a "stubbornly persistent illusion."

This view of time, as an illusory construct hiding a deeper timeless world, was based on his theories of relativity. Einstein and his co-thinkers held this view, of time as illusory, despite the obvious passage of time in the world around us, no matter where we look. The widely-held view today is that Einstein finally won the long war, decisively, between Heraclitus and Parmenides. Despite appearances, nothing flows and the passage of time is just that: only appearance.

I suggest in this paper, however, that this conclusion is premature. Einstein's thinking is indeed an example of rationalism trumping empiricism and it is time for us to take a more empirical approach to these foundational questions of physics and philosophy. Today's physics lauds empiricism rhetorically, but in practice a rationalist approach often holds sway, particularly with respect to the nature of time.

2. An overview of Special Relativity and Lorentzian Relativity

In discussing the nature of time with respect to modern physics, I will focus on the Special Theory of Relativity (SR) and avoid discussion of the general theory. Einstein's 1905 theory of relativity adopted the Lorentz transformations directly, unchanged from Lorentz's own version of these equations (Einstein 1905, Lorentz 1895 and 1904, in Lorentz 1937). Einstein's key difference from Lorentz's version of relativity (first put forth in 1895, but developed further in later work) was to reinterpret Lorentz's equations, based on a radically different assumption about the nature of physical reality. Lorentz interpreted the relativistic effects of length contraction and time dilation—which follow straightforwardly from the Lorentz transformations—as resulting from interaction with an ether that constituted simply the properties of space (Lorentz's ether was not some additional substance that pervades space, as was the case in some earlier ideas of the ether). Einstein, to the contrary, interpreted these effects as resulting from the dynamics of spacetime, a union of space and time into a single notion, and dismissed the ether as "superfluous."

Because Lorentz's and Einstein's versions of relativity both use the Lorentz transformations, they will yield in many cases the same empirical predictions. The prevailing view today, then, is that while these two theories are empirically indistinguishable there are other considerations, relating to parsimony primarily, that render special relativity the preferred approach. I discuss below, however, why we now have good empirical reasons to distinguish between these two interpretations—in favor of the Lorentzian approach.

Length contraction and time dilation occur as a result of the assumed absolute speed of light because either space or time, or both, must distort if we consider the speed of light to be invariant. This is because speed is measured simply by dividing distance traveled by the time elapsed; and if the speed of light remains the same in all circumstances then space and/or time must distort in order to maintain this invariance. As an object travels closer and closer to the speed of light, its length must decrease (length contraction) and/or the time elapsed must increase (time dilation) – but only from the perspective of an observer in a different inertial frame. In the original inertial frame there is no length contraction or time dilation.

"Moving clocks run slow" is a good shorthand for relativistic time dilation, but again only from the perspective of a different inertial frame. Time moves at the same rate for an observer in the moving frame of reference, no matter what one's speed in relation to other frames. Relativistic effects only occur when considering the relationship between two different frames of reference, not in the same frame.

Similarly, as an object approaches closer to the speed of light, time slows down (dilates), per the t' equation in Figure 1, shrinking asymptotically to zero, from the perspective of a stationary observer.

There is an empirical basis for SR that is an important part of its history: the 1872 Michelson-Morley experiments found a null result in trying to detect a difference in the speed of light through the ether, as measured from different velocities of our planet during its orbit. However, Lorentz created his theory of relativity specifically to explain these empirical data, a decade before Einstein's alternative approach, and Lorentz suggested that Michelson-Morley's null result occurred because of interaction between moving objects and the ether. That is, as objects move through apparently empty space, which is better conceived of in Lorentz's theory as the ether field and not truly empty, there is a drag effect that causes matter to contract as it moves closer to the speed of light. Similar to how a bar of iron will expand or contract based

$$x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$y' = y$$

$$z' = z$$

$$t' = \frac{t - \frac{v}{c^2} \cdot x}{\sqrt{1 - \frac{v^2}{c^2}}}.$$

Figure 1: The Lorentz transformations as adopted by Einstein's Special Relativity (source: Einstein, 1955).

on its temperature, the same bar will expand or contract based on its velocity through the ether.

Lorentz viewed time dilation as a "mathematical fiction" or "coordinate effect," not a real physical effect like length contraction. A coordinate effect is, for example, like changing time zones when traveling (Galison 2004). When we change time zones there is no real loss or gain of time. Time passes continuously no matter what time zone we're in and we don't literally gain or lose an hour as we change time zones. Rather, each time zone is just a different convention for keeping track of the same shared passage of time. Just so with the time dilation of the Lorentz transformations: the "local time" of each frame of reference is a way to keep track of time between different frames of reference, but global time proceeds independently of the conventions used for measuring the local time. Galison writes:

> Lorentz called t_{local} "local time" (*Ortszeit*), the same word used in everyday life to describe the (longitude-dependent) time of Leiden, Amsterdam, or Djakarta. The crucial point was this: Lorentz's local time was purely a mathematical fiction used to simplify an equation.

In SR, however, there is no global time and the apparent passage of time itself is rendered an illusion. This is the case because if time is malleable and the speed of light absolute, then there is no privileged time and no universal "now." We can slice the universe into an infinite number of possible "nows" depending on the speed at which we move in relation to the distribution of matter and energy in our universe. The sum of these infinite slices of "now" is known as the "block universe." Its name is clear enough as to its consequences: all nows exist in some manner concurrently ("at the same time," which itself is paradoxical) in the block universe. There is no privileged past, present or future. And this is why there is no true change in SR, no passage of time. This is the basis for Einstein's assertion that the passage of time is an illusion.

If this is the case, why do we see nothing but evidence of change, of the passage of time, all around us? Bardon 2013 highlights this conflict between theory and experience: "This is the core challenge in the contemporary philosophy of time: how to reconcile the seeming ineliminability of the experience of the passage of time (manifest time) with the cold, hard conclusions of logic and physics (scientific time)."

The present paper is an attempt at a solution to this core challenge. The solution I suggest is, based on the accumulated empirical evidence, a return to either the Lorentzian interpretation of the Lorentz transformations or a variant thereof (one of the various extant neo-Lorentzian approaches). In sum, we have enough evidence now to make a strong empirical case for preferring Lorentz's relativity over Einstein's relativity, or at least one of the various neo-Lorentzian versions of relativity theory. I review this evidence in the following sections.

3. Has cosmology rendered Special Relativity out of date?

We have learned a great deal about the universe since Lorentz and Einstein created their theories. In 1905, we had little inkling that our galaxy was just one of literally hundreds of billions of other galaxies (or maybe even trillions, based on the most recent analysis in 2016). We had no idea that there was a cosmic microwave background. We didn't realize that the cosmological principle was not accurate. And we had no idea about quantum entanglement or the Higgs field.

But we did have knowledge of the "cosmic frame" of reference, consisting at that time of the fixed stars. In practice, in cosmology, astronomy and in space exploration, there is always a background frame of reference, and this has serious implications for SR. I will go through the various lines of evidence in favor of a preferred frame of reference above and beyond the fixed stars frame of reference.

3.1. The CMB is a cosmic frame of reference

Mansouri and Sexl 1977, among many others (e.g., Reinhardt, et al. 2007), has suggested that the cosmic microwave background (CMB) should be considered a cosmic frame:

> The discovery of the cosmic back-ground radiation has shown that cosmologically a preferred system of reference does exist. This system is defined and singled out much more unambiguously to be a candidate for a possible "ether frame" than was the solar rest frame in Einstein's days.

The CMB is the more accurate equivalent of the fixed stars as a cosmic frame—more accurate because it is changing less over time than the fixed stars. And, as discussed below, it exhibits some pronounced anisotropies, making its orientation detectable anywhere in the universe, as best we can tell. (A recent example of using the CMB as a preferred rest frame is found in Riess et al. 2016 (p. 15): "z is the redshift in the rest frame of the CMB corrected for coherent flows…").

The existence of the CMB means that in practice there is always a common/preferred frame of reference for use in navigation and orientation more generally, no matter where we are in the universe. This alone doesn't invalidate SR but it weighs against Einstein's interpretations of the Lorentz transformations because SR postulates that the laws of physics are the same for all inertial frames (this is the "principle of relativity," one of Einstein's two postulates in his 1905 paper), thus there is no preferred frame. But in our actual universe there is a preferred frame formed by the CMB, or large-scale baryonic structures, or a combination of both, as discussed below.

3.2. The cosmological principle has been falsified

The cosmological principle is the longstanding notion that our little piece of space and time shouldn't be special. We should, taking the big picture, be quite average. Keel 2007 states the principle as follows:

> "Viewed on a sufficiently large scale, the properties of the universe are the same for all observers." This amounts to the strongly philosophical statement that the part of the universe which we can see is a fair sample, and that the same physical laws apply throughout.

This principle suggests that when we look out at the universe it should look generally the same in every direction. And similarly with time: when we look backwards and project forwards we should expect more or less the same universe as we see now. We cannot, of course, look out at the universe without looking backwards in time, but we can project the future, and under the cosmological principle the future should generally look the same as the present and the past. Or so the principle supposes.

The cosmological principle was a reasonable assumption in our first efforts at developing modern empirically-informed cosmological theories because with a sample size of just one—our little planet and our human species constituting the only example of intelligent life that we know of at this point—we should indeed assume that the rest of the universe is essentially like our neighborhood of the universe, until proven wrong . That is, we shouldn't assume that things are radically different outside of our particular milieu because all we know with any intimacy is our own milieu, until we have good evidence to suggest otherwise. This is really just common sense.

It is becoming increasingly apparent, however, that the cosmological principle is inaccurate, both spatially and temporally. There are a number of very large structures in our universe, including the CMB just discussed as well as many others, that seem to contradict the cosmological principle. The largest baryonic structure, and most recently discovered, is the Hercules-Corona Borealis Great Wall discovered in 2013 by Horvath, et al. (Horvath, 2015; Bagoly et al 2015). This structure is 2-3,000 megaparsecs (Mpc) in size. The Sloan Great Wall was the previously largest structure at about 400 Mpc.

Even larger structures in the background energy structure of the universe, the CMB discussed above, have been found and dubbed playfully "the axis of evil" or AOE, because of the implications of this very large-scale structure for the standard ΛCDM model of cosmology. The AOE, as its name suggests, is a literal axis that extends through the entire universe, showing that there is, if the data and its interpretation are accurate, an identifiable orientation to the universe. Examining the Wilkinson Microwave Anisotropy Probe (WMAP) data in a 2006 paper, Wiaux et al. conclude that "nothing at present allows us to discard the possibility of a global universe anisotropy, simple violation of the cosmological principle hypothesis."

Land and Magueijo 2008 states in reviewing the evidence for the AOE: "it must be said that while everyone agrees on the presence of the 'axis of evil' in the data, its extent is still debated." Liu et al 2016, in reviewing new data on the AOE, supports the existence of the AOE and states: "If the anomalies are not caused by foreground residuals or systematic effects, we are facing a challenge [in our] understanding of fundamental physics and the nature of the cosmos."

These matter and energy structures, if new data continue to support their existence, should be considered strong support for refuting the spatial cosmological principle because they show that the universe is not isotropic at the large-scale.

Temporally, matters are not quite so clear since our theories of cosmic evolution are themselves still evolving. However, under the Big Bang cosmology, the universe does not seem to be, in the flat universe that we are thought to be living in, temporally symmetric either. This issue is deep and highly debatable, as Carroll's excellent book, From Eternity to Here , describes (Carroll 2010). Carroll makes a case for temporal symmetry based on a cyclic universe model in which the past and the future do in fact look essentially the same. Carroll acknowledges that his arguments are new and speculative, and we are assured of much thriving debate on this issue for years to come. However, even if the universe is temporally symmetric (at very large timescales) we already know, based on the arguments above, that it is not spatially symmetric. Based on this reasoning alone, we can conclude that the Cosmological Principle is very likely not accurate, and should probably be considered falsified.

This information supports the notion that there is a preferred reference frame with a definite orientation in space and time – the Cosmic Microwave Background and the large-scale matter structures just discussed – which further weighs against SR's view that there is no preferred frame.

3.3. Does quantum mechanics contradict Special Relativity?

Another empirical challenge to Special Relativity arises from the collapse of the wavefunction in quantum mechanics. This collapse, a key feature of the Copenhagen interpretation, is considered to be instantaneous or at least many times the speed of light, apparently contradicting SR's assumption that the speed of light is a cosmic speed limit. As we'll see below, however, this conflict interpretation is hotly debated. Salart, et al. 2008 found that quantum collapse occurs at least 10,000 times the speed of light. Carroll 2010 states (p. 231):

> The arrow of time is ... a fundamental puzzle, and it's possible that quantum mechanics will play a crucial role in resolving that puzzle. And there's something else of more direct interest: That process of measurement, where all of the interpretational tangles of quantum mechanics are to be found, has the remarkable property that it is irreversible . Alone among all of the well-accepted laws of physics, quantum measurement is a process that defines an arrow of time: Once you do it, you can't undo it. And that's a mystery.

How does this quantum effect mesh with SR? One method for reconciling these two pillars of modern physics is to suggest that quantum collapse takes place outside of space and time and is thus not physical (or is physical in some other manner) (see , e.g., Brooks 2014 or Walleczek and Grössing 2016). This interpretation presents some problems in terms of parsimony, particularly if we can offer a different interpretation that allows for all of physical reality to coexist in the same set of dimensions, the same reality. Lorentzian relativity, which I'll label LR from now forward, suffers the same issue as SR in this context because it also includes the speed of light as an asymptotic speed limit (because it also uses the Lorentz transformations). Some versions of neo-Lorentzian relativity, however, don't suffer from this issue because there is no necessary speed limit of causal effects in some neo-Lorentzian approaches. As such, quantum effects are simply very fast effects that present no particular interpretational challenge for these neo-Lorentzian approaches.

Callender 2007 examines in detail whether wavefunction collapse necessarily violates SR, and concludes that it does under both the standard Copenhagen interpretation and in hidden-variable interpretations, but there is no conflict for all other interpretations of quantum mechanics: "With all these qualifications now in place, we can only say that [philosopher of science] Popper's conclusion [that wavefunction collapse necessarily weighs in favor of Lorentz's interpretation] threatens most if one adopts a standard collapse or hidden variable interpretation of quantum mechanics as well as a standard reading of Lorentz invariance." (Callender goes on, nevertheless, to present a vigorous defense of tenseless time in physics, which is beyond the scope of the present paper to address.)

Walleczek and Grössing 2016 suggests a new approach that would reconcile apparently superluminal quantum collapse, including in hidden variable approaches like the de Broglie-Bohm interpretation, and relativity theory by proposing an "effective non-signalling" constraint that allows for superluminal influences but not superluminal signaling or communication. They state the problem clearly: "The present work offers a communication-theoretic analysis of the conceptual impasse that exists between (1) the possibility of superluminal influences and (2) the impossibility of superluminal signalling as required by special relativity: Does the presence of superluminal influences necessarily imply superluminal signalling and communication?" The authors propose that "Shannon signals," that is, physical signaling or communication between "epistemic entities," do not occur with quantum collapse, but "non-Shannon signals," which involve physical influences but not signaling or communication between epistemic entities, are permissible. This distinction, the authors suggest, saves quantum effects from being "not physical" and thus offers a path toward reconciling SR and nonlocality.

My view is that this distinction between influences and signaling between epistemic entities is strained because it rests on an assumption that a certain set of physical limits applies to epistemic agents but don't apply to the rest of the universe. Why would nature operate in this radically emergent binary manner when all the evidence of biology suggests that the evolution of life and consciousness occurs in steady incremental fashion? Based on this objection, I find Walleczek and Grössing's attempt to save SR from falsification due to conflicts with non-locality to be problematic.

As we'll see in the discussion below about J. S. Bell's work on quantum theory vis a vis SR, there are two primary choices in approaching this apparent conflict between quantum nonlocality and SR: 1) look for a way, as Walleczek and Grössing have attempted, to make a reasonable distinction between superluminal influences and superluminal signaling/communication, in order to save SR from this apparent falsification; or 2) accept that superluminal signaling/communication is indeed occurring and that this is further evidence that SR should be considered falsified. The second option allows for de Broglie-Bohm quantum theory to stand, as does the first option.

The second option is anathema to the large majority of physicists and philosophers today who have long accepted SR as a powerful and foundational theory of modern physics. For example, Walleczek and Grössing 2016 assumes that any interpretation that violates SR is "physically unrealistic": "As a consequence, relativity theory would be violated which would render an ontological quantum theory, like de Broglie–Bohm theory, physically unrealistic." But given the weight of evidence that challenges SR, plus the other benefits of alternative interpretations of the Lorentz transformations considered further below, we shouldn't shy from considering option 2, which is indeed more physically realistic than option 1.

In conclusion, wavefunction collapse, whether instantaneous or simply faster than the speed of light, seems to present another significant challenge to SR.

4. Octupole deformation in barium nuclei challenges time symmetry

A more recent line of evidence also weighing against SR is the 2016 finding that there is an orientation to the octupole deformation in barium nuclei. Bucher, et al. 2016 concludes that "despite significant uncertainties on the measurement, the data also indicate an octupole strength larger than calculated in various theoretical approaches." In describing this work for the public, Scheck, one of the authors of the new study, stated: "We've found these nuclei literally point towards a direction in space. This relates to a direction in time, proving there's a well-defined direction in time and we will always travel from past to present."

While the new paper and the researchers both avoid discussing whether there is a conflict with SR, this implication mentioned by Scheck seems obvious. If further research supports this recent finding, which, as the paper describes, does currently include large measurement uncertainties, it will pose another serious empirical challenge to SR and provide further support for a Lorentzian or neo-Lorentzian approach instead.

5. Changing views about alternatives to SR

Now that we have reviewed the main empirical challenges to SR, let's review some of the historical theoretical discussions surrounding SR and alternatives. J. S. Bell, the colorful Irish physicist who formulated the Bell inequalities, which formed the theoretical basis for Aspect's non-locality experiments, was a supporter of the Lorentzian view. He stated in a 1986 interview with physicist Paul Davies (Davies 1986):

> [T]he pre-Einstein position of Lorentz and Poincaré, Larmor and Fitzgerald was perfectly coherent, and is not inconsistent with relativity theory. The idea that there is an aether ... is a perfectly coherent point of view. The reason I want to go back to the idea of an aether here is because ... the suggestion that [in nonlocality experiments] behind the scenes something is going faster than light. Now if all Lorentz frames are equivalent, that also means that things can go backward in time ... [This] introduces great problems, paradoxes of causality, and so on. And so it is precisely to avoid these that I want to say there is a real causal sequence which is defined in the aether.

Yuri Balashov, a philosopher at the University of Georgia, stated in Balashov 2000:

> [T]he idea of restoring absolute simultaneity [which is the basis for the Lorentzian interpretation of relativity theory] no longer has a distinctively pseudo-scientific flavor it has had until very recently. It is a well-known fact that one could accept all the empirical consequences of SR (including length contraction, time dilation, and so on) and yet insist that there is a privileged inertial reference frame, in which meter sticks really have the length they have and time intervals between events refer to the real time.

Hawking, in discussing Einstein's development of our modern theory of gravity, general relativity, states: "[Einstein's] theory of general relativity further complicates this matter by proposing that gravity gives rise to the structure of space itself. To put this plainly, gravity is defined even in 'empty' space, and thus, there must be something" even in empty space. He adds: "That 'something' is the ether, or, in modern language, a field... In many respects, this is one of the most important contributions of relativity to physics. In the modern view, all forces arise from fields. In quantum theory... the particles themselves arise from the field."

In a little-known tale of 20th Century physics, Einstein himself regretted his 1905 dismissal of the ether as "superfluous," in his seminal paper. Einstein's own thinking evolved to the point that he realized that some type of (relativistic) ether was theoretically necessary after all. Einstein called this the "new ether," but changed his terminology over time, as we shall see below [Footnote 1].

[Footnote 1. For a thorough discussion of Einstein's ideas on the ether, based on primary documents in German, with English translations, see Einstein and the Ether (2000) by Ludwik Kostro.]

In 1915, Einstein published his general theory of relativity, which asserted a very different conception of space and time than that put forth in 1905. In general relativity, space has no independent existence; rather, it is a consequence of the various fields that are ontologically fundamental. Shortly after his momentous general relativity paper was published, he exchanged letters with Lorentz. Lorentz argued throughout his career that some notion of the ether was necessary for a valid description of reality. Einstein conceded eventually that indeed a non-material but still physical ether was necessary to explain inertia and acceleration. Einstein first described his "new ether" in a 1916 letter to Lorentz:

> I agree with you that the general theory of relativity is closer to the ether hypothesis than the special theory. This new ether theory, however, would not violate the principle of relativity, because the state of this ... ether would not be that of a rigid body in an independent state of motion, but every state of motion would be a function of position determined by material processes.

Einstein also wrote in a 1919 letter to Lorentz:

> It would have been more correct if I had limited myself, in my earlier publications, to emphasizing only the non-existence of an ether velocity, instead of arguing the total non-existence of the ether, for I can see that with the word ether we say nothing else than that space has to be viewed as a carrier of physical qualities.

From 1916 to 1918, Einstein was in the thick of discussions with a number of colleagues about the nature of space and the ether, with respect to general relativity. As Walter Isaacson recounts in his biography of

Einstein (Isaacson 2008), Einstein's thinking changed dramatically during this period. In 1918, he published a response to critics of special and general relativity. In this dialogue, Einstein writes that the "diseased man" of physics, the "aether," is in fact alive and well, but that it is a relativistic ether in that no motion may be ascribed to it.

In 1920, Einstein became more emphatic regarding the ether, recognizing explicitly that the ether was a necessary medium by which acceleration and rotation may be judged, independently of any particular frame of reference:

> To deny ether is ultimately to assume that empty space has no physical qualities whatever. The fundamental facts of mechanics do not harmonize with this view... Besides observable objects, another thing, which is not perceptible, must be looked upon as real, to enable acceleration or rotation to be looked upon as something real ... The conception of the ether has again acquired an intelligible content, although this content differs widely from that of the ether of the mechanical wave theory of light ... According to the general theory of relativity, space is endowed with physical qualities; in this sense, there exists an ether. Space without ether is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring- rods and clocks), nor therefore any spacetime intervals in the physical sense.

Again, Einstein stressed that this new ether was relativistic. Einstein struggled with these ideas for much of his career. As a realist, Einstein argued during the middle and latter parts of his career that physics must attempt to describe what is truly real and not avoid discussion of concepts that cannot be directly detected – such as the ether – even if they seem to be logically necessary due to indirect evidence. So for Einstein, even though the ether was considered undetectable, he deduced its existence because of its effects on observable matter through inertia, acceleration and rotation. In this manner, then, the new ether was detectable.

In sum, while Einstein viewed his new ether as relativistic, it is an important step in reinterpreting the Lorentz transformations to recognize that even Einstein, who dismissed the ether as "superfluous" in his 1905 paper on special relativity, brought this concept back into his physics with general relativity and his later work. LR relies on physical interaction with a physical ether as the mechanism for relativistic effects. This ether can be viewed simply as space itself, but not space as a true void because the space of modern physics has defined qualities. As Hawking states above: space is not truly empty. This Lorentzian ether is not relativistic in the sense that Einstein suggested because it does not abide by the special principle of relativity. Rather, it is the background frame that Einstein sought to dispel by making his special principle of relativity one of his axioms in his 1905 paper.

6. Is the Higgs field a new ether?

Frank Wilczek, a Nobel Prize-winning physicist at MIT, writes in his 2008 book The Lightness of Being: Mass, Ether and the Unification of Forces :

> No presently known form of matter has the right properties [to play the role of the ether]. So we don't really know what this new material ether is. We know its name: the Higgs condensate [or Higgs field], after Peter Higgs, a Scots physicist who pioneered some of these ideas. The simplest possibility ... is that it's made from one new particle, the so-called Higgs particle. But the [ether] could be a mixture of several materials. ... [T]here are good reasons to suspect that a whole new world of particles is ripe for discovery, and that several of them chip in to the cosmic superconductor, a.k.a the Higgs condensate.

As the title of Wilczek's book suggests: he argues from many lines of evidence that there is in fact an ether that undergirds space, which he calls alternately the ether, the Grid or the "cosmic superconductor."

Lawrence Krauss, a well-known physicist and science popularizer, wrote of the Higgs field announcements in 2012 in a way that supports a revival of the ether concept (Krauss 2012):

> The brash notion predicts an invisible field (the Higgs field) that permeates all of space and suggests that the properties of matter, and the forces that govern our existence, derive from their interaction with what otherwise seems like empty space. Had the magnitude or nature of the Higgs field been different, the properties of the universe would have been different, and we wouldn't be here to wonder why. Moreover, a Higgs field validates the notion that seemingly empty space may contain the seeds of our existence.

As such, the evidence regarding the Higgs field, or some similar field and particle if it is ultimately determined that the 2013 evidence was not the Higgs itself, may lend support to the ether concept and, more generally, to the idea that there is a total field that undergirds our reality; the "seeds of our existence," as Krauss states.

7. Some theories of quantum gravity suggest violations of SR

An additional non-empirical argument merits mention here. A number of approaches to quantum gravity – a theory that would reconcile general relativity with quantum mechanics – suggest violations of SR. These are purely theoretical considerations at this point, since none of these theories has been tested at this juncture in a manner that would support or deny the suggested violations of SR. Botermann et al. 2014 states: "Interest in [Lorentz Invariance] tests have been further boosted by the search for a theory reconciling quantum theory with general relativity, as many attempts for such a quantum gravity explicitly allow Lorentz violation, making it a potential discriminatory experimental signature for the underlying theory."

Lorentz Invariance refers, of course, to violations of the principle of special relativity that is at the heart of Einstein's SR. This terminology is admittedly confusing, but it arises from the fact that Einstein's 1905 SR paper adopted the Lorentz transformations, as we've discussed above. So SR uses the Lorentz transformations but explicitly rejects the Lorentzian interpretation of those transformations in favor of the spacetime approach that Einstein championed.

8. Is special relativity more parsimonious than Lorentzian relativity?

Knowledgeable physicists will acknowledge that LR is a viable approach given that both use the Lorentz transformations and are thus generally not considered to be empirically distinguishable. This dilemma about which theory is better is sometimes described as an "aesthetic" debate, not because the difference in interpretations is trivial but because without empirical data to make a choice we must look to other considerations like aesthetics and parsimony. As discussed above, however, there is indeed a substantial amount of data that can empirically distinguish these two interpretations – but this state of affairs is not widely acknowledged yet.

Physicists who argue in favor of Einstein on this issue (the large majority still would today) rest their arguments often on the notion that Special Relativity is more parsimonious because it can explain the same phenomena with fewer components; namely the absence of an ether.

A related parsimony argument centers on our assumptions about the speed of light. Einstein assumed that the speed of light was constant no matter the speed of the observer, as an explanation of the Michelson-Morley data. We can assume otherwise, however, particularly considering that no other speeds in the universe behave this way. That is, all other speeds do in fact change based on the speed of the observer.

In the context of measuring the speed of light, Einstein's assumption leads to an ε value of 0.5 in the following light speed measurement equation first formulated by Reichenbach 1924:

$$t_2 = t_1 + \varepsilon(t_3$$

-

t_1)
(1)

ε of 0.5 is a prima facie parsimonious assumption, despite it being highly counterintuitive, because it allows for an easier measurement of the speed of light by using mirrors to reflect light back to the source (see Jammer 2006 for more, particularly the last chapter). Operationally, this allows an experimenter to shoot a ray of light, at t_1, at a mirror, reached at t_2, and measure the time elapsed for the light's return at t_3. By dividing the elapsed time by two, we can derive the average speed of light over this distance. This technique only works for determining the one-way speed of light if one assumes that the speed out is the same as the speed back, which equates to an ε of 0.5. But, again, any other speeding object would not have the same speed in both directions because of other forces impacting the object differently based on its direction, such as air speed. And if the observer was herself moving during this experiment, any other moving object would indeed show a different speed out and back.

Einstein's assumed isotropic speed of light made sense at the time operationally, but we now know that many problems arise from this assumption, including how to reconcile the obvious flow of time in quantum mechanics, in the cosmic frame, and in everyday experience with this assumption. Reichenbach stated: "If the special theory of relativity prefers the first definition, i.e., sets ε equal to 1/2, it does so on the ground that this definition leads to simpler relations."

We are then left with an ostensibly simplifying assumption that leads ultimately to a more complex and sometimes self-contradictory and empirically-challenged system than other alternative assumptions, including the more intuitive notion that the speed of light does in fact change based on the speed of the observer.

In order to explain various phenomena, it is in my view more parsimonious to adopt the LR version of relativity and an ε different than $\frac{1}{2}$. This approach accords with the various lines of evidence discussed above (CMB frame of reference, large-scale non-homogeneity, quantum collapse, octupole deformation, etc.), as well as the passage of time. Under this approach, the specific value of ε depends on the speed of the frame through the ether.

Maudlin 2012 describes an approach to SR that doesn't rely on the Lorentz transformations, relying instead on basic assumptions about the nature of space and light:

> When we first introduced the notion of a Lorentz coordinate system, it was completely unconnected with any physical procedures: the coordinates were used only as an abstract way to specify the intrinsic geometry of Minkowski space-time. Next, we connected that geometry to the behavior of matter by a set of physical principles: the Law of Light, the Relativistic Law of Inertia, and the Clock Hypothesis. Finally, we have shown that if these principles are accepted, then a certain physical procedure, employing inertially moving ideal clocks and light rays in a vacuum, will result in the assignment of Lorentz coordinates to Minkowski space-time. At no point in this procedure have we so much as mentioned the "speed of light," or postulated that the "speed of light is constant": Minkowski space-time does not support any objective measure of the speed of anything. Nor have we anywhere invoked the notion of an "inertial coordinate system" or postulated that "all inertial systems are equivalent" or that "the laws of physics take the same form in all inertial systems." Rather, we have postulated a certain geometrical structure to space-time, invested that structure with physical significance for the behavior of visible matter by means of some physical postulates, and then described how to use the matter to construct coordinate systems.

As Maudlin states, however, the approach he employs relies on a set of assumptions, including the "Law of Light," which Maudlin 2012 defines as follows: "The Law of Light can only be formulated in a space-time that associates a light-cone with each event. Note that the Law of Light mentions nothing about the source of the light save that the source emits at a particular event. So the Law of Light implies the phenomenon cited above: two light rays emitted from the same point in a vacuum will arrive together at a distant observer." That is, the Law of Light from the outset requires that light behave differently than all other physical phenomena we know of because its velocity is postulated to be independent of the speed of the emitting source.

Accordingly, Maudlin's Law of Light is very similar to Einstein's light speed postulate in Einstein 1905, which states "that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body." The difference, as Maudlin highlights, is that the Law of Light postulates nothing about the velocity of light. But as Maudlin 2012 also acknowledges [Footnote 2], the velocity of light may be measured in relation to any chosen frame of reference and it will be the same velocity in all cases, based on the fact that the postulate would not allow any other finding.

We are, then, even under Maudlin's alternative approach to SR, back to the issue of postulating either the isotropic/absolute speed of light or the existence of an absolute space/ether, which is the same dichotomy distinguishing SR and LR.

[Footnote 2. Maudlin 2012 states: "Light, in itself, has no speed, since there is no absolute time or absolute space in Relativity. But relative to a coordinate system, we can assign a light ray a coordinate speed." This is, of course, the case for any speed because speed is only ever knowable in relation to other things.]

9. Some advantages of adopting a Lorentzian or neo-Lorentzian notion of relativity

Callender 2007 and Janssen 2002 tread some of the same ground covered in the present paper. Janssen 2002 argues that SR is still the superior interpretation when compared to alternatives. However, Callender 2007 agrees that the Lorentzian interpretation is warranted and probably a superior interpretation to SR in some ways [Footnote 3], but he disagrees that Lorentzian relativity rescues tensed time (the passage of time), due largely to the "coordination problem" between a psychologically preferred frame and the preferred frame in physics. I won't address the coordination problem in this paper but Zimmerman 2011 does.

[Footnote 3. "[Lorentzian Relativity] shouldn't be viewed as a desperate attempt to save absolute simultaneity in the face of the phenomena, but it should rather be viewed as a natural extension of the well-known Lorentz invariance of the free Maxwell equations. The reason why some tensers [thinkers who view the passage of time as an objectively real phenomenon] have sought all manner of strange replacements for special relativity when this comparatively elegant theory [Lorentzian Relativity] exists is baffling."]

Despite Callender's vigorous argumentation against tensed time—the objectively real passage of time—it is not clear why those who prefer a tensed notion of time can't simply posit that the preferred frame of physics is the preferred frame universally, even if we couldn't know what that frame is. We do in fact have a strong candidate already for the preferred frame, as discussed above: the CMB plus very large-scale structures like the Great Wall and the Axis of Evil.

This approach – preferring a Lorentzian or neo-Lorentzian interpretation – renders the universe ontologically not relativistic in the sense of SR, but still allows us to use the Lorentz transformations to translate between different frames of reference. This ability to translate between frames of reference was the original intent behind Poincare's, Lorentz's, Fitzgerald's and Einstein's work on relativity theory. This approach, as discussed above, renders length contraction a result of interaction between matter and the preferred frame (ether or the total field or whatever term we prefer) and renders time dilation a coordinate effect only.

Very few discussions of SR explain the physical basis for the relativistic effects of length contraction and time dilation. Callender 2007 explicitly states that it is the "spacetime structure" that causes these phenomena, and suggests that this is a more parsimonious explanation than LR offers, with its ether friction suggestion. However, the spacetime structure that Callender alludes to is not a physical mechanism; rather, it reduces to the assumption of the relativity of simultaneity that was the key step in Einstein's original 1905 paper on SR.

That is, by assuming the relativity of simultaneity, which results in a particular measurement convention for the speed of light, length contraction and time dilation necessarily result from the Lorentz transformations. But there is no physical mechanism proposed for these phenomena in SR. Why do objects contract the more they approach the speed of light? All SR can say is "because we assume, for operational simplicity, the relativity of simultaneity, which results in an intermingling of space and time into a single spacetime."

But we can simply change the assumption from the relativity of simultaneity to absolute simultaneity and the mathematical results of the Lorentz transformations and their empirical successes don't change. Instead, if we adopt Lorentz's explanation of these phenomena we gain a physical mechanism for length contraction, which is caused in LR by interaction with space itself, which we know now is not actually empty. So it is not "spacetime structure" in LR that leads to length contraction but "space structure," akin to a drag or friction effect that increases as an object's speed relative to space increases. This is a more satisfying physical mechanism because it is natural that if space is not truly empty that there would indeed be some kind of drag effect analogous to friction. We may describe it as "space friction" or "ether friction."

Time dilation in LR is reduced to a coordinate effect akin to changing time zones. There is no physical or real temporal change in changing frames of reference. Rather, there is only a change in convention in terms of how we measure time and translate between different frames of reference. This approach to time dilation resolves all manner of time paradoxes like the Twins Paradox, in a very elegant way: there is no paradox in LR because there is no differential aging of the separated twins, just different conventions for telling time for the separated twins.

But perhaps the larger benefit of LR is reconciling our fundamental experience of the passage of time, and the overwhelming evidence of the passage of time in the natural world, with a key theory of modern physics. Earlier in my essay I discussed Bardon's challenge: "This is the core challenge in the contemporary philosophy of time: how to reconcile the seeming ineliminability of the experience of the passage of time (manifest time) with the cold, hard conclusions of logic and physics (scientific time)." Because LR doesn't result in physical time dilation there is a real passage of time and an absolute simultaneity in the universe (even if we can't know in practice what events are truly simultaneous with each other). "Scientific time" and "manifest time" become one and the same under this approach.

A real passage of time and a real order of events—the A-series approach to time in the philosophy of time—reconciles the dramatic departure from human experience and empirical fact that has existed over the last hundred years since SR and its block universe notion of time became widely accepted. We need not sacrifice the utility of the Lorentz transformations; we should instead reinterpret their significance in a manner that is commonsensical, elegant, and empirically sound.

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Appendix 1. Weighing the evidence for physical time dilation.

The main argument of this paper does not depend on the evidence for physical time dilation. The main argument is that even though Einstein's and Lorentz's interpretations of the Lorentz transformations are generally (but in some key ways not) empirically equivalent, we should nevertheless interpret the Lorentz transformations as Lorentz himself did: that relativistic effects are due to interaction with space/ether, based on the larger empirical findings that are discussed in the paper. This core argument does not rest on particular evidence regarding physical time dilation because time dilation occurs, as either a coordinate effect or a physical effect, under both interpretations of the Lorentz transformations.

The core of the debate comes down to how we interpret the relativistic effects that are contained in the equations, as discussed in the body of my paper: do we rely on "spacetime structure" to explain relativistic effects (as Einstein did with his postulated isotropic speed of light and the combined spacetime that flows from this assumption) or physical interaction with space/ether (as Lorentz did)?

However, since Lorentz suggested that time dilation was not a real physical phenomenon but, rather, a "mathematical fiction," or coordinate effect only (Galison 2004), evidence showing that physical time dilation is a real phenomenon rather than a coordinate effect only would weigh in favor of the Einstein approach rather than the Lorentz approach, all else equal. I argue, of course, in the paper that all else is not equal, and this is why the argument does not hinge on the evidence with respect to time dilation.

I offer in this appendix, however, some considerations on the evidence collected thus far on physical time dilation – do clocks actually measure different elapsed times in different moving frames? – and I conclude that this evidence is weaker than required to be considered a real physical phenomenon at this time. If I am right, this further weighs in favor of the Lorentzian interpretation of the transformations. If physical time dilation is real, however, this weighs more in favor of the Einstein interpretation.

I will look at three key papers that examine time dilation. This is obviously not a comprehensive examination of the evidence – time and space will not permit that kind of examination. By examining three key papers instead I hope to provide a reasonable overview of the state of the science in this area. It also turned out, serendipitously, that each of these three papers suffers from different types of issues that, in different ways, cast serious doubt on their purported support for SR.

First, I'll examine the well-known Hafele-Keating experiment (Hafele and Keating 1972, "Around the world atomic clocks: observed relativistic time gains"), which was one of the first experiments that found significant time dilation effects, and also received significant media attention at the time and since. The experiment involved shipping four cesium clocks on jetliners traveling different directions around the world and then comparing their readings.

The HK experiment had many serious issues from the outset, as their 1972 paper itself describes. The authors identify two main experimental accuracy issues: 1) the fact that they were measuring effects on the order of 0.1 microseconds per day and their machinery's accuracy was only within 1 microsecond per day; 2) in correcting the data for this issue they needed to also correct for unpredictability in expected drift in each clock, which they attempted to do with two different methods discussed.

With respect to the first method for correcting for naturally-occuring time drift in the four clocks employed for the experiment, ”the average rate method,” the authors state (p. 169): ”Reliability of results with the average rate method, however, depends on the unlikely chance that only one rate change occurred during each trip and that it occurred at the midpoints. Furthermore, there is no obvious method for estimating the experimental error. Nevertheless, the average rate method does produce convincing qualitative results.”

The last sentence is rather incredible given the first two sentences.

With respect to the second method, the authors state (p. 177): ”An analysis of these data revealed the times and magnitudes for correlated rate changes during each trip. Thus significant rate changes were identified and ascribed to each clock. A piecewise extrapolation of the time trace for each clock relative to MEAN(USNO), with proper accounting for these identified rate changes, then produced the relativistic time differences [observed].”

We have to dig a bit deeper to find why this method, rather than being an appropriate adjustment, seems instead to be a strong example of cherry picking the data. Kelly 2000 looks at the original data collected by HK from the four cesium clocks used in the experiment (this data was not published in the original paper), after the author request the original report from the US Naval Observatory, and concludes (emphasis added):

> The [US Naval Observatory] standard station had some years previously adopted a practice of replacing at intervals whichever clock was giving the worst performance. On a similar basis, the results of Clock 120 [one of the four used by HK] should have been disregarded. That erratic clock had contributed all of the alteration in time on the Eastward test and on the Westward test, as given in the 1971 report. Discounting this one totally unreliable clock, the results would have been within 5ns and 28ns of zero on the Eastward and Westward tests respectively. This is a result that could not be interpreted as proving any difference whatever between the two directions of flight.

Accordingly, under Kelly 2000’s re-examination of the raw data, it seems that we should accord little to no weight to this now iconic experiment purporting to find strong evidence of physical time dilation – that is, real differences in the elapsed time of traveling clocks.

Turning to the second paper, Reinhardt et al. 2007 conducts a complex experiment, the latest in a long line of Ives-Stillwell-type experiments, specifically using lithium ion resonance frequencies and saturation spectroscopy in ion storage rings. The experiment measured the frequency of similarly-accelerated lithium ion groups, at 3.0% and 6.4% of the speed of light, respectively. By comparing the resonance frequency of the two groups to the frequency of the measurement lasers, the time dilation prediction of SR can be tested. The experiment predicts that the product of the two measurement lasers’ (parallel and anti-parallel to the direction of the ions) frequency will match the product of the frequency of the ions’ frequencies in the laboratory rest frame.

The paper states: “Time dilation is one of the most fascinating aspects of special relativity as it abolishes the notion of absolute time. . . . Here we report on a method, based on fast optical atomic clocks with large, but different Lorentz boosts, that tests relativistic time dilation with unprecedented precision.” There are no traditional clocks involved, however; the “clocks” mentioned refers to the frequency of the accelerated lithium ions, which will change with acceleration when compared to the rest frame frequencies. While not a traditional clock, this change in frequency functions as a clock under the same principles as any clock: by measuring a certain type of periodic motion.

The paper briefly discusses the need for a test theory in order to examine the purported relativistic effects and settles on the Robertson Mansouri Sexl (RMS) test framework, which is the most common test theory for measuring relativistic effects. RMS assumes an arbitrarily chosen rest frame and, if there is deviation from expected results in the rest frame, this deviation is interpreted as support for the Einsteinian no-rest frame approach.

Reinhardt et al. 2007 resulted in the most accurate measurements of time dilation at the time of the experiment (there is a similar paper, Botermann et al. 2014, that finds even more accurate results), a value of $|\hat{\alpha}|$[?] 8.4 x 10_{-8}. This indicates, if the results are accurate, that any deviation from the expected time dilation of Einstein's theory is small indeed, at less than one in a hundred million. The paper states that within the "RMS framework, this result constrains the existence of a preferred reference frame in the universe (for example, the cosmic-microwave-background frame)."

This is an apparently strong empirical result, but, importantly, it does not distinguish between the ether-interaction Lorentz interpretation and Einstein's structure of spacetime-interaction interpretation of the Lorentz transformations. This is the case because the experimenters, in evaluating the results within the RMS framework, used the lab itself as the rest frame, Σ, which is permissible under the RMS test theory (any frame can be chosen as the rest frame in RMS). Thus, the conclusion about the results constraining a CMB reference frame (or other basis for a background reference frame) don't match up with the measured results.

Since the measured result occurs as a result of using the Lorentz transformations, regardless of whether we follow the Einstein interpretation or the Lorentz interpretation, *the RMS test framework, and this experiment specifically, cannot be used to distinguish between the two interpretations.* Accordingly, this experiment is not necessarily a test of physical time dilation because it can equally validly be interpreted as finding time dilation as a coordinate effect only. Indeed, Mansouri and Sexl 1977 states: "Thus the much debated question concerning the empirical equivalence of special relativity and an ether theory taking into account time dilatation and length contraction but maintaining absolute simultaneity can be answered affirmatively." In other words, Lorentz's ether-based approach and Einstein's approach are, according to Mansouri and Sexl, empirically equivalent – in terms of measuring the relativistic effects of time dilation and length contraction. And experiments that use the RMS test theory to evaluate results aren't able to distinguish between these two approaches.

A little more explanation may be helpful in terms of why the Reinhardt et al. experiment, and related Ives-Still experiments that use the RMS test theory, are not able to distinguish between these different interpretations. Reinhardt et al. 2007 assumes the lab as the rest frame for comparison against the expected SR results. If, however, relativistic effects were in fact due to interactions with the ether/field rest frame (as Lorentz supposed) the RMS test theory cannot make this distinction. The physical core of the Lorentz interpretation is that length contraction results from interaction with the ether as physical objects move through the ether. But time dilation was, for Lorentz, a mathematical artifact (coordinate effect only) – a result of mathematically reconciling Maxwell's equations with dynamics – and not a real physical effect. The lab rest frame is obviously not the same as the actual ether frame, the underlying fabric/field of space, so we would not under Lorentz's approach expect to find any physical length contraction or other dynamical interactions with the ether when using the lab rest frame.

Mansouri and Sexl 1977 define the "ether system" as follows: "This ether system is defined by the requirements that the Einstein [synchronization technique] and the transport synchronization of clocks agree and that, furthermore, light propagation is isotropic in the ether system." Einstein synchronization and slow clock transport synchronization procedures would agree in Lorentz's ether frame but wouldn't agree in the lab frame posited as rest frame because this is not Lorentz's ether/field frame. Accordingly, the RMS test theory approach that substitutes the moving lab inertial frame as the rest frame (Σ) cannot distinguish between Lorentz and Einstein's interpretations of the Lorentz transformations.

Looking at our third paper, both Reinhardt et al. 2007 and Botermann et al. 2014 (a follow up to the 2007 paper that finds slightly more accurate results) cite Wolf and Petit 1997 as one of the previous best tests of time dilation and as an example of "non-storage-ring experiments" (p. 864): "The new upper limit of $|\hat{\alpha}|$[?] 8.4 x 10^{-8} is more than an order of magnitude smaller than that obtained from non-storage-ring experiments." Reinhardt et al. 2007 also states, again citing Wolf and Petit 1997: "We also provide the only test of time dilation more sensitive than that derived from the global positioning system." Accordingly, let's examine this third paper purporting to test relativistic effects.

Wolf and Petit 1997, looking at possible deviations from the constant speed of light between ground-based maser clocks and moving GPS satellite-based atomic clocks, found no deviation from the isotropic speed of light at the unprecedented (in 1997) accuracy of 5 X 10^{-9}, accounting for systematic errors, and at 2 X 10^{-8} without accounting for such errors.

The authors warn of the risk of presupposing the validity of SR in testing the assumptions and predictions of relativity, and they make a number of methodological adjustments to avoid doing so:

> Additionally one has to ensure that corrections applied to the raw timing data used for orbit determination and the measurement of T do not presuppose the validity of special relativity. In fact, two corrections are routinely applied to GPS timing data, which are of relativistic origin and therefore do imply $\delta c = 0$: the correction for the gravitational redshift and the second-order Doppler shift of the rate of the satellite clock with respect to coordinate time, and the correction for the so-called Sagnac effect, which is due to the rotation of the Earth during signal transmission.

Nevertheless, they fall into the trap of tautologically presupposing the validity of SR by their use of slow clock synchronization and Einstein clock synchronization as an ongoing re-synchronization technique to maintain synchronization during the operation of the GPS system (indirectly in both cases, since they simply used available data from the GPS system rather than conducting their own experiment). This is a fatal flaw. Results that are tautologically determined are by definition unscientific and invalid.

The paper states: "δc is the deviation from c of the observed velocity of a light signal traveling one way along a particular spatial direction with the measuring clocks synchronized using slow clock transport." Slow clock transport is by definition equivalent to Einstein synchronization in the same inertial frame. And under Einstein synchronization the constant speed of light, regardless of the motion of the observer, is assumed. This is an operational assumption made in order to provide a simple and reliable way to synchronize distant clocks. It is important to note also that ongoing re-synchronization cannot, of course, be done using slow clock transport; Einstein synchronization (using light signals) must be used. Einstein states in his well-known book on SR and GR (p. 27 of the 1952 edition, emphasis in the original):

> There is only one demand to be made of the definition of simultaneity, namely, that in every real case it must supply us with an empirical decision as to whether or not the conception that has to be defined is fulfilled. That my definition satisfies this demand is indisputable. That light requires the same time to traverse [a given path] is in reality neither a supposition nor a hypothesis about the physical nature of light, but a stipulation which I can make of my own free will in order to arrive at a definition of simultaneity.

This technique does provide a concrete method for defining simultaneity and thus for synchronizing distant clocks, but we must be careful to not use this technique and then forget that we have from the outset assumed an isotropic c in order to achieve synchronization. Unfortunately, Wolf & Petit overlooked this issue in their methodology.

The 1997 paper is often cited (over 100 citations) as strong support for relativistic effects. While finding the methodological tautology in this paper is not readily apparent to the casual reader, it is surprising that no other physicists or philosophers have noticed this fatal flaw in this well-known paper.

In sum, based on this admittedly non-comprehensive review of key time dilation papers, the evidence for physical time dilation doesn't seem to be very strong. This conclusion weighs further in favor of the Lorentzian ether-based interpretation of the Lorentz transformations and the view that apparent time dilation effects are better interpreted as coordinate effects only rather than physical time dilation.