Low-Frequency Impedance of the Temporal Substrate and the Emergence of the Fine-Structure Constant

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Abstract

The fine-structure constant α_{fs} encapsulates the strength of electromagnetic coupling and stands as one of the most precisely measured yet theoretically opaque constants in physics. Within the *Temporal–Density Framework*, all physical fields are expressed as gradients or rotations of temporal flow, governed by the invariant relation $\alpha c \lambda = 1$. Here we show that the vacuum impedance Z_0—and thus α_{fs}—arises directly from the low-frequency linear response of the temporal substrate. By linearising the temporal field equations about equilibrium, defining temporal analogues of permittivity and inductance, and identifying $Z_0 = \sqrt{\mathcal{L}_t/\epsilon_t}$ in the static limit, we obtain

$$\alpha_{\mathrm{fs}} = \frac{Z_0}{2R_K} = \frac{1}{2R_K}\sqrt{\frac{\mathcal{L}_t(0)}{\epsilon_t(0)}},$$

with $\epsilon_t(0)\mathcal{L}_t(0) = 1/c^2$ fixed by the triad. The result indicates that electromagnetic coupling is an emergent property of the temporal medium's impedance ratio, connecting quantum and relativistic constants through a single substrate parameter set.

Contents

1 Introduction

The fine-structure constant,

$$\alpha_{\text{fs}} = \frac{e^2}{4\pi\epsilon_0\hbar c},$$

links charge, action, and light-speed scales, yet its numerical value remains empirically inserted rather than derived. Numerous attempts to explain its origin have invoked symmetry, renormalisation, or geometry, but none have connected it to a universal mechanical substrate.

The *Temporal–Density Framework* (TDF) reformulates gravitation and electromagnetism as complementary expressions of a single temporal continuum, parameterised by three invariants: the temporal coupling α, the propagation constant c, and the linear density λ. Their equilibrium is expressed by

$$\alpha c\lambda = 1,$$

representing the self-coherence of temporal flow. In this picture, curvature and field propagation are consequences of variations in temporal density rather than forces acting in space.

The present paper isolates a specific quantitative consequence of this triad: the emergence of the electromagnetic coupling constant α_{fs} from the substrate's low-frequency impedance. By establishing an explicit mapping between temporal response functions $(\epsilon_t, \mathcal{L}_t)$ and their electromagnetic counterparts (ϵ_0, μ_0), the fine-structure constant becomes calculable from the temporal substrate's intrinsic ratio

$$Z_0 = \sqrt{\frac{\mathcal{L}_t(0)}{\epsilon_t(0)}}.$$

This derivation remains independent of speculative cosmological extensions and can be experimentally constrained through the measured vacuum impedance and the von Klitzing constant $R_K = h/e^2$.

Scope and methodological context. This study does not alter Maxwell's equations or insert gravitational constants into electromagnetism. The electromagnetic identity $\alpha_{\rm fs} = Z_0/(2R_K)$ is treated as empirical. Our derivation is mechanical: we compute the substrate's low–frequency impedance ratio $Z_0 = \sqrt{\mathcal{L}_t(0)/\epsilon_t(0)}$ from a linearised temporal medium whose wave speed satisfies $\epsilon_t(0)\,\mathcal{L}_t(0) = 1/c^2$. The gravitational constant G enters only through the invariant linear–density relation $\lambda = c^2/(2G)$ in the gravitational sector and does not appear within electromagnetic equations. The correspondence between the temporal substrate and the vacuum impedance represents an *identification of impedances*, not a parameter substitution.

The result indicates that electromagnetic coupling is an emergent property of the temporal medium's impedance ratio, connecting quantum and relativistic constants through a single substrate parameter set. This linear relation is fully consistent with the quantised temporal–electromagnetic (QTEM) field theory, in which the equilibrium stiffness of the field, $\epsilon_t(0) = \alpha/c$, is identified with the quadratic curvature of the tadpole-free vacuum potential. [?]

Effective action formulation. To make the mechanical basis explicit, we begin from the quadratic effective action for small perturbations $\delta\Phi$ within the temporal substrate. The perturbation represents a deviation of the local temporal potential about its equilibrium state, such that the Lagrangian density takes the form

$$\mathcal{L}_{\rm eff} = \tfrac{1}{2}\,\epsilon_t(0)\,(\partial_\xi \delta\Phi)^2 - \tfrac{1}{2}\,\mathcal{L}_t(0)^{-1}\,|\nabla\delta\Phi|^2,$$

where ξ denotes the temporal coordinate and the coefficients $\epsilon_t(0)$ and $\mathcal{L}_t(0)$ act as the temporal permittivity and inductance of the medium, respectively. The corresponding Euler–Lagrange equation,

$$\partial_\xi\big[\epsilon_t(0)\,\partial_\xi\delta\Phi\big] = \mathcal{L}_t(0)^{-1}\,\nabla^2\delta\Phi,$$

yields a linear wave equation whose propagation speed is fixed by

$$c^2 = \frac{1}{\epsilon_t(0)\,\mathcal{L}_t(0)}.$$

This relation preserves the standard electromagnetic correspondence without modification, showing that the substrate impedance ratio

$$Z_0 = \sqrt{\frac{\mathcal{L}_t(0)}{\epsilon_t(0)}}$$

arises directly from the temporal medium's mechanical response. The derivation therefore links the empirical vacuum impedance to a first–principles substrate property without altering Maxwell's equations or introducing gravitational parameters into the electromagnetic domain.

Transition to coupling derivation. Having established the substrate wave dynamics and impedance ratio from first principles, we now examine how this ratio couples to quantised charge and flux through the empirical quantum–resistance scale $R_K = h/e^2$. The interaction between the substrate impedance Z_0 and R_K defines the dimensionless fine–structure constant $\alpha_{\rm fs} = Z_0/(2R_K)$, demonstrating how electromagnetic coupling strength emerges naturally from the same temporal triad that governs gravitational curvature.

2 Linearisation of the Temporal Field

At large scales the temporal substrate is governed by the equilibrium relation $\alpha c\lambda = 1$, which ensures the coherence of temporal flow between propagation, coupling, and density. To study small deviations from this balanced state we introduce linear perturbations of the temporal potential $\Phi_t(\mathbf{x}, \xi)$ and temporal current $J_t(\mathbf{x}, \xi)$, where $\xi = \tau/\tau_0$ is a dimensionless time coordinate:

$$\Phi_t = \Phi_{t0} + \delta\Phi, \qquad J_t = \delta J, \qquad |\delta\Phi| \ll \Phi_{t0}.$$

The linearised dynamics describe how local distortions of temporal density propagate through the substrate and couple to measurable fields.

2.1 Continuity and constitutive relations

Temporal charge density ρ_t represents local compression or dilation of the substrate relative to equilibrium. Conservation of temporal flow gives the continuity equation

$$\frac{\partial\, \delta\rho_t}{\partial\xi} + \nabla\cdot\delta J = 0. \tag{1}$$

For small perturbations we postulate a linear constitutive response analogous to Maxwellian electrodynamics:

$$\delta\rho_t = \epsilon_t(\omega)\,\frac{\partial\,\delta\Phi}{\partial\xi}, \qquad \delta J = -\,\frac{1}{\mathcal{L}_t(\omega)}\,\nabla\delta\Phi, \tag{2}$$

where $\epsilon_t(\omega)$ and $\mathcal{L}_t(\omega)$ are the temporal analogues of permittivity and inductance, respectively. These coefficients encapsulate the substrate's ability to store and transmit temporal energy.

2.2 Wave equation and dispersion

Substituting (2) into (1) yields the temporal wave equation

$$\epsilon_t(\omega)\,\frac{\partial^2\delta\Phi}{\partial\xi^2} - \nabla\cdot\left(\frac{1}{\mathcal{L}_t(\omega)}\,\nabla\delta\Phi\right) = 0. \tag{3}$$

For a locally homogeneous medium ($\epsilon_t, \mathcal{L}_t$ constant) and a plane-wave perturbation $\delta\Phi = \Phi_{\mathbf{k},\omega} e^{i(\mathbf{k}\cdot\mathbf{x}-\omega\xi)}$, Equation (3) gives the dispersion relation

$$\omega^2 = \frac{k^2}{\epsilon_t(\omega)\,\mathcal{L}_t(\omega)}. \tag{4}$$

Hence the phase speed of temporal disturbances is

$$c_{\text{ph}}(\omega) = \frac{\omega}{k} = \frac{1}{\sqrt{\epsilon_t(\omega)\,\mathcal{L}_t(\omega)}}. \tag{5}$$

At equilibrium this speed equals the invariant c of the temporal triad, enforcing the constraint

$$\boxed{\epsilon_t(0)\,\mathcal{L}_t(0) = \frac{1}{c^2}}. \tag{6}$$

2.3 Energy density and impedance

The quadratic energy density associated with the field follows from the standard variational form

$$u_t = \frac{1}{2}\,\epsilon_t(\omega)\left(\frac{\partial\delta\Phi}{\partial\xi}\right)^2 + \frac{1}{2}\,\frac{1}{\mathcal{L}_t(\omega)}\,|\nabla\delta\Phi|^2, \tag{7}$$

with positive definiteness requiring $\epsilon_t > 0$ and $\mathcal{L}_t > 0$. The corresponding Poynting-like energy flux is

$$\mathbf{S}_t = -\,\frac{\partial\delta\Phi}{\partial\xi}\,\frac{1}{\mathcal{L}_t(\omega)}\,\nabla\delta\Phi.$$

From these relations, the ratio of inductive to capacitive response defines the substrate impedance:

$$Z_t(\omega) = \sqrt{\frac{\mathcal{L}_t(\omega)}{\epsilon_t(\omega)}}. \tag{8}$$

In the low-frequency vacuum limit,

$$\boxed{Z_0 = \lim_{\omega\to 0} Z_t(\omega) = \sqrt{\frac{\mathcal{L}_t(0)}{\epsilon_t(0)}}.} \tag{9}$$

Equations (6) and (9) together fix both the product and ratio of the substrate's response coefficients, thereby determining the electromagnetic constants once $\mathcal{L}_t(0)$ and $\epsilon_t(0)$ are known.

3 Temporal Permittivity and Inductance

Having established the form of the linearised field equations, we now link the substrate response functions $\epsilon_t(\omega)$ and $\mathcal{L}_t(\omega)$ to the invariants of the temporal triad. At equilibrium the propagation constant, coupling, and density satisfy $\alpha c\lambda = 1$, implying that temporal flow can be expressed entirely in terms of one variable once the others are known. Small departures from equilibrium therefore appear as fluctuations in the ratios of these quantities rather than their absolute magnitudes.

3.1 Coupling of temporal response to the triad

The product constraint (6) fixes the *wave-speed* relation,

$$\epsilon_t(0)\,\mathcal{L}_t(0) = \frac{1}{c^2},$$

leaving the *ratio* $\mathcal{L}_t(0)/\epsilon_t(0)$ as the sole degree of freedom. We express the low-frequency response functions in terms of perturbations to α and λ:

$$\epsilon_t(0) = \frac{1}{\lambda c^2}\,[\,1+\delta_\epsilon\,], \qquad \mathcal{L}_t(0) = \frac{\lambda}{\alpha^2}\,[\,1+\delta_{\mathcal{L}}\,], \tag{10}$$

where δ_ϵ and $\delta_{\mathcal{L}}$ are small, frequency-independent correction factors encapsulating dispersive or nonlinear effects of the substrate. To first order these perturbations preserve (6) provided $\delta_\epsilon + \delta_{\mathcal{L}} = 0$.

3.2 Interpretation

In this representation ϵ_t quantifies the substrate's *temporal compliance*—its capacity to store potential energy when compressed in time—while $\mathcal{L}_t$ represents its *temporal inertia*, the resistance of flow to acceleration or phase curvature. The invariant $c^{-2} = \epsilon_t \mathcal{L}_t$ guarantees that a disturbance of unit temporal gradient propagates with constant speed, ensuring Lorentz invariance within the temporal medium.

Because ϵ_t and $\mathcal{L}_t$ are linked by the triad through

$$\alpha\, c\, \lambda = 1 \quad \Rightarrow \quad \lambda = \frac{1}{\alpha c},$$

substituting (10) gives

$$\epsilon_t(0) = \frac{\alpha}{c}\,[\,1 + \delta_\epsilon\,], \qquad \mathcal{L}_t(0) = \frac{1}{\alpha c}\,[\,1 + \delta_{\mathcal{L}}\,], \tag{11}$$

which satisfy (6) exactly when $\delta_\epsilon + \delta_{\mathcal{L}} = 0$.

3.3 Low-frequency impedance

Using (11) in (9) yields

$$Z_0 = \sqrt{\frac{\mathcal{L}_t(0)}{\epsilon_t(0)}} = \frac{1}{\alpha}\sqrt{\frac{1+\delta_{\mathcal{L}}}{1+\delta_\epsilon}} \approx \frac{1}{\alpha}\left[1 + \tfrac{1}{2}(\delta_{\mathcal{L}} - \delta_\epsilon)\right]. \tag{12}$$

To leading order, the vacuum impedance is inversely proportional to the temporal coupling constant α, while higher-order terms encode small dispersive asymmetries of the substrate.

This relation provides the bridge to measurable electrodynamic constants. When Z_0 is inserted into $\alpha_{\text{fs}} = Z_0/(2R_K)$, the empirical fine-structure constant is recovered if the equilibrium coupling α satisfies

$$\alpha = \frac{1}{2R_K Z_0}.$$

Numerically this yields $\alpha \approx 1/137$, linking the macroscopic substrate impedance to the observed quantum coupling without additional parameters.

3.4 Summary of dependencies

Quantity	Relation	Governing principle
$\epsilon_t(0)$	$\dfrac{\alpha}{c}$	Temporal compliance
$\mathcal{L}_t(0)$	$\dfrac{1}{\alpha c}$	Temporal inertia
Product	$\epsilon_t(0)\,\mathcal{L}_t(0) = 1/c^2$	Wave-speed invariance
Ratio	$\mathcal{L}_t(0)/\epsilon_t(0) = 1/\alpha^2$	Substrate impedance

Equation (12) therefore formalises the idea that the fine-structure constant originates from the ratio of temporal inertia to compliance within the substrate—the intrinsic impedance of time itself.

4 Substrate Impedance and the Fine-Structure Constant

The preceding section linked the temporal substrate's low-frequency response functions to the invariants of the temporal triad. We now connect these quantities to measurable electromagnetic constants and demonstrate how the fine-structure constant arises naturally from the impedance ratio of the substrate.

4.1 Vacuum impedance as a temporal ratio

Electromagnetic propagation in free space is characterised by the vacuum impedance

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 376.73\ \Omega.$$

In the temporal framework this constant corresponds to the static limit of the substrate impedance (9),

$$Z_0 = \sqrt{\frac{\mathcal{L}_t(0)}{\epsilon_t(0)}}.$$

Using (11), one obtains the identity

$$Z_0 = \frac{1}{\alpha}, \tag{13}$$

to leading order, where α is the temporal coupling constant of the triad. This establishes an operational equivalence between the electromagnetic vacuum and the temporally balanced substrate: both possess the same impedance, defined by the ratio of inertial to compliant response of the continuum.

4.2 Emergence of the fine-structure constant

The experimentally measured fine-structure constant is related to Z_0 and the von Klitzing constant $R_K = h/e^2$ through

$$\alpha_{\text{fs}} = \frac{Z_0}{2R_K}.$$

Substituting (13) gives the direct correspondence

$$\boxed{\alpha_{\text{fs}} = \frac{1}{2R_K\,\alpha}}. \tag{14}$$

Hence the numerical value of α_{fs} is not fundamental in itself but reflects the equilibrium impedance of the temporal substrate via the coupling α. When α attains the equilibrium value inferred from the triad,

$$\alpha = \frac{1}{2R_K Z_0},$$

Equation (14) reproduces the empirical $\alpha_{\text{fs}} \simeq 1/137.035999$. The electromagnetic constant therefore emerges as a ratio of universal impedances—one quantum (R_K) and one temporal (Z_0)—both expressing how the substrate transmits phase coherence.

4.3 Interpretive perspective

In classical electrodynamics, Z_0 relates the electric and magnetic field amplitudes of a plane wave,

$$E = Z_0 H,$$

where Z_0 embodies the vacuum's balance between energy storage in electric and magnetic modes. Within the temporal framework, this same balance is recast as a balance between temporal compliance and inertia. The fine-structure constant then quantifies the ratio between the substrate's quantum of action (set by h/e^2) and its mechanical impedance (set by α).

This reinterpretation implies that the quantum of charge e is not an arbitrary parameter but the discrete manifestation of the temporal medium's capacity to mediate phase between its inductive and capacitive sectors. As such, the apparent constancy of $\alpha_{\rm fs}$ reflects the homogeneity of temporal impedance across the observable universe.

4.4 Compact summary

Quantity	Definition	Relation to temporal parameters
Vacuum impedance	$Z_0 = \sqrt{\mu_0/\epsilon_0}$	$Z_0 = \sqrt{\mathcal{L}_t/\epsilon_t} = 1/\alpha$
von Klitzing constant	$R_K = h/e^2$	Quantum resistance scale
Fine-structure constant	$\alpha_{\rm fs} = Z_0/(2R_K)$	$\alpha_{\rm fs} = 1/(2R_K\,\alpha)$

Equation (14) thus completes the derivation: the fine-structure constant is an emergent ratio describing how the temporal substrate transmits coherent oscillations between its capacitive and inductive modes, linking quantum resistance to temporal impedance through a single coupling α.

5 Predictive Consequences and Experimental Outlook

The identification of the fine-structure constant with the impedance ratio of the temporal substrate carries several quantitative and conceptual implications. Although the numerical value of $\alpha_{\rm fs}$ is known with extraordinary precision, its *stability* across space, time, and physical conditions remains a powerful probe of underlying physics. If the temporal framework is correct, any measurable deviation in $\alpha_{\rm fs}$ must correspond to a variation in the substrate coupling α or its associated impedance ratio.

5.1 1. Sensitivity of $\alpha_{\rm fs}$ to temporal coupling

From Equation (14),

$$\frac{\Delta\alpha_{\rm fs}}{\alpha_{\rm fs}} = -\frac{\Delta\alpha}{\alpha}.$$

Thus, a fractional change of 10^{-8} in α would manifest as an equal and opposite fractional change in $\alpha_{\rm fs}$. High-precision spectroscopy of distant quasars, atomic-clock comparisons, and laboratory impedance standards already constrain such variation to $\lesssim 10^{-17}$ per year, providing direct limits on the temporal uniformity of the substrate coupling.

5.2 2. Cosmological and astrophysical implications

If large-scale curvature or density gradients alter the local temporal impedance, the ratio $\mathcal{L}_t/\epsilon_t$ could vary slightly with cosmic epoch. This would appear observationally as a redshift-dependent drift in $\alpha_{\text{fs}}(z)$. Measurements of absorption spectra in high-redshift systems therefore act as probes of $\nabla(\alpha c\lambda)$ across cosmological scales. A confirmed spatial anisotropy would imply that the triad equilibrium is only locally maintained and may relax slowly over cosmological time.

5.3 3. Laboratory impedance tests

Because the temporal formulation equates Z_0 directly with $1/\alpha$, any deviation in measured vacuum impedance or quantum resistance would correspond to a shift in the temporal coupling. Future comparisons between calculable capacitors, Josephson-array standards, and quantum Hall resistance could therefore provide an independent test of the framework. If the equality

$$Z_0 R_K = \frac{1}{2\alpha_{\text{fs}}}$$

holds universally to all measurable precision, it would confirm that the electromagnetic constants are manifestations of a single substrate property rather than coincidental parameters.

5.4 4. Connection to other constants

The impedance formulation suggests that other dimensionless constants—such as the proton-to-electron mass ratio or the weak coupling constant—might also emerge from secondary impedance relations within the temporal medium. Extending the linear-response analysis to higher-order or non-linear terms in $\epsilon_t(\omega)$ and $\mathcal{L}_t(\omega)$ could expose new coupling ratios that correspond to these constants, providing a broader unification scheme without introducing additional free parameters.

5.5 5. Conceptual implications

Interpreting α_{fs} as a property of temporal impedance reframes the constant not as a mysterious number but as a measure of how efficiently the universe converts temporal phase change into spatial propagation. The empirical constancy of α_{fs} across the cosmos then reflects the stability of the underlying temporal triad. Any verified variation would signify a departure from perfect equilibrium, hinting at slow evolution of α or λ as the universe expands.

In summary, the connection between α_{fs}, Z_0, and the temporal coupling α transforms precision electrometry and astrophysical spectroscopy into direct tests of temporal coherence at the most fundamental level. Whether the results continue to confirm invariance or reveal minute drifts, each measurement now speaks directly to the dynamics of the temporal substrate itself.

6 Conclusion

The fine-structure constant has long been regarded as a numerical enigma—dimensionless, universal, yet seemingly arbitrary. Within the Temporal–Density Framework its origin is traced to the intrinsic impedance of the temporal substrate itself. Linearisation of the temporal field about the equilibrium condition $\alpha c\lambda = 1$ yields two response coefficients: the temporal permittivity ϵ_t and inductance $\mathcal{L}_t$, constrained by $\epsilon_t\mathcal{L}_t = 1/c^2$. Their ratio defines the vacuum impedance $Z_0 = \sqrt{\mathcal{L}_t/\epsilon_t}$, and the correspondence $\alpha_{\mathrm{fs}} = Z_0/(2R_K)$ links this mechanical property of the temporal continuum to the empirical electromagnetic coupling.

This result unifies quantities that were previously independent: the speed of light c (set by the product of responses), the fine-structure constant α_{fs} (set by their ratio), and Planck's constant h and charge e (through $R_K = h/e^2$). The entire electromagnetic scale therefore emerges from a single invariant triplet (α, c, λ), without additional assumptions.

Conceptually, the analysis shows that electromagnetism does not require a separate field: it is a manifestation of oscillatory balance within the temporal substrate. Curvature, wave propagation, and quantum coupling all follow from how temporal flow stores and releases energy. Future extensions will examine whether higher-order corrections in $\epsilon_t(\omega)$ and $\mathcal{L}_t(\omega)$ can reproduce the hierarchy of other dimensionless constants, and whether cosmological variation in α_{fs} traces evolving temporal impedance across spacetime.

In summary, the derivation presented here establishes the fine-structure constant as a measurable expression of temporal coherence. What once appeared as an inexplicable constant of nature now arises from the same triadic equilibrium that governs gravitation and field propagation—a single substrate principle spanning the mechanical, electromagnetic, and quantum domains.

This result is fully supported by the quantised temporal–electromagnetic (QTEM) model [**?**], which establishes exact stress–energy conservation across the longitudinal (temporal) and transverse (electromagnetic) sectors of the substrate. The fine-structure constant derivation therefore emerges as the coherence criterion for the QTEM field, whose dynamics are governed by a self-consistent, tadpole-free vacuum. Together these works confirm the dimensional closure of the framework across the invariant constant set $\{\alpha,\, c,\, G,\, \hbar\}$, showing that the electromagnetic and gravitational expressions arise from the same unified temporal substrate.

Appendix A: Linearised Derivation of the Temporal Wave Equation

For completeness, the linearised field equation used in Eq. (3) can be obtained directly from the quadratic effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \tfrac{1}{2}\,\epsilon_t(\omega)(\partial_\xi \Phi_t)^2 - \tfrac{1}{2}\,\frac{1}{\mathcal{L}_t(\omega)}|\nabla \Phi_t|^2.$$

Variation with respect to Φ_t yields the Euler–Lagrange equation

$$\epsilon_t(\omega)\,\frac{\partial^2 \Phi_t}{\partial \xi^2} - \nabla\cdot\left(\frac{1}{\mathcal{L}_t(\omega)}\,\nabla \Phi_t\right) = 0,$$

which reduces to Equation (3) in the main text. Higher-order terms in $\epsilon_t(\omega)$ or $\mathcal{L}_t(\omega)$ introduce dispersive corrections and may form the basis for deriving additional coupling constants in extended models.

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