The Lorentz transformation in a fishbowl: a comment on Cheng and Read's "Why not a sound postulate?"

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Abstract

In support of their contention that it is the absence of a subsisting medium that imbues the speed of light with fundamentality, Bryan Cheng and James Read discuss certain "fishbowl universes" in which physical influences evolve, not at the speed of light, but that of sound. The Lorentz transformation simulated in these sonic universes, which the authors cite from the literature of analogue gravity, is not that of Einstein, for whom an aether was "superfluous", but that of the earlier relativity of Lorentz and Poincaré, which did suppose such a medium. The authors' intention is not to argue analogically, but simply to contrast the situation of light with that of sound. However, I argue that these universes are too successful as analogues to support the authors' case. By reducing Lorentzian relativity to its bare essentials, they provide a compelling demonstration of the viability and explanatory strengths of the earlier theory. They show how a thoroughly wave-theoretic treatment of the Lorentz transformation would explain why all aspects of matter transform in like manner, thereby avoiding a difficulty that was a significant reason for the demise of Lorentzian relativity after 1905. Importantly, these sonic universes also suggest a unifying explanation, not only of the Lorentz transformation and de Broglie wave, but of the principle of relativity, which was merely postulated, rather than explained, by Einstein in 1905.

Keywords analogue gravity · Occam's razor · Lorentz transformation · Lorentzian relativity · de Broglie wave · principle of relativity

Introduction

In their intriguingly entitled paper, "Why Not a Sound Postulate?" [1], Bryan Cheng and James Read argue that it is the self-subsistence of electromagnetic waves that imbues the speed of light with "fundamentality". They explain:

> [B]y the 'fundamentality' of a theory of waves, we mean this: the theory describes waves which are understood to be self-subsistent,

> rather than to be oscillations in some medium. In this sense, sound waves are not fundamental, as they can be understood as higher-level descriptions of oscillations in some antecedently-given ontology - viz., the air. By contrast, electromagnetic waves are fundamental, for they are not to be understood as higher-level descriptions of oscillations in some antecedently-given ontology .... [O]ne understands that the electromagnetic field just is the wave: unlike air in the case of sound, the electromagnetic field here is not ontologically prior to the wave.

But the speed of light has a fundamental significance that seems far more interesting than any lack of a supporting medium. The Lorentz transformation implies that the velocity c is not merely the limiting velocity for the transport of energy and information, but the underlying velocity of evolution of all physical influences, by which I mean any effect involved in the structure or interactions of an elementary particle.

Nor should it be it necessary to stray too far from orthodoxy to question the authors' assertion that there is no supporting medium. Einstein vacillated on this issue (see generally Kostro [2]), and it was when he was declaring the aether "superfluous" that he was also finding it necessary to postulate rather than explain the principle of relativity [3]. And of course the "vacuum", so called, is no longer the featureless nothingness once supposed.

I will elaborate upon these issues below. However, my primary objective in this "comment" is to follow the authors into the curiously unorthodox "fishbowl universes"[1] that they have cited from the literature of analogue gravity, where my intention will be to demonstrate the inability of the current orthodoxy to explain the physical basis of the Lorentz transformation.

In these sonic universes, there is by construction only one fundamental velocity, and in the rudimentary wave structures described in these models, it will be possible to discern, not only the physical origin of the Lorentz transformation, but also that of the mysterious de Broglie wave, and of the principle of relativity itself.

But as the originators of these ingenious models inform us[2], the Lorentz transformation being simulated is not that of the special relativity of Einstein, for whom the luminiferous aether was "superfluous", but that of that earlier theory, associated primarily with Lorentz and Poincaré, that is generally thought to have favoured the existence of a light-supporting medium and privileged frame of reference.

[1] For the expression "fishbowl universe", see Barceló and Jannes [4].

[2] Whilst carefully denying that they are actually advocating an aether model, see Todd and Menicucci [5], at p. 1271, and.Barceló and Jannes [4], Sect. 4, who state that whereas everything arises from the medium in their model, " the luminiferous ether supposedly only affected electromagnetic phenomena". Yet Poincaré, at least, had seen that all fundamental forces must evolve at the velocity c, referring specifically to gravity, which was the only other fundamental force then known, see Poincaré [6] [7].

It is clearly not the intention of Cheng and Read to argue analogically for the revival of that Lorentzian relativity and its luminiferous aether. They have invoked these sonic models in a cause rather different from the usual concern of analogue gravity, which is to assess the plausibility of some theoretically predicted, but empirically inaccessible, phenomenon by investigating an analogue in which the corresponding feature *is* accessible. For instance, a notable interest of analogue gravity is Hawking radiation, which was predicted theoretically and would have significant consequences for the thermodynamics of black holes, but is thought to be too weak for detection by methods currently available.

In discussing these fishbowl universes, the authors' intention is merely to contrast the situation of electromagnetic waves with that of sound waves. As the authors explain, both waveforms satisfy a wave equation, but in the universe that we inhabit (the actual universe), it is only the electromagnetic wave that satisfies the requirements of Poincaré invariance, that is to say, the invariance of the velocity in question under spatial rotations and Lorentz transformations. In the case of sound, the symmetries of the Poincaré group are broken: the velocity of sound relative to an observer is not invariant, but varies with the velocity of that observer with respect to the medium.

The authors consider universes (see their footnote 16) in which the materials from which clocks and other measuring devices are constructed are "governed by sonic Poincaré invariant laws". They refer in particular to models of Barceló and Jannes [4] and Todd and Menicucci [5], "situated in the broader context of 'analogue gravity' - the investigation of relativistic physics by way of surrogate physical systems"[3].

In these sonic analogues, there is necessarily a sound-carrying medium and, for sound waves, a privileged frame of reference. Cheng and Read dismiss at the outset the possibility that electromagnetic waves might also require a supporting medium. Citing Occam's razor, they assert that "there was for Einstein, and indeed still is, neither theoretical reason nor experimental evidence for implementing an ether in electromagnetism".

But when William of Occam asserted that "it is vain to do with more what can be done with less"[4], he was assuming a "less" and a "more" of otherwise equal plausibility. From a consideration of these simple fishbowl universes, in which the workings of covariance have been laid bare in a manner that leaves little room for disanalogy, I will argue *firstly* that it is in fact the theory of Lorentz and Poincaré that is the ontologically less extravagant, and *secondly,* that the explanatory advantages of the earlier theory are in any case of far greater import than any consideration of simplicity or parsimony.

[3] For comprehensive introductions to analogue gravity, the authors refer to Barceló et al [8] and Volovik [9] , and for philosophical discussions, Crowther et al [10] and Dardashti et al [11].

[4] As quoted by J. McFadden in his recenly published book on Occam's razor *[12], at p.51*

The fishbowl universes

Consider a closed laboratory in which the velocity c_s of sound is measured by devices formed from material in which all physical influences evolve at the same velocity as sound. Barceló and Jannes [4] describe a Michelson-Morley interferometer in which the arms comprise arrays of equally spaced quasiparticles, which in a collective oscillation produce disturbances that evolve at the velocity c_s in all directions. They show that if this quasi-interferometer moves at a velocity $v < c_s$ with respect to the laboratory, it must experience a Fitzgerald-Lorentz contraction with a Lorentz factor,

$$\gamma = (1 - \frac{v^2}{c_s^2})^{-\frac{1}{2}}, \tag{1}$$

based on the velocity c_s rather than that of light.

Todd and Menicucci [5] show in their model how *all* the curious changes predicted by the Lorentz transformation - not only the contraction, but also the dilation of time and the failure of simultaneity - might be replicated by a chain of sound clocks, these being akin to light clocks except that the return journey between opposed mirrors is made by sound waves rather than electromagnetic waves.

As an internal observer - an observer within the fishbowl - moves through the enclosed medium at some velocity $v < c_s$, sonic signals from behind will reach the observer at the relative velocity $c_s - v$, and those from ahead with the relative velocity $c_s + v$. If this observer were capable of distinguishing these velocities, Poincaré invariance would be lost. But since everything else within this universe is similarly constituted from underlying wave-like effects of velocity c_s, the internal observer and any measuring device moving with that observer will suffer in like manner the changes described by the sonic Lorentz transformation, and in consequence, neither observer nor measuring device will be able to detect the difference in velocity.

On the other hand, an observer who is looking in from outside the fishbowl *will* perceive this difference and will recognize that the sound-carrying medium constitutes a privileged frame of reference for what is occurring within the fishbowl. That this medium is effectively non-existent for the internal observer is thus a kind of illusion induced by Poincaré invariance.

The perfection of this illusion places stringent demands on velocities. The velocity of the signal must be non-relativistic. If that were not so, effects related to the velocity c of light would become apparent, for instance the dependence of relative velocities on Einstein's law for the composition of velocities. For the Lorentz transformation to be simulated, the velocity of any object moving through the medium must of course be less than that of the signal. And the underlying influences from which measuring devices and observers are constituted must all have the velocity c_s of the sonic signal being measured.

I would suggest, with respect, that these models provide no support for the authors' position regarding the fundamentality of c. What they demonstrate is not that light is unique in not requiring a subsisting medium, but that if such a medium does exist, the covariance of the Lorentz transformation will have rendered it undetectable. That covariance has this effect is well-recognized, and it was largely with this result in mind that the Lorentz transformation was conceived (see, for instance Poincaré [13]). However, the manner in which Lorentzian relativity renders the medium undetectable is demonstrated in a particularly transparent manner when we are encouraged to imagine the workings of covariance from the perspective of an external observer [5].

But these sonic analogues take the argument for Lorentzian relativity a good deal further than that. For one thing, they suggest the solution to a difficulty with the theory that seemed intractable in the physics of 1905. By the end of the nineteenth century, it had been realized (notably by Lorentz himself [15]) that if matter transforms in accordance with the Lorentz transformation, this would explain the observed invariance of the speed of light. It had also been understood by then that these same changes would ensure that the laws of physics are the same in all inertial frames in accordance with the principle of relativity, which had been enunciated by Poincaré as an empirical but unexplained fact (Poincaré [13]). But it was not apparent why matter should change in exactly that fortuitous manner, or indeed that it did so.

What seemed to be required was some all-encompassing principle that would explain the universal effect of the Lorentz transformation, irrespective of how matter might ultimately be found to be constituted. As Einstein recalled in his *Autobiographical notes* [16]:

> I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results.

Einstein located his "universal formal principle" in the postulatory basis of his special relativity, and subsequently, following Minkowski [17], in the notion of a transformation in a four-dimensional spacetime (of which more will be said below). But what these sonic models suggest is that a "constructive" approach, of the kind that Einstein despaired of finding in 1905, might be based on what might be termed a "principle of construction", namely that everything will necessarily transform in like manner if everything is formed in like manner from underlying influences of the same fundamental velocity.

[5] It is not suggested by the authors of these analogue papers that we actually inhabit a fishbowl universe. And yet it is commonly supposed that our own "big bang" universe is finite and thus in some way bounded, which would suggest the likelihood of boundary conditions consistent in turn with a privileged frame of reference. The possibility of such boundary conditions is discussed indeed by Cheng and Read (referring in particular to Wallace [14]) in the interesting and wide-ranging analysis with which they conclude their paper.

These fishbowl universes may themselves seem hopelessly unlikely, but in the universe that we actually inhabit, it must likewise be assumed, both in special relativity and in Lorentzian relativity, that there is only the one fundamental velocity, that of light. If there were other such velocities, each would have its own Lorentz transformation and Lorentz factor γ, and the laws of physics could not then be the same from one inertial frame to the next (Shanahan [18]).

There are of course velocities that differ from c, those for example of massive objects, sound waves, and refracted light. But in each case, the velocity in question must be considered the net effect of underlying influences that *do* evolve at velocity c. Unlike c, such a velocity does not remain unchanged on a change of inertial frame, but as Einstein explained in 1905 [3], transforms in accordance with the relativistic formula for the composition of velocities.

In the parlance of fundamentality (see Tahko [19]), these other velocities are not fundamental, but existentially and compositionally dependent on the velocity c.

Occam's razor

Lorentz and Poincaré supposed a subsisting medium and privileged frame of reference, whereas according to Einstein in 1905 [3]:

> The introduction of a 'luminiferous ether' will prove to be superfluous inasmuch as the view here to be developed will not require an 'absolutely stationary space' provided with special properties.

But, although the two theories may be empirically indistinguishable, they differ significantly, not only in what they suggest regarding the structure of space and time (a point recently stressed by Knox [20]), but also, as I will argue below, in their ability to explain the Lorentz transformation, the de Broglie wave, and the principle of relativity.

As the fishbowl models demonstrate, Lorentzian relativity provides a mechanism for the Lorentz transformation and, as I will show in the next two sections, physically reasonable explanations for both the de Broglie wave and the principle of relativity. In comparison, special relativity explains neither the Lorentz transformation, nor the principle of relativity, while in the context of special relativity, the de Broglie wave is ontologically mysterious.

This is not to diminish in the slightest degree the contributions of Einstein and Minkowski. But in 1905 Einstein neither explained, nor purported to explain, why light has the same velocity for all inertial observers or why the laws of physics are the same in all inertial frames. Showing an impressive confidence in the elegance of physical law, he simply adopted as postulates, both the principle of relativity and the constancy of the speed of light, and proceeded to demonstrate how these assumptions lead via the Lorentz transformation to a self consistent treatment of the electrodynamics of moving bodies [3].

In effect, Einstein recognized in the principle of relativity, a fundamental symmetry of Nature (see for instance Martin [21]) and in so doing, was able to side-step the difficulties that had confounded Lorentz in explaining why all material objects should transform in like manner. But Einstein explained neither the apparent constancy of the speed of light, nor the physical basis of the principle of relativity, and nor therefore did he explain the origin of the Lorentz transformation.

Pursuing some earlier insights of Poincaré (Poincaré [6] [7]), Minkowski showed in 1908 how the Lorentz transformation could be treated as a rotation in a four-dimensional manifold [17]. It is Minkowski who must be thanked for worldlines and light cones and the convenient and intuitive picture provided by his spacetime diagrams.

It might also be thought that Minkowski had at last provided a satisfactory explanation of why every aspect of matter changes in like manner from one inertial frame to the next: the transformation of spacetime would carry with it everything within that spacetime. But what Minkowski actually described in 1908 was the freedom to undertake a "projection in space and time" from what he referred to as the "absolute world" (Minkowski [17], Sect. II). In considering what such a projection might entail, it is important to distinguish what actually changes from what is merely observed to change.

Consider a space traveller - let us call her Sally - who is moving through the galaxy at some relativistic speed. To Sally the stars have become ellipsoidal in form and are closing ranks along her path. But Sally will know that she and her spacecraft cannot have caused an actual physical contraction of the Universe. She will be aware that this contraction is an illusion induced by her state of motion.

Sally will also understand the source of the illusion. She will know that a change in coordinates may occur either in an active sense (where the object is rotated) or in a passive sense (where it is the coordinate system that is transformed). Sally will realize that since the galaxy remains as it was, it must be she who has changed. And since it is Sally who has changed, any additional change in the space and time that she occupies would be redundant.

One might wish to argue at this point that it is a change in space and time that brings about the change in Sally. But there are several difficulties with that view. One is that the more direct and ontologically less extravagant way to effect a change in an object is to simply have it change rather than to invoke a change in space and time to explain that change.

Another is the elusive nature of this supposed change in space and time. How are we to contemplate a spacetime that is able to contract in one way for one object and in a different way for another that is moving through the same space but in a different direction? In fact, as Sally realized above, the observed change in space is an illusion induced by a change in perspective. Thus what must be explained is the source of an illusion? In the context of special relativity, none of this is explained at all, let alone satisfactorily.

A third problem, mentioned briefly already above, is that any actual, as distinct from merely perceived, change in space and time would be redundant. From the standpoint of an observer in the inertial frame of the Earth, Sally's accelerated velocity has induced in her, the changes described by the Lorentz transformation. Sally has herself realized that it is she who has changed in this way and not the universe around her. But these changes are exactly of the form and degree necessary to induce in Sally the illusion that it is not she who has changed but the surrounding universe. Any additional change in Sally's space and time would thus be redundant, not simply in the sense of being unnecessary, but as constituting a duplication, a doubling, of the effects on Sally of the Lorentz transformation.

As the sonic models have shown, Lorentzian relativity does not share those problems. If matter comprises wave-like influences having the same fundamental velocity with respect to some privileged frame of reference, an object (such as Sally) that changes velocity with respect to that frame must necessarily experience the changes in length, time and simultaneity described by the Lorentz transformation. Moreover, if it is the moving object that changes and not the space and time occupied by that object, there is no longer the necessity of explaining a spacetime that contracts in one direction for one object and in a different direction for another moving relatively to the first.

What these sonic models do not explain is the emergence of the de Broglie wave, and I suggest that it is this wave that clinches the argument for Lorentzian relativity. The de Broglie wave is evidence, not only of the wave structure of matter, but of how this wave structure adapts to a change of inertial frame.

The de Broglie wave

In the absence of a generally accepted understanding of what this wave is and of how it comes into existence, it may not seem surprising that the de Broglie wave has no analogue in the fishpond universes discussed above, or indeed, it would seem, in any other model discussed in the literature of analogue gravity[6].

Yet this is a serious deficiency when one of the concerns of analogue gravity is the possibility of a theory of quantum gravity. If matter did not possess the wave characteristics described by the de Broglie wave, there could not be a quantum mechanics for massive particles, not at least a quantum mechanics in its current form.

To be plausible, a model of a massive particle should not only reproduce the de Broglie wave, but provide an explanation in doing so of the Planck-Einstein relation,

$$E = \hbar\omega_E = \hbar\gamma\omega_o, \tag{2}$$

[6] For instance, the otherwise. comprehensive "living review" by Barceló et al [8] makes no reference at all to the de Broglie wave.

and the de Broglie relation,

$$p = \hbar\kappa_{dB} = \hbar\gamma\,\omega_o \frac{v}{c^2}, \tag{3}$$

which relate the energy E and momentum p, respectively, of the moving particle to the frequency ω_E and wave number κ_{dB} of its associated de Broglie wave, and which in so doing provide the basis for the Schrödinger and other equations of quantum mechanics for massive particles (where $\hbar$ is the reduced Planck's constant, ω_o is the natural or characteristic frequency of the particle at rest, v is the velocity of the particle, and c is that of light).

A massive particle acts in many ways as if it actually is this curious wave of frequency ω_E and wave number κ_{dB}. The optical path defined by the de Broglie wave has consequences for quantization, its evolving phase is related precisely to the dilation of time and failure of simultaneity predicted by the Lorentz transformation, and its wave vector $\boldsymbol{\kappa}_{dB}$ seems to "pilot" the particle through interference, diffraction and refraction.

It may thus be instructive to consider how and where the de Broglie wave has gone missing from the fishbowl universes discussed above. I will first show that a wave factor with the characteristics of the de Broglie wave is necessarily induced whenever a moving particle or its fields are represented, as they have been in these models, by counter-propagating waves having the same velocity in the rest frame of the particle.

Consider, as in the sonic model of Barceló and Jannes [4], a quasi-particle comprising the superposition of incoming and outgoing rays, which we will assume to have the velocity c (of light), frequency ω_o, and wave number κ_o, that is,

$$\psi\,(\mathbf{r}, t) = \sin\kappa_o r\cos\omega_0 t \tag{4}$$

which has the idealized[7] form of a spherical standing wave centred at $\mathbf{r} = 0$.

Following a boost in the x-direction, and switching now from polar to Cartesian coordinates, spherical wave (4) becomes the travelling wave,

$$\Psi\,(x, y, z, t) = \sin\kappa_o\sqrt{\gamma^2(x - vt)^2 + y^2 + z^2}\;\cos[\omega_0\gamma(t - vx/c^2), \tag{5}$$

of which the first factor,

$$\sin\kappa_o\sqrt{\gamma^2(x - vt)^2 + y^2 + z^2}, \tag{6}$$

is a carrier wave, evolving in the x-direction at the velocity v and having the contracted ellipsoidal form predicted by the Lorentz-Fitzgerald contraction, while

[7]While this simple structure is obviously unphysical, it can be shown that all standing waves, of whatever form, give rise to a de Broglie wave under the Lorentz transformation, see Shanahan [22]

the second factor becomes, with the assistance of Eqn. (2),

$$\cos(\omega_E t - \kappa_{dB} x), \tag{7}$$

which is a sinusoidal modulation (or dephasing) advancing through the carrier wave (6) at the superluminal velocity c^2/v of the de Broglie wave. This wave factor also has the frequency and wave number of the de Broglie wave and will be taken here to be that wave.

Unlike the de Broglie wave considered alone, the full modulated wave (5) is a manifestly covariant relativistic object, capable in principle of taking its place in the tensor equations of relativistic physics. The Lorentz-Fitzgerald contraction appears in the carrier wave (6), while the dilation of time and failure of simultaneity are described by the modulation (7). The effect of the modulation is that the parts of the moving wave are no longer cresting in unison, but in sequence, those ahead lagging in phase those behind. The modulation thus describes a progressive loss of phase in the direction of travel corresponding exactly in effect to the failure of simultaneity in that direction predicted by the Lorentz transformation.

This modulation should thus have had an analogue in these sonic universes. In both the models discussed above, the predictions of the Lorentz transformation (though in the interferometer of Barceló and Jannes [4], only the predicted contraction), were deduced from changes in what were in effect counter-propagating waves of velocity c_s. In the interferometer of Barceló and Jannes, these were wave-like disturbances propagating from each quasiparticle in an array of such quasiparticles. In the chain of sound clocks described by Todd and Menicucci [5], the counter-propagating waves comprised sequences of sound pulses making return trips between opposed reflectors. These structures were thus capable in principle of replicating the de Broglie wave as a modulation, as might have become apparent had the derivations proceeded in terms of the changing frequencies and wave numbers of those counter-propagating waves.

But the derivations found in those papers are effectively pre-quantum. They proceed very much as Einstein did in 1905 from a consideration of rigid measuring rods and arrays of clocks. Todd and Menicucci [5] tell us that their sound clocks are separated by "spacing arms", while Barceló and Jannes [4], at 194, employ "emergent vector fields and sources to produce a rigid bar". In each case, the comparison undertaken is not between the differing characteristics of waves propagating longitudinally and transversely with respect to the direction of motion, but between the differing times taken for return trips in those directions.

In 1905, Einstein had no knowledge of the de Broglie wave. But in these fishbowl universes, the existence and nature of this superluminal effect will be readily apparent to an external observer, who will understand that the standing wave from which a quasi-particle is formed must necessarily become a modulated travelling wave as the particle moves through the medium.

The principle of relativity

The changes of length, time and simultaneity described by the Lorentz transformation are precisely of the form and degree necessary to ensure that the laws of physics are the same in all inertial frames of reference. This is so in both special relativity and Lorentzian relativity, but in special relativity, it is not apparent why space and time should change in precisely this way. In the context of special relativity, the Lorentz transformation seems a fortuitous but inexplicable property of the given universe.

But if it is not space and time that are transformed, but what is occupying space and time, the question that must instead be asked is why *matter* should change in exactly the required way, and this is a question that does suggest an answer.

If we assume, as in the sonic models, that a massive particle is in some sense a standing wave, there must be an inertial frame in which it is not only observed to be a standing wave, but in fact *is* that standing wave. In other words, there must be some inertial frame, in which the velocity of light is not only observed to have the velocity c, but (as with the velocity c_s in the sonic relativity of the fishbowl) does in fact have this velocity. In any other inertial frame, the covariance of the transformation will ensure that to an observer within that frame, the modulation goes unnoticed and light presents nonetheless with the velocity c.

But if a massive particle is a standing wave in only that one privileged frame, we need to consider why it should adopt the distorted and modulated form described by the Lorentz transformation in every other frame?

Part of the answer comes from trigonometry. If waves that have a velocity that is invariant with respect to some inertial frame converge on, or diverge from, a point that is stationary in that frame, the orientation of those waves must experience the effects of aberration if they are to continue to be convergent on, or divergent from, that same point as it moves. And if those converging and diverging waves are to combine with a particular phase, for instance to form a node at that central point, they must experience, not only the changes in orientation due to aberration, but the changes in frequency and wave number described by the Doppler effect. The result of these changes is that the standing wave changes so as to form the modulated travelling wave described by Eqn. (5).

But why, when the standing wave is subjected to an impressed force, does it not simply fall apart? Of course, when a particle is subjected to sufficient force it does fall apart. It disintegrates. And while the standard model with its many free parameters does not entirely explain what is holding a particle together, it can be understood that a particle owe its persistence of form to a binding energy that may involve a complex interplay of internal effects - forces, constraints, symmetries, topologies - some perhaps as yet unknown - and even where known, imperfectly understood.

Except in the privileged frame, the wave structure of the particle will experience the distortions described by the Lorentz transformation. But the covariance that accompanies those distortions will ensure that the equations governing the evolution and interactions of the particle remain form-invariant. The particle's interactions will thus depend, not on the particle's velocity and disposition with respect to the privileged frame, but on its velocities and dispositions relative to everything that surrounds the particle, as also to those between the constituent parts of the particle itself.

According to this view, the laws of physics remain the same from one frame to the next, not because of a fortuitous change in space and time, but because the survival of a particle in its characteristic form demands that its structure change from one inertial frame to the next in the covariant manner described by the Lorentz transformation.

Could the same argument be put in the context of special relativity? The difficulty is that the arrow of explanation becomes reversed. In Lorentzian relativity, the argument is that the stability of matter requires that a particle rearrange itself between inertial frames in a manner that maintains the interrelationships that ensure its existence. While it is true that in special relativity the changes in space and time described by the Lorentz transformation do also ensure those interrelationships, it is not apparent why space and time should change in precisely that way.

The distinction can be expressed in terms of fundamentality: in the context of special relativity, the principle of relativity is a fundamental symmetry of Nature, but this is essentially because it is a symmetry of unexplained origin; in the wave-theoretic treatment of Lorentzian relativity described above, the principle of relativity is not strictly speaking fundamental at all, but emergent along with the Lorentz transformation and the de Broglie wave from the underlying wave structure of matter and radiation.

This leaves Einstein's other postulate, the light postulate, to be explained. However, in the context of Lorentzian relativity, this is not the puzzle that it is in a theory in which the relative velocity of light is the same for all observers. In Lorentzian relativity, it is only necessary to suppose the invariance of c with respect to a privileged frame of reference, its observed invariance in other frames being a consequence of covariance.

Concluding remarks

These unlikely fishbowl universes have an ontological simplicity that might well have appealed to the Friar of Occam. In the Lorentzian relativity simulated in these universes, all underlying forces and effects evolve at the same velocity, thus explaining in parsimonious manner, the origins of the de Broglie wave, the Lorentz transformation and the principle of relativity.

In the complexities of the actual universe, it may not be as readily apparent that there is only the one underlying velocity and that all other velocities are existentially dependent on that velocity. But the all-encompassing ambit of the Lorentz transformation implies that here also there is only one such velocity, the velocity c of light. I have argued in this paper that it is this, rather than the apparent absence of a subsisting medium, that imbues c with fundamentality.

As these sonic universes have illustrated, the detection of such a medium would be difficult to reconcile with the covariance maintained by the Lorentz transformation, as also with the principle of relativity, which relies on that covariance. It would thus seem prudent to regard the existence or otherwise of this medium as an open question.

And yet if the authors had been arguing analogically for the existence of a subsisting medium, a sonic universe might well have provided a plausible analogue. As explained above, the Lorentz transformation could be seen as a consequence of the way in which the wave structure of a massive particle must rearrange itself to move through the medium, the dephasing described by the de Broglie wave would emerge as evidence of that wave structure, and the workings of covariance could be imagined from a external perspective free of the illusions induced by that covariance.

References

[1] B. Cheng, J. Read, Why Not a Sound Postulate? Found. Phys. **51,** 71 (2021)

[2] L. Kostro, Einstein and the Ether, Apeiron, Montreal (2000)

[3] A. Einstein, Zur elektrodynamik bewegter korper, Ann. Phys. **17**, 891 (1905)

[4] C. Barceló, G. Jannes, A real Lorentz–Fitzgerald contraction, Found. Phys. **38**, 191 (2008)

[5] S. L. Todd, N.C. Menicucci, Sound clocks and sonic relativity, Found. Phys. **47**, 1267 (2017)

[6] H. Poincaré, Sur la dynamique de l'électron, Comp. Rend. **140**, 1504 (1905)

[7] H. Poincaré, Sur la dynamique de l'électron, Rendiconti del Circolo matematico di Palermo, **21**, 129 (1906)

[8] C. Barceló, S. Liberati, M. Visser, Analogue gravity, Living Rev. Relativ. 14 (2011)

[9] G. E. Volovik, The Universe in a Helium droplet, Oxford U. P., Oxford (2003)

[10] K. Crowther, N. Linneman, C. Wüthrich, What we cannot learn from analogue experiments, Synthese 198, Suppl. 16, 3701 (2021)

[11] R. Dardashti, K. P. Y. Thébault, E. Winsberg, Confirmation via analogue simulation: what dumb holes could tell us about gravity, Br. J. Philos. of Sci. 68, 55–89 (2017)

[12] J. McFadden, Life is Simple, Basic Books, London (2021)

[13] H. Poincaré, The present and future of mathematical physics, Bull. Sci. Math. **28**, 302 (2014)

[14] D. Wallace, Fundamental and emergent geometry in Newtonian physics, Br. J. Philos. Sci. **71**, 1 (2020)

[15] H. A. Lorentz, Electromagnetic phenomena in a system moving with any velocity smaller than that of light, Proc. Roy. Neth. Acad. **6**, 809 (1904)

[16] A. Einstein, Autobiographical notes, in P. A. Schilpp (ed.) *Albert Einstein: Philosopher-Scientist,* Harper, New York (1959)

[17] H. Minkowski, Raum und Zeit, Phys. Zeit. **10**, 104 (1909)

[18] D. Shanahan, A Case for Lorentzian Relativity, Found. Phys. **44**, 349 (2014)

[19] T. E. Tahko, Fundamentality, The Stanford Encyclopedia of Philosophy (Fall 2018 Ed.), E. N. Zalta (ed.)

[20] E. Knox, Physical relativity from a functionalist perspective, Studies in History and Philosophy of Modern Physics **67**, 118 (2018)

[21] C. A. Martin, On continuous symmetries and the foundations of modern physics, in K. Brading, E. Castellani (eds.), Symmetries in physics, Cambridge U. P., Cambridge U. K. (2003)

[22] D. Shanahan, What might the matter wave be telling us of the nature of matter? IJQF **5**, 165 (2019)