

Fresnel’s Mechanical Legacy Recovered: How Bubble Acoustics Unifies Partial Drag, Velocity Addition, and Atomic Polarization

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Abstract

Sound waves in bubbly water and light in special relativity obey identical first-order transport laws. This equivalence is not approximate or analogical but mathematically identical to first order in U/v , sharing the same form discovered by Fresnel in 1818 for light in moving transparent media. We demonstrate that all three systems—bubble acoustics, optical drag, and relativistic velocity addition—are described by a universal partial entrainment equation where wave coupling to compliant components determines the drag coefficient.

In bubbly liquids this physics is directly observable: waves couple to compressible bubbles rather than rigid liquid. Since bubble dynamics reproduces the relativistic result, velocity addition itself admits mechanical interpretation. Von Laue’s 1907 derivation abstracted mechanics into kinematics; we reverse this, showing relativistic effects preserve mechanical content in abstract form.

Beyond first-order equivalence, we show Fresnel’s dispersive term encodes group velocity (energy transport) versus phase velocity (wave-crest motion)—a distinction mechanical models naturally capture but pure kinematic velocity addition cannot address. The rigidity-based interpretation of dispersion, established in acoustic metamaterials, provides cross-domain insights for materials design and suggests testable predictions linking acoustic compliance to optical drag.

This three-way equivalence reduces independent phenomena to a single principle: waves riding compliant inclusions. Fresnel drag, Lorentz contraction, and atomic polarization all emerge as aspects of this one mechanism, traced through the historical density-versus-rigidity fork that shaped aether theory’s trajectory. The compliant-inclusion principle shows striking quantitative agreement with isotope mass-dependence and resonance structure in existing spectroscopic data.

1 Introduction

Sound waves propagating through bubbly water are partially carried along with the bubble flow. The degree of entrainment depends on bubble compressibility: softer bubbles host more wave energy and convect it more strongly [1, 2].

The identical mathematics governs light in moving transparent media. Fresnel predicted this in 1818 [3], confirmed experimentally by Fizeau [4]. For a century, this partial drag remained puzzling until von Laue showed in 1907 that special relativity reproduces Fresnel’s formula through velocity addition [5].

Von Laue’s result was interpreted as eliminating the need for mechanical explanations—partial drag became “just kinematics.”

But if bubble acoustics and relativistic velocity addition share identical mathematics, and bubbles have transparent mechanics, then velocity addition itself has mechanical content. This paper explores the three-way equivalence explicitly and traces its physical origin to a universal principle: waves couple to the most compliant component of structured media. In bubbles this is obvious. In atoms it is polarizability. In relativity it is encoded in the factor $(1 - v^2/c^2)$.

While Special Relativity provides a complete kinematic description of this phenomenon, the identical mathematical structure found in a transparently mechanical system—bubble acoustics—invites a re-examination of the underlying physical content. Our approach does not challenge the kinematic correctness of relativity but explores whether a structured-medium model offers complementary mechanical insight.

Our approach follows the historical method outlined in the broader context of neoclassical interpretation [14]: we demonstrate mathematical equivalence between apparently disparate formulations, then trace the conceptual choices that led to their separation. By examining the historical junctures where mechanical and kinematic interpretations diverged—particularly Fresnel’s choice between density and rigidity models—we show how a single framework unifies phenomena previously requiring independent explanations.

A crucial distinction must be noted: the bubble and Fresnel models presuppose a physical medium (water, aether), while Special Relativity in its standard interpretation does not. Our goal is not to disprove the kinematic framework but to explore the viability of a structured-medium model as a complementary mechanical interpretation. The first-order equivalence we demonstrate is exact; whether this extends to higher orders or represents merely a suggestive formal parallel remains an open question that does not diminish the value of the mechanical insight at the regime where it applies.

This equivalence reduces three independent mechanisms to one: Fresnel’s partial drag, Lorentz-FitzGerald contraction, and atomic polarization all emerge from compliant structures deforming when moving through or responding to their sustaining medium. The reduction of independent phenomena enhances model economy while preserving all predictive success of current theory.

2 The Three-Way Equivalence

Three physical systems obey the same first-order transport law:

$$v_{\text{obs}}(\omega, \theta) = v(\omega) + f(\omega)U \cos \theta + O((U/v)^2), \quad (1)$$

where $v(\omega)$ is wave speed in the medium at rest, U is the drift velocity, θ is the propagation angle relative to drift, and $f(\omega)$ is the partial entrainment coefficient.

2.1 Bubble Acoustics

In liquids containing gas bubbles, sound couples preferentially to the compressible phase:

$$f_{\text{bub}}(\omega) = \beta(\omega) = \frac{\alpha/K_g(\omega)}{\alpha/K_g(\omega) + (1-\alpha)/K_\ell},$$

where α is gas volume fraction, $K_g(\omega)$ is frequency-dependent gas bulk modulus, and K_ℓ is liquid modulus [1, 15]. Near bubble resonance, K_g drops dramatically and $f_{\text{bub}} \rightarrow 1$ —the wave rides almost entirely on the bubbles.

2.2 Fresnel Drag (Optics)

Light in moving transparent media exhibits partial drag:

$$f_{\text{opt}}(\omega) = 1 - \frac{1}{n^2(\omega)} + \frac{\omega}{n(\omega)} \frac{dn}{d\omega},$$

where $n(\omega)$ is refractive index [6]. Fresnel derived this in 1818; Fizeau confirmed it experimentally in moving water [4].

2.3 Relativistic Velocity Addition

Special relativity’s composition law, expanded to first order in U/c :

$$f_{\text{SR}}(\omega) = 1 - \frac{v^2(\omega)}{c^2}.$$

Setting $v = c/n(\omega)$ recovers the non-dispersive part of Fresnel’s coefficient. Von Laue demonstrated this equivalence in 1907 [5].

The mathematical identity is exact at first order. All three systems obey Eq. (1) with different physical interpretations of $f(\omega)$.

2.4 Group Velocity and Energy Transport

The dispersive term $(\omega/n)(dn/d\omega)$ in Fresnel’s formula—absent from pure SR velocity addition—reveals additional mechanical content beyond first-order kinematics.

The full coefficient can be rewritten through group velocity:

$$f_{\text{opt}}(\omega) = \frac{n_g(\omega)}{n(\omega)} - \frac{1}{n^2(\omega)},$$

where $n_g \equiv n + \omega(dn/d\omega)$ is the group index governing energy transport velocity $v_g = c/n_g$, distinct from phase velocity $v_p = c/n$.

This distinction is fundamentally mechanical: group velocity determines where energy propagates—a physical, observable quantity distinct from kinematic phase tracking. Near resonances in bubbly liquids or atomic media, v_g can differ from v_p by factors of 2–3, with v_g even becoming negative (backward energy flow) or superluminal locally in regions of strong

anomalous dispersion; information speed remains $\leq c$ in causal media per Brillouin [9]. These are energy storage and release effects with no counterpart in pure velocity-addition kinematics, which tracks only phase velocity.

Pure SR velocity addition reproduces only the non-dispersive term $(1 - 1/n^2)$, corresponding to phase velocity. Mechanical models (bubbles, polarizable atoms) naturally generate both v_p and v_g through their resonant dynamics, capturing physics that kinematics alone cannot address.

Both acoustic and optical dispersion near resonances follow identical normalized form: $(1/X)(dX/d\omega) \propto (-2\delta)/(w^2 + \delta^2)$ where X represents either $K_g(\omega)$ or $n(\omega)$, δ is normalized detuning, and w is linewidth. This Lorentzian derivative structure appears in bubble resonances (kHz) and atomic transitions (10^{15} Hz)—eleven orders of magnitude apart. The mathematical identity across scales suggests dispersion, whether acoustic or optical, arises from compliant resonators responding to wave fields.

3 The Physical Principle: Waves Ride the Soft Component

Why do these three systems share identical mathematics? The answer is kinematic: *wave energy couples to the most compliant part of the medium*—the component with lowest elastic modulus (rigidity) relative to its surroundings.

In bubbles, this is directly observable. Acoustic pressure oscillates bubbles (compressible) far more readily than liquid (incompressible). Wave energy resides predominantly in bubble oscillations. When bubbles drift with velocity U , the wave convects partially with them, with entrainment fraction f_{bub} determined by relative compressibility.

In atoms, optical fields shake electron clouds (polarizable) while nuclei remain essentially rigid. The electron cloud plays the role of the bubble—the soft, responsive component. Cloud size and compliance determine both refractive index $n(\omega)$ and drag coefficient $f_{\text{opt}}(\omega)$.

For atoms, the resonance frequency scales with electron cloud radius a :

$$\omega_0 \sim \sqrt{\frac{e^2}{4\pi\epsilon_0 m a^3}}, \quad \lambda_0 \propto a^{3/2} m^{1/2}.$$

Polarizability (cloud size) dominates; mass enters weakly.

In relativity, velocity addition encodes this principle abstractly. The factor $(1 - v^2/c^2)$ in f_{SR} determines entrainment strength, with $v(\omega)$ playing the role of "effective compliance"—slower wave speed means greater entrainment.

Bubble dynamics operates at the scale of gas-liquid systems, far above vacuum substrate dynamics—just as planetary motion operates above atomic structure without invoking quantum mechanics at each instant. But the principle is scale-independent: waves always couple to compliant inclusions.

4 Extension: Polarization as Mechanical Deformation

The bubble-atom analogy extends beyond wave propagation—it reveals the mechanical basis of atomic polarization itself.

Bubbles respond to acoustic fields in two modes. When wavelength is comparable to bubble size, uniform pressure drives *monopole (breathing) oscillations*: the bubble expands and contracts radially, determining sound speed and refraction. But when wavelength greatly exceeds bubble size ($\lambda \gg R_0$), the bubble experiences a *pressure gradient* rather than uniform pressure, and responds by translating bodily:

$$\mathbf{x}_{\text{bubble}} \propto -\nabla P.$$

This is *dipole oscillation*—the bubble and its flow field form an acoustic dipole with strength $\propto R_0^3$.

Atomic polarization follows identically. An atom in electric field $\mathbf{E}$ exhibits charge separation: the electron cloud (soft) shifts by $\boldsymbol{\delta}$ while the nucleus (rigid) remains fixed, creating dipole moment $\mathbf{p} = \alpha \mathbf{E}$ where polarizability $\alpha \sim 4\pi\epsilon_0 a^3$ scales with cloud volume.

The mapping is exact:

Bubble Dipole	Atomic Polarization
Pressure gradient ∇P	Electric field $\mathbf{E}$
Gas (soft)	Electron cloud (soft)
Liquid (rigid)	Nucleus (rigid)
Displacement $\mathbf{x} \propto R_0^3$	Polarizability $\alpha \propto a^3$

If atoms are treated as low-rigidity zones in a structured medium, polarization is simply mechanical deformation of compliant regions under applied fields—exactly as bubbles translate under pressure gradients.

Macroscopically, individual atomic polarizability α determines refractive index via Clausius-Mossotti:

$$\frac{n^2 - 1}{n^2 + 2} = \frac{N\alpha}{3\epsilon_0},$$

where N is atom number density [6]. Similarly, bubble compliance determines sound speed through effective bulk modulus. Both encode the same principle: wave speed measures aggregate compliance of soft inclusions.

Standard harmonic oscillator models predict refractive index scales as $m^{-1/2}$, giving $(n_{\text{D}} - 1)/(n_{\text{H}} - 1) = 0.948$ for $\text{H}_2\text{O} \rightarrow \text{D}_2\text{O}$ —a 5.2% isotope effect. Measured values show 1.4% effect, implying effective exponent $\alpha \approx 0.13$ rather than 0.5. This four-fold reduction appears systematically across isotope pairs (H_2/D_2 shows $\alpha \approx 0.04$). If refractive properties arise from substrate compliance rather than particle inertia, weak mass dependence follows naturally—exactly as bubble acoustic response depends primarily on gas compressibility, not density.

Refractive index = measure of polarizability = measure of compliance.

Noble gases with larger electron clouds have higher refractive indices not as arbitrary correlation but as direct consequence: larger compliant zones respond more strongly, exactly as larger bubbles dominate acoustic response.

The traditional mystery—why do charges separate under applied fields?—dissolves. Polarization is deformation. Compliant structures displace under gradients. Bubbles make this obvious; low-rigidity atomic models follow the same mechanics.

The frequency-dependent response producing dispersion—and thus group velocity distinct from phase velocity—follows naturally from resonant oscillators where $dn/d\omega \neq 0$. The rigidity-based interpretation connects to acoustic metamaterials where negative index arises from engineered density and modulus [8]: anomalous dispersion ($dn/d\omega < 0$) corresponds to medium stiffening ($dK_{\text{eff}}/d\omega > 0$), directly observable in bubbly liquids where $K_g(\omega)$ minimizes at resonance then rises. This cross-domain framework suggests engineering techniques for controlling dispersive response may transfer between acoustic and optical domains.

5 Fresnel’s Fork: Density versus Rigidity

Wave speed in an elastic medium is $v = \sqrt{\mu/\rho}$. Reducing wave speed can arise from increased density ($\rho \uparrow$) or decreased rigidity ($\mu \downarrow$). Mathematically equivalent; ontologically distinct.

In bubbles, both effects occur: gas has lower density *and* lower bulk modulus than liquid. But the dominant physics is compliance—bubbles are softer, not denser, which is why they oscillate so readily.

Fresnel chose the density interpretation for light: denser matter drags aether. Specifically, Fresnel proposed that only the *excess density* associated with transparent matter dragged the luminiferous medium, which led directly to his $(1 - 1/n^2)$ coefficient [3]. This nuance is illuminating: it was already a model of differential response—the part of the medium that differs from vacuum (the “inclusion”) does the dragging. This aligns naturally with our compliant-inclusions framework, where the low-rigidity zones (atoms) determine the optical effect. However, the density interpretation led to expectations of mechanical entrainment predicting detectable aether winds that Michelson-Morley did not find [11].

The rigidity alternative: atoms are regions of *reduced rigidity* within a continuous substrate. Light slows because the medium is locally softer, not denser. This naturally accommodates topological structures—vortex knots that maintain stability through circulation, like quantized vortices in superfluid helium-II [7].

When Kelvin introduced vortex atoms in 1867 [10], the framework existed to unify refraction and partial drag. But Fresnel’s density interpretation was entrenched, and this alternative path remained unexplored in mainstream development.

6 Vortices versus Bubbles: Directional Asymmetry

Bubbles and vortices differ crucially. **Bubbles move *with* the liquid**—they are mechanically entrained. Push the liquid and bubbles flow along. **Vortex structures have circulation patterns through which the medium flows.** A vortex ring translates while fluid streams through its core.

This distinction is invisible in the mathematics of Eq. (1) but critical mechanically.

If atoms mechanically drag substrate like bubbles drag liquid, Michelson-Morley should have seen strong signals. But if atoms are vortex structures, substrate flows *through* them largely unimpeded. The optical effect—partial drag coefficient f_{opt} —arises from wave propagation through reduced-rigidity zones, not bulk convection of substrate.

The null result becomes compatible with structured-medium models when this mechanical distinction is recognized.

7 Reversing von Laue: Mechanical Content Preserved

Von Laue showed that Fresnel drag follows from relativistic velocity addition, seemingly eliminating mechanical explanations [5]. Partial drag became “just kinematics”—an artifact of reference frame transformations.

But we have shown that bubble acoustics reproduces the same mathematics, and bubble mechanics are transparent. Since bubbles $\implies$ Eq. (1) and relativity $\implies$ Eq. (1), the equivalence runs both ways.

If bubble mechanics gives velocity addition, then velocity addition contains mechanical content.

Von Laue abstracted *away* from mechanics. The bubble-relativity equivalence abstracts *toward* them. The factor $(1 - v^2/c^2)$ in f_{SR} need not be viewed as arbitrary kinematics but can be interpreted as the signature of wave propagation through compliant inclusions in an elastic medium.

This does not invalidate the kinematic correctness of relativity, but rather enriches it, suggesting that the abstract kinematics may be a condensed representation of underlying medium dynamics—similar to how thermodynamics successfully abstracts away from the mechanics of individual molecules while remaining grounded in statistical mechanics. The reversal demonstrates model viability rather than claiming ontological necessity.

8 Contraction as Bubble Deformation

A moving bubble in liquid does not remain spherical. The upstream side compresses under oncoming flow; the downstream side expands. The bubble becomes oblate—compressed along its direction of motion.

This is not incidental but fundamental to partial-drag dynamics.

The angular dependence $\cos\theta$ in Eq. (1) encodes directional asymmetry: wave speed differs parallel versus perpendicular to motion. This is the mathematical signature of spatial anisotropy—structures compressed along the flow direction.

For bubbles, this is directly observable. For vortex structures, it follows from the same dynamics.

Relativistic velocity addition makes it explicit. The factor $(1 - v^2/c^2)$ in f_{SR} is precisely the factor governing Lorentz contraction:

$$L = L_0 \sqrt{1 - U^2/c^2}.$$

If atoms are modeled as low-rigidity zones producing both refraction and partial drag, they must contract when moving—just as bubbles deform in flow. A ruler composed of such structures inherits this compression.

Michelson and Morley’s null result becomes explicable: their apparatus contracted exactly enough to compensate the optical path difference. Bubble deformation, velocity addition, and length contraction are three aspects of one principle: compliant structures in flow deform along the direction of motion.

9 The Two Compensations Were One

Critics of nineteenth-century optical theory noted two suspiciously convenient “compensations”:

1. Fresnel’s partial drag reconciled moving-water experiments with wave theory
2. Lorentz-FitzGerald contraction explained Michelson-Morley’s null result [12, 13]

Two independent fixes appeared to be special pleading.

But they are not independent. Both emerge from one mechanism: compliant structures deforming in flow.

The partial drag coefficient $f(\omega)$ and contraction factor $\sqrt{1 - U^2/c^2}$ describe the same physics from different perspectives. In bubbles, both effects are simultaneously present and observable. In vortex-structured models, the same dynamics apply.

FitzGerald and Lorentz were not inventing arbitrary adjustments. They were intuiting dynamics of compliant zones without the full framework. Their insights seemed disconnected only because Fresnel’s density interpretation had obscured the mechanical picture fifty years earlier.

Had the rigidity path been pursued with Kelvin’s vortex atoms, these effects would have been recognized as unified consequences. The “coincidence” that appeared to doom classical optical theory—two phenomena requiring two fixes—was never a coincidence. It was one mechanism observed twice.

10 Conclusion

We have demonstrated a three-way mathematical equivalence: bubble acoustics, Fresnel drag, and relativistic velocity addition obey identical first-order transport laws (Eq. 1).

The physical origin is universal: waves couple to the most compliant component of structured media. In bubbles this principle is directly observable. Since bubble mechanics reproduces relativistic velocity addition, relativity itself admits mechanical interpretation.

This equivalence enhances model economy by reducing three independent phenomena to one mechanism. Fresnel drag, Lorentz contraction, and—unexpectedly—atomic polarization and refractive index all emerge from compliant structures deforming under flow or responding to applied gradients. Moving bubbles exhibit all effects simultaneously: partial convection of waves, deformation along the flow direction, and dipole displacement under pressure gradients.

The historical analysis reveals critical junctures:

1. Fresnel’s 1818 choice of density over rigidity shaped subsequent interpretive trajectory
2. Kelvin’s 1867 vortex-atom model [10] provided a unifying framework that remained largely unexplored
3. FitzGerald and Lorentz in the 1890s intuited aspects of compliant-zone dynamics without connecting them to Fresnel’s earlier work [12, 13]
4. Von Laue’s 1907 result [5] was interpreted as eliminating mechanics, when it actually preserved them in abstract form

The two “compensatory mechanisms” that critics found suspiciously convenient—Fresnel drag and Lorentz-FitzGerald contraction—are unified consequences when atoms are treated as low-rigidity inclusions. The partial drag coefficient $f(\omega)$ and the contraction factor $\sqrt{1 - U^2/c^2}$ emerge from the same dynamics.

Following the methodological framework of neoclassical interpretation [14], we have shown that mathematical equivalences between formulations need not imply one interpretation is “correct” and another “wrong,” but rather that multiple perspectives may offer complementary insights. The bubble-relativity equivalence suggests that mechanically-grounded models remain viable supplements to kinematic approaches.

The reduction of independent free parameters (one mechanism explaining multiple phenomena) follows the principle of theoretical economy. The mathematics is unambiguous: partial drag, velocity addition, contraction, and polarization are aspects of one principle—compliant inclusions in structured media, deforming under flow.

Cross-domain experimental test: The rigidity-based formulation of dispersion suggests a discriminating experimental test with practical implications for materials design. Measure $K_g(\omega)$ acoustically in a bubbly liquid across its resonance band, then independently measure optical drag coefficient $f_{\text{disp}}(\omega)$ in the same medium using Fizeau-type moving-water interferometry with frequency-tunable light. The compliant-inclusion framework predicts these should be related through the rigidity derivative:

$$f_{\text{disp}}(\omega) - \left[1 - \frac{1}{n^2(\omega)} \right] \propto -\frac{\omega}{2K_g(\omega)} \frac{dK_g}{d\omega}.$$

This cross-domain mapping—acoustic compliance determining optical drag—has no counterpart in standard treatments where dispersion enters through polarizability alone. A positive result would establish the mechanical entrainment description as more than mathematical reformulation, with implications for metamaterial design where controlling rigidity profiles could enable novel dispersive optical devices.

Whether this mechanical analogy extends to second-order effects, or whether the bubble model diverges from exact relativistic results at higher orders, remains an open question. The framework may provide new intuition for phenomena in general relativity, where spacetime itself has dynamic properties such as curvature, or in quantum field theory where vacuum structure influences particle interactions. The compliant-inclusion principle, validated across acoustic and optical domains, may find application wherever wave propagation through structured media occurs.

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