Dynamic Enforcement of Lorentz Invariance for Translating Wave Packets in a Linear Elastic Continuum

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Abstract

In a previous work, we demonstrated that gravitational lensing can be modeled as anisotropic refraction in a hyper-elastic continuum. A longstanding objection to medium-based models of the vacuum is the null result of interferometric experiments (e.g., Michelson–Morley), which are commonly interpreted as ruling out the existence of a preferred reference frame. We revisit this problem by modeling physical matter not as rigid bodies, but as self-stabilized standing-wave structures governed by the continuum's linear wave equation. We show that, for such structures to maintain phase coherence while translating uniformly through the medium, they must undergo dynamic length contraction and time dilation. The Lorentz transformations are derived analytically from the classical wave equation, demonstrating that Lorentz invariance emerges as a stability condition of the matter–medium coupling rather than as a fundamental postulate of an otherwise structureless background. Consequently, a linear elastic vacuum is observationally indistinguishable from relativistic spacetime in the weak-field, linear regime.

Keywords: Lorentz Invariance; Elastic Vacuum; Continuum Mechanics; Wave Mechanics; Analog Gravity

1 Introduction

In Ref. [?], it was shown that the phenomenological predictions of General Relativity concerning light deflection can be reproduced by modeling the vacuum as a hyper-elastic continuum.

In that framework, gravity arises from gradients in density and elastic moduli induced by stress. However, any attempt to attribute physical structure to the vacuum encounters the null results of ether-drift experiments, most notably Michelson–Morley [2], which are widely interpreted as excluding the existence of a detectable preferred frame. This interpretation relies on a tacit assumption: that measuring instruments (interferometer arms, clocks) behave as rigid bodies whose physical dimensions and internal rates are independent of their motion relative to any underlying medium. If, instead, matter itself is constituted by wave packets propagating within the same continuum, this assumption no longer holds. In this work, we show that Lorentz invariance need not be imposed as a fundamental symmetry of the background. Rather, it arises as a dynamically enforced equilibrium condition for wave-based matter. By modeling physical objects as soliton-like standing-wave structures, we derive the Lorentz contraction and time-dilation factors required to preserve phase coherence under uniform translation. This analysis complements numerical and lattice-based studies [3, 4] by providing a closed-form continuum derivation.

2 Physical Model: Matter as Standing-Wave Structures

We consider a homogeneous, isotropic linear elastic continuum. As established in Ref. [?], small-amplitude transverse excitations ψ obey the classical wave equation

$$\frac{\partial^2 \psi}{\partial t^2} = c^2 \nabla^2 \psi, \tag{1}$$

where $c = \sqrt{\mu/\rho}$ is the characteristic wave speed of the medium. A physical "object" (such as a ruler or an atom) is modeled as a bounded standing-wave structure formed by the superposition of counter-propagating modes. In the rest frame of the medium, a one-dimensional standing wave of length L_0 is described by right- and left-moving components with identical wavenumber k_0 and frequency $\omega_0 = ck_0$. The resulting spatial interference pattern is stationary, with nodes separated by π/k_0. No specific microscopic ontology is assumed; the analysis is purely kinematic and concerns the constraints imposed by phase coherence in a linear medium.

3 Length Contraction from Phase-Coherence Constraints

We now consider a standing-wave structure translating uniformly at velocity v along the x-axis relative to the medium. For the object to remain a stable, cohesive entity, the internal interference pattern defining its spatial extent must translate rigidly at the same velocity v. This requires asymmetric internal wavevectors. Let the forward-propagating component have wavenumber k_+ and the backward-propagating component have wavenumber k_-. The drift velocity of the interference envelope is

$$v_{\text{env}} = c\,\frac{k_+ - k_-}{k_+ + k_-}. \tag{2}$$

Requiring $v_{\text{env}} = v$ yields

$$\beta = \frac{v}{c} = \frac{k_+ - k_-}{k_+ + k_-} \quad \Rightarrow \quad \frac{k_+}{k_-} = \frac{1+\beta}{1-\beta}. \tag{3}$$

To fix the absolute scale of the internal modes, we impose invariance of the transverse oscillation frequency in the instantaneous rest frame of the wave packet. This requires the geometric mean of the Doppler-shifted wavenumbers to equal the rest-frame value,

$$\sqrt{k_+ k_-} = k_0. \tag{4}$$

The geometric mean uniquely preserves the dispersion relation $\omega^2 = c^2 k^2$ under reciprocal Doppler shifts, ensuring that the rest-frame mode energy remains unchanged. Solving these constraints gives

$$k_+ = k_0\gamma(1+\beta), \qquad k_- = k_0\gamma(1-\beta), \tag{5}$$

with $\gamma = (1-\beta^2)^{-1/2}$. The spatial envelope wavenumber is $K = (k_+ + k_-)/2 = k_0\gamma$. Since physical length scales inversely with wavenumber,

$$L = \frac{L_0}{\gamma} = L_0\sqrt{1 - \frac{v^2}{c^2}}. \tag{6}$$

Length contraction therefore emerges as a direct consequence of phase stability for a translating standing-wave structure.

4 Time Dilation from Phase-Rate Reduction

The time measured by a physical system is defined by the rate of its internal cycles. In the present model, this corresponds to the oscillation frequency of the standing wave evaluated in the comoving frame. In the laboratory frame, the forward and backward components have frequencies $\omega_\pm = ck_\pm$. An observer moving with the wave packet measures frequencies

$$\omega'_\pm = \omega_\pm \mp v k_\pm. \tag{7}$$

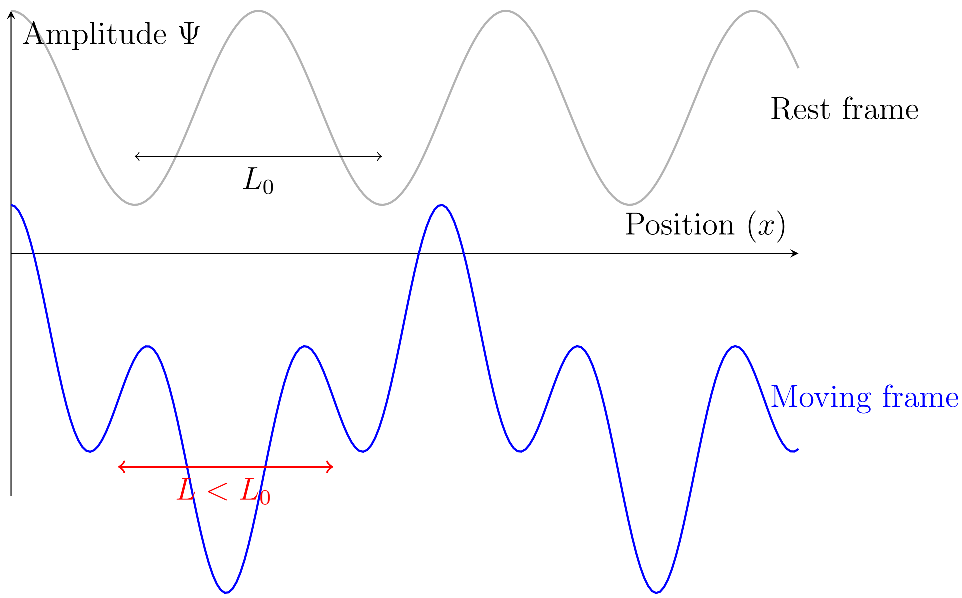

Figure 1: **Illustrative visualization of dynamic length contraction.** A stationary standing wave (top) compared with the interference pattern of a translating wave packet (bottom). The reduced node spacing in the moving case reflects the phase-coherence constraint derived analytically in the text.

For the forward component,

$$\omega'_{+} = ck_{+}(1-\beta) = \omega_0\gamma(1-\beta^2) = \frac{\omega_0}{\gamma}, \tag{8}$$

and similarly for the backward component. Both internal modes therefore oscillate at the reduced frequency ω_0/γ in the object's rest frame. The corresponding time interval satisfies

$$\Delta t = \gamma\Delta t_0, \tag{9}$$

demonstrating that any clock constructed from wave-interference processes undergoes time dilation under uniform translation.

5 The Interferometric Null Result

We now apply these results to a Michelson interferometer of rest arm length L_0 translating at velocity v.

1. **Parallel arm.** The physical arm contracts to $L_\parallel = L_0/\gamma$. The round-trip time is

$$T_\parallel = \frac{L_0/\gamma}{c-v} + \frac{L_0/\gamma}{c+v} = \frac{2L_0}{c}\gamma. \tag{10}$$

2. **Perpendicular arm.** The effective transverse propagation speed is $\sqrt{c^2 - v^2} = c/\gamma$, yielding

$$T_\perp = \frac{2L_0}{\sqrt{c^2 - v^2}} = \frac{2L_0}{c}\gamma. \tag{11}$$

The round-trip times are identical:

$$\Delta T = T_\parallel - T_\perp = 0. \tag{12}$$

An observer composed of wave-based matter therefore cannot detect uniform motion relative to the continuum using internal interferometric measurements.

6 Discussion

The preceding derivations show that the kinematics of Special Relativity arise naturally for wave-supported matter in the linear elastic regime. Lorentz transformations appear not as fundamental postulates, but as equilibrium conditions required for the stability of translating wave packets. This interpretation reconciles medium-based models of gravity with the empirical success of relativistic kinematics. If matter and radiation obey the same underlying wave equation, their dynamical scaling properties necessarily coincide. The equivalence holds strictly within the linear regime considered here. Nonlinear effects in the constitutive relations, corresponding to strong-field or high-energy phenomena, may provide observational distinctions between geometric and material interpretations.

7 Conclusion

We have shown that length contraction and time dilation arise as necessary phase-coherence conditions for standing-wave structures translating in a linear elastic continuum. By enforcing stability, the Lorentz transformations follow directly from the classical wave equation without being assumed as fundamental symmetries. This demonstrates that the hyper-elastic vacuum model remains fully consistent with the null results of interferometric experiments.

Declarations

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