

Fundamental Principles of Physics: A Unified Conceptual Perspective from Geometry, Interaction, and Emergence v4

J.W. Krol

2025

Abstract

This article synthesises several foundational structures of modern physics into a single coherent perspective. The aim is not to propose a new physical theory, but to expose the common mathematical and conceptual backbone that underlies quantum mechanics, general relativity, and classical field theory. The central principle is that rotational invariance on every local two-dimensional plane forces the Euclidean/Lorentz metric and thereby the universal decomposition into parallel and orthogonal interactions, represented by the inner and wedge product. This two-dimensional interaction structure generates geodesic motion, curvature, and the algebra of fields.

The second principle is that dissipation redistributes ordered (macroscopic) motion into unordered (microscopic) motion, producing entropy and causing deviations from geodesic trajectories. This leads naturally to a geometric interpretation of dissipative dynamics as orthogonal corrections in local two-dimensional interaction planes.

Finally, we discuss the role of the universal constants c , h , and G . The speed of light c sets the scale-free measure of causal structure; Planck's constant h initiates the formation of microscopic ordered structures; and Newton's constant G drives large-scale aggregation and macroscopic order. Together with the geometric background, these constants determine the dynamical hierarchy of physical structure. This exposition is a conceptual synthesis, complementary to the more algebraic development in [1]

While the proposed role of dissipation as a bridge between quantum and gravitational scales is speculative, it is presented here as a structurally coherent possibility rather than a completed theory.

1 Rotational Invariance and the Geometric Backbone

1.1 Complex Structure and Two-Dimensional Planes

At the most elementary level, the axiom

$$i^2 = -1$$

defines the complex numbers and the rotation operator on the unit circle. The complex exponential

$$e^{i\theta} = \cos \theta + i \sin \theta$$

encodes all rotations in a two-dimensional plane, and the modulus constraint

$$\cos^2 \theta + \sin^2 \theta = 1$$

is an algebraic identity independent of any metric. The universal decomposition of a quantity into parallel and orthogonal components originates here.

In higher-dimensional spaces, any two non-collinear vectors $a^\mu, b^\mu \in T_p\mathcal{M}$ span a unique 2D subspace

$$\Pi(a, b) := \text{span}\{a, b\},$$

and all interactions between them occur entirely within this plane.

1.2 The Metric from Rotational Invariance

If the laws of physics are invariant under all rotations in each local plane $\Pi(a, b)$, then the norm must satisfy the parallelogram law. By the Jordan–von Neumann theorem, this implies that the norm arises from an inner product. On spacetime, the existence of a finite invariant signal speed c forces the metric to take Lorentzian signature

$$\eta_{\mu\nu} = \text{diag}(-1, +1, +1, +1).$$

Thus the complex structure, rotational invariance and causal structure jointly determine the pseudo-Euclidean geometry of relativity.

1.3 Inner and Wedge Product and the Role of Clifford Algebra

The metric $g_{\mu\nu}$ induces two fundamental bilinear operations on the tangent space $T_p\mathcal{M}$: the inner product and the wedge product. These encode the decomposition of any pair of vectors into parallel and orthogonal components. Their structure is most naturally and compactly described within the framework of *Clifford algebra* (geometric algebra), denoted $Cl(p, q)$ for a metric of signature (p, q) .

Let $a^\mu, b^\mu \in T_p\mathcal{M}$ be arbitrary vectors. The inner product is defined as

$$a \cdot b := g_{\mu\nu} a^\mu b^\nu,$$

representing the parallel interaction component. Clifford algebra extends this to the *geometric product*

$$ab := a \cdot b + a \wedge b,$$

where the outer (wedge) product $a \wedge b$ is the grade-2, antisymmetric component. Its squared norm is

$$|a \wedge b|^2 = (a \cdot a)(b \cdot b) - (a \cdot b)^2.$$

This quantity measures the oriented area of the parallelogram spanned by a and b , and therefore encodes the orthogonal interaction component. In the Clifford algebra $Cl(3, 1)$ of Lorentzian spacetime, such bivectors generate Lorentz transformations:

$$R(\theta) = e^{\frac{1}{2}\theta(a \wedge b)},$$

generalising the complex exponential $e^{i\theta}$ to higher dimensions.

Thus the pair $(a \cdot b, a \wedge b)$ forms the universal two-dimensional interaction structure: every interaction between two directions resides entirely in the plane $\Pi(a, b)$ spanned by them. The inner product measures how much of b lies parallel to a , while the bivector $a \wedge b$ measures the orthogonal component and generates rotations in that plane.

In geometric algebra, these two operations—inner and wedge—are not independent constructs but the grade-decomposition of a single geometric product. This unifies rotations, Lorentz transformations, curvature bivectors, electromagnetic field tensors, angular momentum, and commutators in quantum mechanics within a single algebraic framework. The universality of the Clifford algebra formulation reflects the deeper fact that physics is built from two-dimensional interaction planes and the symmetries that act within them.

2 Geodesics as Chained Two-Dimensional Interactions

2.1 Parallel Transport and Local Dynamics

A timelike worldline $x^\mu(\tau)$ with velocity $u^\mu = \frac{dx^\mu}{d\tau}$ evolves according to

$$u^\nu \nabla_\nu u^\mu = a^\mu.$$

The worldline is geodesic when

$$a^\mu = 0.$$

Geometrically, this means that on each infinitesimal segment, the tangent vector is transported parallel to itself without an orthogonal component. Since each transport step lives in a 2D plane $\Pi(u, \delta x)$, a geodesic is a one-dimensional chain of locally trivial 2D interactions. Its “shortest path” property arises from the absence of accumulated rotation in these panels.

3 Dissipation and Deviation from Geodesic Motion

3.1 Microstructure and Redistribution of Motion

Consider a collection of microscopic constituents with momenta p_i^μ . Write

$$p_i^\mu = m_i u^\mu + q_i^\mu, \quad \sum_i q_i^\mu = 0.$$

The total macroscopic momentum is

$$P^\mu = M u^\mu, \quad M = \sum_i m_i,$$

while the microfluctuations q_i^μ represent disordered motion.

Dissipation transfers energy from the macroscopic ordered mode u^μ into the ensemble of unordered modes $\{q_i^\mu\}$, increasing entropy.

3.2 Stress-Energy Tensor and Dissipative Forces

The energy-momentum tensor takes the general form

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu + pg^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu + \pi^{\mu\nu},$$

with heat flux q^μ and shear stress $\pi^{\mu\nu}$. Conservation $\nabla_\mu T^{\mu\nu} = 0$ yields the effective force

$$u^\mu \nabla_\mu u^\nu = a_{\text{diss}}^\nu,$$

where a_{diss}^ν is orthogonal to u^ν and arises from gradients of q^μ and $\pi^{\mu\nu}$. Dissipation therefore rotates the velocity vector within successive 2D planes $\Pi(u, a_{\text{diss}})$, producing deviations from geodesic motion.

4 From Local Two-Dimensional Interaction Structure to Global Conservation Laws

A central theme of this essay is that all physical interactions arise from the two elementary bilinear operators associated with a local two-dimensional plane: the inner product (parallel component) and the wedge product (orthogonal component). This section shows that the transition from local differential operators to global integral laws—and the associated conservation laws of classical field theory—is not an extra assumption but a logical consequence of this 2D interaction structure combined with geometric (Lorentz) symmetry.

4.1 Local 2D Operators as the Source of All Field Derivatives

Every differential operator of vector calculus is built from the inner and wedge products restricted to an infinitesimal 2D plane:

$$\nabla f \leftrightarrow \text{parallel projection in } \Pi, \quad \nabla \times \mathbf{F} \leftrightarrow \text{orthogonal rotation in } \Pi, \quad \nabla \cdot \mathbf{F} \leftrightarrow \text{parallel flow}$$

All three operators therefore express how a field interacts with its neighbours along infinitesimal 2D panels. No higher-dimensional structure is needed: every interaction is decomposable into parallel (inner) and orthogonal (outer) components.

4.2 From Local Structure to Global Relations

The classical integral theorems of vector calculus follow purely from this local 2D structure together with smoothness. Let V be a three-dimensional region, $S = \partial V$ its boundary, and $C = \partial S$ the boundary curve of a surface patch.

The three fundamental relations are:

Fundamental theorem for gradients.

$$\int_A^B (\nabla f) \cdot d\mathbf{r} = f(B) - f(A).$$

The gradient encodes parallel change in every local 2D plane, and the integral accumulates these parallel components along a curve.

Divergence theorem (Gauss).

$$\oint_S \mathbf{F} \cdot \mathbf{n} dS = \int_V (\nabla \cdot \mathbf{F}) dV.$$

Divergence is the local parallel flux density in each 2D plane; Gauss' theorem states that its global integral equals the net flux through the boundary.

Stokes' theorem.

$$\oint_C \mathbf{F} \cdot d\mathbf{r} = \iint_S (\nabla \times \mathbf{F}) \cdot \mathbf{n} dS.$$

Curl is the local 2D rotation (wedge component) of a field; Stokes' theorem relates its accumulation to the circulation along the boundary curve.

In all three cases, the global integral forms arise by summing the local 2D interactions across an extended region.

4.3 Conservation Laws as Consequences of Symmetry

The key point is that none of these integral relations require the explicit postulate of a conservation law. Instead, they are consequences of:

1. the decomposition of all interactions into inner and wedge products in local 2D planes;
2. Lorentz (or Euclidean) symmetry, which makes these decompositions invariant under rotations and boosts;
3. smoothness of fields, enabling the accumulation of local contributions.

Conservation then follows automatically. For example:

- In electrodynamics, Gauss' law follows because \mathbf{E} is generated by a potential whose curl vanishes except at sources.
- In hydrodynamics, $\nabla \cdot \mathbf{v} = 0$ is the statement that the flux of \mathbf{v} through a closed surface equals the sum of all local divergences— which vanish for incompressible flow.
- In general relativity, the Bianchi identity

$$\nabla_\mu G^{\mu\nu} = 0$$

is the geometric analogue of Stokes' theorem: curvature is a sum of local 2D rotations, and its divergence vanishes as a direct consequence of the antisymmetry of the Riemann bivector.

Thus the conservation of energy–momentum,

$$\nabla_\mu T^{\mu\nu} = 0,$$

is not an additional axiom. It is the dual statement of the Bianchi identity arising from the 2D interaction structure of curvature.

4.4 Summary

The classical integral theorems and all associated conservation laws follow directly from the same principles developed throughout this essay:

1. all interactions occur within local 2D planes via inner and wedge products;
2. Lorentz symmetry ensures invariance of these interactions under rotations and boosts;
3. global conservation laws arise by integrating these local interactions across extended domains.

In this perspective, conservation is not a separately assumed feature of physical law. It is the inevitable large-scale manifestation of the fundamental 2D algebraic structure from which all field dynamics originate.

Thus, the familiar conservation laws of classical and modern physics appear not as ad hoc axioms, but as unavoidable shadows cast by the local 2D algebraic structure of nature

5 The Role of the Fundamental Constants

5.1 The Speed of Light c as the Hyperbolic Rotation Scale

The constant c does more than set the slope of the light cone; it determines the scale on which *Lorentz boosts become hyperbolic rotations* in every timelike 2D plane $\Pi(t, x)$. In the same way that ordinary rotations in a spatial plane are generated by bivectors $e_i \wedge e_j$, Lorentz boosts in spacetime are generated by *timelike* bivectors of the form $t \wedge x$. In geometric algebra, a boost with rapidity φ in the t - x plane is expressed as

$$R(\varphi) = \exp\left(-\frac{\varphi}{2} t \wedge x\right).$$

The relation between rapidity and physical velocity is fixed by c :

$$v = c \tanh \varphi, \quad \gamma = \cosh \varphi, \quad \gamma \frac{v}{c} = \sinh \varphi.$$

Thus the Lorentz transformation has the exact form of a hyperbolic rotation:

$$\begin{pmatrix} ct' \\ x' \end{pmatrix} = \begin{pmatrix} \cosh \varphi & -\sinh \varphi \\ -\sinh \varphi & \cosh \varphi \end{pmatrix} \begin{pmatrix} ct \\ x \end{pmatrix}.$$

In this representation, c appears as the *rotation scale* that unifies spatial rotations and Lorentz boosts into a single group:

$$\text{SO}(3) \subset \text{SO}(3, 1).$$

Without c , one could not form a hyperbolic plane $\Pi(t, x)$ with the invariant quantity

$$-(c dt)^2 + dx^2,$$

and hence no Lorentzian metric could exist. The constancy of c therefore ensures that the same two-dimensional rotation structure—elliptic rotations in spatial planes and hyperbolic rotations in timelike planes—governs all physical interactions. Boosts are simply the Lorentzian analogue of ordinary rotations, with c setting the relative scaling between the temporal and spatial axes.

Thus, c is not merely the speed of light: it is the geometric constant that allows the complex-rotation structure of physics to extend consistently from Euclidean planes to Lorentzian spacetime.

5.2 Planck's Constant h as the Quantum of Two-Dimensional Action

In the same way that the constant c encodes the invariant geometric structure of hyperbolic rotations in spacetime, Planck's constant h determines the invariant structure of rotations in *phase space*. The fundamental quantum relation

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

expresses that the elementary unit of physical action is not a one-dimensional quantity but a *two-dimensional area element* in the plane $\Pi(x, p)$ spanned by position and momentum.

More generally, in symplectic geometry the canonical 2-form

$$\omega = dp \wedge dx$$

is the analogue of the spacetime area form in Lorentzian geometry. Quantisation arises from the condition that the integral of this 2-form over any elementary phase-space cell is discrete:

$$\int_{\Sigma} \omega = nh, \quad n \in \mathbb{Z}.$$

Thus h is the “quantum of oriented area” in the 2D interaction planes of phase space, in the same sense that curvature is an oriented area in the 2D parallel-transport planes of spacetime. The commutator relation

$$[A, B] = i\hbar C$$

is precisely the algebraic statement that the generator of transformations between observables is a bivector in the phase-space Clifford algebra $\text{Cl}(2, 0)$.

Planck's constant therefore sets the scale of microscopic order by determining which phase-space areas can exist. At the quantum level, motion is organised through discrete rotations in these 2D phase-space planes, just as classical spacetime motion is organised through rotations in 2D Lorentzian planes.

5.3 Newton's Constant G as the Coupling of Geometric and Material Two-Dimensional Structures

Curvature in General Relativity is encoded by the Riemann tensor $R^\rho_{\sigma\mu\nu}$, which measures the failure of parallel transport around an infinitesimal 2D loop spanned

by the directions μ and ν :

$$R^\rho{}_{\sigma\mu\nu}v^\sigma = (\nabla_\mu\nabla_\nu - \nabla_\nu\nabla_\mu)v^\rho.$$

This is fundamentally a two-dimensional, bivector-valued object; curvature is the *accumulated rotation* associated with the oriented area element $dx^\mu \wedge dx^\nu$.

Newton’s constant G specifies how strongly this geometric 2D structure couples to the 2D interaction structure contained in the stress–energy tensor $T_{\mu\nu}$. The Einstein field equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

equates two quantities of identical algebraic type:

- $G_{\mu\nu}$: the contraction of the curvature bivector into a symmetric second-rank tensor representing the net rotational content of spacetime,
- $T_{\mu\nu}$: the sum of parallel (inner-product) and orthogonal (wedge-product) energy–momentum flows of matter fields.

Thus G is not simply “the strength of gravity”; it is the universal constant that determines the *conversion factor between geometric rotation in two-dimensional planes and the dynamical stresses generated by matter*. In this sense G plays the same role for macroscopic structure formation that h plays for microscopic structure formation: both quantify how 2D interaction structures give rise to ordered, observable phenomena.

5.4 Summary

The three constants c , h , and G correspond to three distinct but deeply connected two-dimensional interaction structures:

- c fixes the invariant hyperbolic geometry of the 2D planes $\Pi(t, x)$, allowing Lorentz boosts to be interpreted as rotations.
- h fixes the invariant symplectic geometry of the 2D planes $\Pi(x, p)$, quantising the allowed oriented areas in phase space.
- G fixes the coupling between the 2D curvature planes of spacetime and the 2D stress planes of matter.

These constants are therefore not arbitrary parameters but the structural coefficients of three complementary manifestations of the same underlying idea: *all fundamental*

interactions, whether geometric or quantum, are governed by two-dimensional plane structures encoded by inner and wedge products.

6 Derived Constants: k_B , α , and λ

In the preceding sections we have argued that the fundamental structure of physics arises from only three ingredients:

1. the *geometric structure* enforced by rotational and Lorentz invariance,
2. the *microstructural ordering scale* set by Planck's constant h ,
3. the *macrostructural ordering scale* set by the gravitational constant G .

All other physical constants appear either as *conversion factors* between descriptions or as *statistical parameters* that emerge from collective behaviour of microstates. In this section we examine three classical examples: Boltzmann's constant k_B , the fine-structure constant α , and the cosmological constant Λ .

6.1 Boltzmann's Constant as a Statistical Scale Factor

The constant k_B does not enter any microscopic equation of motion. It appears only when one chooses to describe a system with a large number of microstates in terms of thermodynamic variables. At its core,

$$S = k_B \ln \Omega$$

merely expresses how the *dimensionless* combinatorial entropy $\ln \Omega$ is mapped to the *macroscopic* quantity S that has the units of energy per temperature. Consequently,

$$k_B = (\text{conversion factor from microstate counting to macroscopic energy})$$

and is therefore not a dynamical constant. It reflects the collective, statistical ordering of micro-degrees of freedom, not a fundamental interaction.

6.2 The Fine-Structure Constant as a Derived Ratio

The dimensionless fine-structure constant

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$$

is often regarded as fundamental because of its ubiquity across quantum electrodynamics. But its definition shows a different nature: it is a *dimensionless ratio* of quantities that belong to distinct structural layers:

- c arises from the geometric structure of motion (hyperbolic rotations),
- \hbar sets the microstructural quantisation scale,
- $e^2/(4\pi\epsilon_0)$ encodes the strength of the emergent long-range electromagnetic interaction between charged microstructures.

Thus α expresses the *relative strength* of one emergent interaction to the underlying geometric and microstructural scales. It is not fundamental in the sense that c , \hbar , and G are: it measures how a collective electromagnetic interaction fits into the deeper geometric framework.

6.3 The Cosmological Constant as an Effective Macroscopic Parameter

The cosmological constant Λ appears geometrically as a uniform curvature term in Einstein's equation. Its physical interpretation is less fundamental:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}.$$

From a microscopic perspective, Λ is an *effective parameter summarising the large-scale distribution of energy and pressure* in the vacuum. In any theory that includes coarse-graining (either over quantum microstructures or over emergent gravitational degrees of freedom) the effective stress-energy tensor acquires a component proportional to $g_{\mu\nu}$.

This term is therefore similar in status to pressure in a fluid: it is a collective, averaged quantity that only exists after coarse-graining, not a primary dynamical coupling. The cosmological constant is not a fundamental constant of motion or geometry; it is the macroscopic trace of the vacuum's microstructure.

6.4 Summary

All three constants analysed in this section share a common feature: they arise *only after* the fundamental geometric and dynamical structures have been fixed. They are emergent or derived in the following sense:

- k_B converts microstate counting into macroscopic energy,

- α expresses the ratio between electromagnetic interaction strength and the fundamental geometric/microstructural scales (c, \hbar) ,
- Λ represents the effective large-scale curvature of the vacuum, produced by coarse-grained microstructure.

None of these constants define the structure of spacetime or the basic laws of motion. They are collective descriptors of how complex systems composed of quantised and gravitationally interacting microstructures behave at larger scales. In this framework, k_B , α and Λ are therefore not fundamental constants but *statistical emergent parameters* derived from the combination of geometry, quantisation, and gravitational ordering.

7 Synthesis

From these principles we can outline the fundamental structure of physics:

1. Rotational invariance in every local 2D plane determines the metric (Euclidean/Lorentz).
2. The metric induces inner and wedge products—the only two elementary interaction modes.
3. Geodesics arise from chaining 2D local interactions without orthogonal rotation.
4. Dissipation redistributes ordered motion into unordered micro-motion, creating deviation from geodesic motion.
5. The constants c , h , and G form the dynamical hierarchy:
 - c : causal and geometric structure,
 - h : microscopic ordering,
 - G : macroscopic ordering.

These principles do not constitute a new physical theory; they expose a common logical structure that is already present in quantum theory, thermodynamics, relativity, and fluid dynamics. The perspective is unifying rather than replacement.

8 Unification of the Quantum and Gravitational Scales via Dissipation

A persistent challenge in foundational physics is the apparent disjunction between the quantum scale, governed by Planck’s constant h , and the gravitational scale, governed by Newton’s constant G . Quantum theory and general relativity describe two regimes with different notions of state, dynamics, and geometry. Yet this separation need not reflect a fundamental incompatibility. In this section we explore the idea—not as a definite claim, but as a structurally plausible possibility—that *dissipation* may act as an interface that links the microscopic and macroscopic layers of physical description, see appendix [A](#) and appendix [B](#)

Dissipation, understood as the redistribution of ordered motion into microscopic degrees of freedom, naturally produces entropy and coarse-grained behaviour. Because gravitational dynamics in general relativity is sensitive to coarse-grained energy–momentum flows, a dissipative mechanism could offer an indirect but consistent route by which microscopic quantum fluctuations shape macroscopic curvature, while curvature in turn constrains the long-wavelength behaviour of matter fields.

8.1 Two Fundamental Scales of Ordered Motion

The constants h and G express two structurally distinct, but not necessarily incompatible, ways in which the Universe organises motion.

Quantum scale (h). Planck’s constant sets the scale of quantised action. Microscopic organisation appears through the formation of stable quantum microstructures—bound states, coherent wave modes, orbital motion—all constrained by commutation relations,

$$[A, B] = i\hbar C,$$

which encode symmetry transformations under $\text{SO}(3, 1)$ at the level of Hilbert space.

Gravitational scale (G). Newton’s constant governs the curvature of space-time under macroscopic energy–momentum distributions. Large-scale order emerges through the formation of stars, galaxies, and cosmic structure, with dynamics governed by the Einstein field equation,

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}.$$

Thus h regulates microscopic ordered motion, while G regulates macroscopic

ordered motion. The question is not whether these principles conflict but whether they communicate across scales.

8.2 Dissipation as a Plausible Interface

Despite their differences, both scales share the same underlying Lorentzian symmetry. What they lack is an intrinsic *scale-bridging mechanism*: quantum theory expresses reversible dynamics in state space, while general relativity expresses reversible dynamics in spacetime geometry.

Dissipation offers a conceptually natural candidate for such a bridge. It redistributes energy from coherent macroscopic motion into microscopic fluctuations, and conversely allows fluctuations to produce smooth, coarse-grained fields.

Let $T^{\mu\nu}$ be a coarse-grained energy-momentum tensor associated with a collection of microscopic constituents. Decomposing individual momenta as

$$p_i^\mu = m_i u^\mu + q_i^\mu, \quad \sum_i q_i^\mu = 0,$$

identifies u^μ as macroscopic ordered motion and q_i^μ as microscopic unordered motion. Transfer between these sectors is dissipative, producing heat flux and viscous stress at the continuum level:

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu + pg^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu + \pi^{\mu\nu}.$$

Within GR, such terms produce deviations from geodesic flow:

$$u^\mu \nabla_\mu u^\nu = a_{\text{diss}}^\nu, \quad a_{\text{diss}}^\nu u_\nu = 0,$$

suggesting that microscopic fluctuations (ultimately regulated by \hbar) may manifest at macroscopic scales as geometric corrections, consistent with the Einstein equation.

These considerations indicate that dissipation is not merely thermal noise, but a mathematically natural candidate for mediating information between the quantum and gravitational regimes.

8.3 Dissipation as a Scale-Connecting Mechanism

If dissipation acts as an interface, then micro- and macro-scales could be linked in the following structurally coherent way:

1. Microscopic physics (governed by \hbar) generates stable quantum microstructures.

2. Dissipation coarse-grains their fluctuations, producing smooth, continuum fields with nontrivial $T^{\mu\nu}$.
3. Spacetime geometry responds to $T^{\mu\nu}$ through the Einstein equation, with strength set by G .
4. Curvature then shapes the long-wavelength evolution of matter, completing a feedback loop.

This picture does not imply that dissipation is the *only* possible bridge. Rather, it is a mechanism that fits naturally within the existing mathematical structures of GR and QM, respects Lorentz invariance, and provides an irreversible ingredient that is otherwise missing from both fundamental theories.

8.4 A Unified View of Motion

Both h and G impose organising principles under the same Lorentzian symmetry group:

- h structures microscopic motion through quantisation,
- G structures macroscopic motion through curvature,
- dissipation, if present, transfers information and energy between the two.

In this view, unification does not entail merging the dynamical equations of GR and QM, but recognising how scale-dependent structures interact. Dissipation provides one plausible route by which microscopic disorder and macroscopic geometry may jointly produce the observed hierarchy of order in the Universe.

9 Three-Layer Physics: Geometry, Dissipation, and Microstates

The analysis suggests that modern physics may naturally be organised into three conceptual layers. These layers do not constitute a new physical theory; they synthesise well-established structures from general relativity, quantum mechanics, kinetic theory, and non-equilibrium thermodynamics.

9.1 Layer 1: Geometry as the Primary Interaction Structure

At the foundational level, the Lorentz group $SO(3, 1)$ constrains all physical interactions. The metric tensor $g_{\mu\nu}$ enforces this symmetry, determining causal structure, geodesics, and curvature via the Einstein tensor $G_{\mu\nu}$. On this purely geometric layer, physics is conservative and fully reversible.

9.2 Layer 2: Dissipation as an Intermediate, Coarse-Grained Layer

The second layer introduces dissipative behaviour, represented by heat flux q^μ , viscous stress $\pi^{\mu\nu}$, and entropy production:

$$\nabla_\mu s^\mu \geq 0.$$

These quantities arise only after coarse-graining over microstates. Dissipation perturbs geodesic motion,

$$u^\mu \nabla_\mu u^\nu = a_{\text{diss}}^\nu,$$

and influences curvature through its contribution to the total stress-energy tensor,

$$G_{\mu\nu} = 8\pi T_{\mu\nu}.$$

This layer is the natural home of irreversible processes and may mediate between the microscopic and geometric regimes.

9.3 Layer 3: Microstates and the Quantum Scale

The deepest layer consists of quantum microstates constrained by \hbar . Here motion is expressed through transformations of state vectors or density matrices, governed by operator algebras. The geometry of state space differs from spacetime geometry, yet both respect Lorentz symmetry in their generators. Microscopic fluctuations can feed into the dissipative layer through coarse-graining.

9.4 Unification Across Scales

The three layers form a hierarchical but interdependent structure:

$$\text{Microstates } (\hbar) \longrightarrow \text{Dissipation} \longrightarrow \text{Geometry } (G_{\mu\nu}).$$

While this hierarchy leaves open alternative mechanisms for unification, it highlights dissipation as a conceptually natural route: it preserves Lorentz invariance, incorporates irreversibility, and matches the observed organisation of physical systems from the microscopic to cosmological scales.

9.5 Conclusion

Physics may achieve coherence not through reducing all layers to one, but through recognising how these layers interlock. Geometry provides the framework for macroscopic motion, quantum microstates supply the foundational degrees of freedom, and dissipation—while not the only possible mechanism—offers a plausible and structurally consistent interface between them. Any successful unification must respect this multi-layer organisation of physical structure.

A Dissipation as the Structurally Required Interface Between Quantum and Geometric Dynamics

In this appendix we formalise the motivation for the claim that dissipative processes provide the only structurally consistent interface between quantum mechanics and general relativity. The argument is not that dissipation is the only conceivable mechanism, but that *among mechanisms compatible with Lorentz invariance, energy–momentum conservation, and coarse-graining*, dissipation is the unique one that can mediate the observed irreversible behaviour of macroscopic systems.

The key insight is that the distinction between *ordered* and *unordered* motion is scale-independent. It appears in quantum theory, classical continuum physics, fluid dynamics, and general relativity.

A.1 Ordered and Unordered Motion at All Scales

Let a physical system possess a dynamical variable X (state vector, density matrix, fluid velocity, etc.). We distinguish:

- **Ordered motion:** the coherent, symmetry-compatible evolution of X obtained from extremising an action, reversible and lossless.
- **Unordered motion:** fluctuations of X that do not arise from symmetry-generated reversible dynamics and cannot be represented as extremal action

flows.

This structural decomposition appears at every scale:

- **Quantum mechanics.** Pure states evolve unitarily (ordered), while decoherence transfers coherence into environmental degrees of freedom (unordered).
- **Continuum physics.** The macroscopic velocity u^μ is ordered, whereas microscopic deviations q_i^μ are unordered:

$$p_i^\mu = m_i u^\mu + q_i^\mu, \quad \sum_i q_i^\mu = 0.$$

- **General relativity.** Geodesic motion represents ordered motion, while heat fluxes q^μ and viscous stresses $\pi^{\mu\nu}$ encode unordered motion arising from coarse-graining.

Thus “ordered” versus “unordered” is not a matter of scale; it is a universal structural distinction.

A.2 Fundamental Reversibility of QM and GR

Fact 1. *Quantum mechanics and general relativity are both fundamentally reversible.*

Quantum mechanics. For a closed quantum system,

$$|\psi(t)\rangle = U(t)|\psi(0)\rangle, \quad U^\dagger U = I.$$

No entropy is produced; the evolution preserves ordered motion exactly.

General relativity. With the Einstein equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu},$$

and the covariant conservation law

$$\nabla_\mu T^{\mu\nu} = 0,$$

energy–momentum flows are reversible. Pure GR contains no mechanism to convert ordered motion into unordered microscopic fluctuations.

Hence neither theory can generate intrinsic irreversibility.

A.3 Dissipation in QM and GR

Fact 2. *The only irreversible processes compatible with the structures of QM and GR are:*

- **decoherence** in quantum mechanics, and
- **viscous/entropic stresses** in relativistic continuum physics.

Both arise from coarse-graining and both are forms of dissipation.

Quantum mechanics (decoherence). Environmental entanglement redistributes coherence:

$$\rho \longrightarrow \rho' = \text{Tr}_{\text{env}}(U \rho_{\text{tot}} U^\dagger),$$

transforming ordered (unitary) motion into unordered environmental fluctuations.

Relativistic continuum physics. After coarse-graining over microscopic degrees of freedom,

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu + pg^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu + \pi^{\mu\nu}.$$

The dissipative terms produce geodesic deviation:

$$u^\mu \nabla_\mu u^\nu = a_{\text{diss}}^\nu, \quad a_{\text{diss}}^\nu u_\nu = 0,$$

where q^μ and $\pi^{\mu\nu}$ are precisely the unordered components.

Thus decoherence and relativistic dissipation are the *same structural operation*: conversion of ordered motion into unordered fluctuations.

A.4 Main Proposition

Proposition. *Any conceptual framework that unifies quantum mechanics and general relativity must include dissipative structure at the interface. No reversible interface can bridge two fundamentally reversible theories while producing the irreversible macroscopic behaviour observed in nature.*

Proof

1. QM and GR both generate strictly reversible, order-preserving dynamics.
2. Macroscopic systems exhibit irreversible behaviour (entropy growth).
3. A reversible theory cannot generate irreversibility:

- Liouville theorem (classical),
 - von Neumann entropy conservation (quantum),
 - $\nabla_\mu T^{\mu\nu} = 0$ (GR).
4. Therefore irreversible behaviour must arise from mechanisms not contained in pure QM nor in pure GR.
 5. The only irreversible mechanisms compatible with Lorentz symmetry, energy-momentum conservation, and microphysical coarse-graining are:
 - quantum decoherence,
 - relativistic heat flux and shear stress.
 6. Both mechanisms correspond to the same structural transformation:

ordered motion \longrightarrow unordered fluctuations.

7. Therefore the only consistent interface between QM and GR that can produce the observed irreversible macroscopic world is *dissipation*.

Dissipation is the structurally required scale-connecting interface.

□

A.5 Structural Summary

The ordered/unordered split applies at all physical scales. Dissipation converts ordered motion into unordered fluctuations, enabling entropy production. Since QM and GR lack internal irreversible mechanisms, any unification must introduce dissipative structure at the interface.

This motivates the three-layer perspective developed in the main text:

microstates (quantum) \longrightarrow dissipation (coarse-graining) \longrightarrow geometry (GR).

B The Planck Cell as a Candidate Interface Scale

This appendix develops a speculative but conceptually motivated hypothesis: that the dissipative interface between microscopic quantum dynamics and macroscopic

geometric dynamics may require a minimal coarse-graining scale. This scale is naturally identified with the Planck cell, the elementary spatiotemporal unit determined by the Planck length ℓ_P and Planck time t_P . The argument is not empirical but structural, based on the interplay between quantisation, geometric curvature, and dissipative irreversibility.

B.1 Motivation: Dissipation Requires Coarse-Graining

Dissipation, as formalised in Appendix A, is the irreversible transfer of ordered motion into unordered microscopic fluctuations. Such a transfer presupposes:

1. a decomposition into ordered and unordered components;
2. a mechanism for redistributing energy between these components;
3. a scale at which this decomposition is meaningful.

In classical hydrodynamics this scale is the “continuum cell.” In statistical mechanics it is the “thermodynamic limit.” But quantum mechanics and general relativity lack any *a priori* coarse-graining scale. Both theories are local and reversible at all mathematically allowed resolutions. Thus neither can independently define the scale at which dissipation becomes well-defined.

B.2 Scaling Incompatibility Without a Minimal Cell

The three universal constants c , h , and G set incompatible scaling relations:

- c defines causal structure (hyperbolic rotations);
- h defines quantum of phase-space area (microscopic structure);
- G defines coupling of geometric curvature (macroscopic structure).

From these one constructs the Planck length and time,

$$\ell_P = \sqrt{\frac{hG}{c^3}}, \quad t_P = \frac{\ell_P}{c},$$

which uniquely connect the three fundamental constants.

Observation. Below the Planck scale, the characteristic geometric curvature predicted by G and the characteristic quantum fluctuations predicted by h cannot be treated within a self-consistent continuum description. Each sector demands incompatible resolutions of the underlying degrees of freedom.

Thus the Planck scale appears as the unique point where the fundamental constants define a common resolution.

B.3 The Planck Cell as a Consistency Condition

Define a *Planck cell* as the smallest region of spacetime whose size simultaneously satisfies:

1. quantum resolution limit: $\Delta x \Delta p \geq \hbar/2$;
2. geometric resolution limit: curvature $R \sim 1/\ell^2$ remains finite;
3. causal resolution limit: signals propagate no faster than c .

Within such a cell, the notions of “microscopic” and “macroscopic” are not yet distinguished. But at scales *larger* than the Planck cell, coarse-graining becomes meaningful, and dissipative redistribution of energy can be consistently defined.

In this sense, the Planck cell provides the minimal “semantic unit” for translating microscopic quantum fluctuations into effective fields that couple to geometry.

B.4 Dissipation Requires a Minimal Semantic Scale

Let E_{ord} and E_{unord} denote ordered and unordered motion within a spacetime region \mathcal{R} . The dissipation rate inside \mathcal{R} is schematically

$$\dot{S} \sim \frac{E_{\text{ord}}}{\Delta V \Delta t},$$

where ΔV is the coarse-graining volume.

As $\Delta V \rightarrow 0$, the dissipative entropy production density diverges:

$$\dot{S} \rightarrow \infty,$$

because the same finite transfer of ordered energy is placed into an infinitesimally small region. This divergence implies:

No dissipative continuum theory can be consistent at arbitrarily small spatiotemporal scales.

Thus dissipation *requires* a minimal cell volume ΔV_{min} .

If one insists that this minimal cell be compatible with c , \hbar , and G simultaneously, the only natural candidate is the Planck cell.

B.5 Proposition: The Planck Cell as the Dissipative Interface Scale

Proposition (Speculative). *If dissipation is the interface that connects quantum dynamics (regulated by \hbar) and geometric dynamics (regulated by G), then the interface must occur at or above a minimal coarse-graining scale set by the Planck cell. Below this scale, neither the quantum nor geometric sectors support a consistent definition of dissipative redistribution of motion.*

Sketch of Argument

1. Dissipation requires coarse-graining of microstates.
2. Without a minimal cell, coarse-graining can be performed at arbitrarily small scales.
3. At such scales, quantum fluctuations (\hbar) and curvature fluctuations (G) become unbounded.
4. The dissipative entropy-production density diverges as $\Delta V \rightarrow 0$, rendering the continuum description inconsistent.
5. The only scale that simultaneously controls quantum fluctuations, geometric curvature, and causal structure is the Planck scale.
6. Therefore dissipation can be consistently defined only at or above this scale.

The Planck cell is a natural candidate for the dissipation interface scale.

B.6 Conclusion

This appendix does not claim that the Planck scale *is* the dissipative interface. Instead, it shows that:

- dissipation requires a minimal coarse-graining cell;
- the Planck scale is the only scale compatible with c , \hbar , and G ;
- below this scale, neither geometry nor quantisation nor dissipation can be consistently defined.

Thus the Planck cell provides a natural and structurally motivated candidate for the boundary between microscopic quantum dynamics and macroscopic geometric dynamics, consistent with the multi-layer framework developed in the main text.

References

- [1] J. W. Krol, *From Rotational Invariance to the Einstein Equation: A Conceptual Chain from Algebra to Geometry*, Essay, 2025.
- [2] P. Jordan and J. von Neumann, *On Inner Product Spaces*, Annals of Mathematics (1935).
- [3] R. M. Wald, *General Relativity*, University of Chicago Press (1984).
- [4] D. Hestenes, *New Foundations for Classical Mechanics*, Kluwer Academic Publishers, 1999.
- [5] C. Doran and A. Lasenby, *Geometric Algebra for Physicists*, Cambridge University Press, 2003.