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VTT Foundational Mathematics, Part II: Emergence of the Informational Tensor and the Crystallization of the Metric

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Abstract

In Part I of the Viscous Time Theory (VTT) program, an informational action principle was introduced, leading to an emergent coherence tensor, viscosity-modified covariant dynamics, and an effective metric induced by informational structure. While this framework explains how geometric notions can arise from informational coherence, a central question remains: under what conditions does an autonomous informational stress-energy tensor emerge as a physically meaningful source term? In this work, we address this question by developing a controlled theory for the *birth* of the VTT tensor as an independent dynamical object. Building on the informational Hessian, coherence gradients, and logical viscosity introduced previously, we identify a critical regime in which accumulation and friction between transduction and memory degrees of freedom can no longer be absorbed into purely geometric terms. In this regime, a non-vanishing tensorial source nucleates. We formulate a precise emergence criterion based on Hessian criticality, derive the leading-order structure of the resulting tensor via a frictional commutator construction, and obtain scaling laws governing its onset near the critical point. We further extract concrete, falsifiable diagnostics that distinguish the purely geometric phase from the source-driven phase, including soft-mode divergence, accumulation thresholds, anisotropic stress patterns, and critical slowing down. Finally, we outline both numerical strategies and an experimentally motivated cavity-QED–inspired protocol to probe this transition. Together, these results extend the VTT framework from emergent geometry to emergent sources, providing a mathematically controlled pathway toward an informational formulation of back-reaction, metric crystallization, and source dynamics.

Keywords: Viscous Time Theory (VTT); informational geometry; emergent stress-energy tensor; Hessian criticality; coherence and accumulation dynamics; metric crystallization; non-equilibrium informational dynamics; cavity QED probes of emergence

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1. Introduction

In the first part of the Viscous Time Theory (VTT) mathematical foundations, an informational variational principle was introduced to describe the dynamics of coherence fields, leading to the emergence of an informational curvature tensor, a viscosity-modified covariant derivative, and an effective metric induced by coherence structure rather than imposed a priori [1]. Within this framework, geometric notions such as curvature, focusing, and expansion arise as macroscopic manifestations of deeper informational processes, and a Raychaudhuri-like identity governs the evolution of coherence congruences in an emergent spacetime geometry [2].

This construction places VTT in dialogue with a long tradition of attempts to interpret gravity and geometry as emergent phenomena rather than fundamental primitives [3–5] rather than fundamental, ranging from thermodynamic and entropic scenarios to information-theoretic and quantum-informational perspectives [6,7]. In these approaches, metric and curvature are not primary objects but effective descriptors of underlying microscopic or informational dynamics [3–7]. Part I of the VTT framework follows this line by showing how an informational action and coherence functional give rise to a well-defined geometric sector, including an emergent metric and curvature tensor [1].

However, a central conceptual and mathematical gap remains. In standard gravitational theories, geometry is not only shaped by internal consistency conditions but is also sourced by stress-energy content through field equations. In the VTT framework developed in Part I, the coherence tensor and emergent metric exist, but no autonomous informational stress-like tensor has yet been identified as a genuinely independent source term. In other words, while geometry emerges, the theory still lacks a precise criterion for when and how a source—interpretable as informational "matter," memory, or accumulated structure—comes into existence as a distinct dynamical entity.

The purpose of the present work is to address this gap by formulating a mathematically controlled theory of the emergence of the VTT tensor as an autonomous object. Rather than postulating such a tensor from the outset, we seek conditions under which it necessarily appears from the underlying informational dynamics already defined in Part I. The central idea explored here is that the interplay between coherence gradients, logical viscosity, and the informational Hessian leads to a critical regime in which accumulation and friction between transduction and memory degrees of freedom can no longer be absorbed into purely geometric terms. At this point, a non-vanishing tensorial source nucleates and becomes dynamically relevant.

More specifically, we identify a criticality condition characterized by the softening of Hessian eigenmodes and the divergence of characteristic accumulation timescales. In this regime, a frictional commutator between informational flows generates a leading-order tensorial structure that can be interpreted as the VTT stress-like tensor. We derive the general form of this object, establish scaling laws near the critical point, and propose a set of diagnostic signatures that distinguish the purely geometric phase from the source-driven phase of the theory.

Beyond the formal derivation, we also outline concrete strategies for probing this transition. These include numerical parameter sweeps in lattice-based coherence models and an experimentally motivated protocol inspired by cavity quantum electrodynamics, designed to detect accumulation thresholds, critical slowing down, and tensorial back-reaction. In this way, the present work extends the VTT program from emergent geometry to emergent sources, providing a bridge between informational microdynamics and macroscopic, source-driven effective laws.

This paper is organized as follows. In Section 2 we recall the essential mathematical structures introduced in Part I, fix notation, and present the theoretical framework and methods leading to the emergence criterion, including the informational Hessian analysis, the frictional commutator, and the unified action principle. In Section 3 we present the main results: the eigenspectrum of the newborn tensor, the formation of informational geodesics, the role of IRSVT (Informational Resonance Spiral Viscous Time) spiral modes, the definition of an informational Planck scale, and the associated experimental and numerical signatures. In Section 4 we discuss the broader implications of these results, including metric crystallization, the informational origin of mass, entropy, and the arrow of time. Finally, Section 5 summarizes the main conclusions and outlines directions for future work.

2. Theoretical Framework and Methods

The present work builds directly on the VTT formalism introduced in Part I, where the informational coherence field, the coherence tensor, the viscosity-modified dynamics, and the emergent metric structure were defined. Here, we do not repeat those constructions. Instead, we specify the subset of mathematical structures and methodological tools required to analyze the emergence of an autonomous VTT tensor in the critical regime.

Part I established that a coherence functional and its second variation give rise to an informational coherence tensor ΔC and an emergent metric g_C. However, it left open the precise conditions—the locus, dynamical regime, and control parameters—under which the informational tensor that acts as a physical stress-like source (hereafter $T_{\mu\nu}^{\mathrm{VTT}}$) first materializes as an autonomous,

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detectable object rather than a mere calculational derivative. The present work addresses this question.

Our strategy is as follows:

1. We formalize the generator of $T_{\mu\nu}^{\mathrm{VTT}}$ as the non-commutativity (or frictional commutator) between transduction and memory/irreversibility operators, schematically $[\nabla_{\Phi}, \Delta Q] \neq 0$.

2. We show how this non-commutativity becomes an actual tensor field when (a) the informational Hessian approaches viscous criticality (small determinant or eigenvalue crossing) and (b) accumulation and time-scale separation drive nonlinear amplification.

3. We derive scaling relations and a minimal emergence theorem, establishing both existence and leading-order structure of $T_{\mu\nu}^{\mathrm{VTT}}$.

4. We map the theoretical framework to experiment via a cavity-QED-inspired protocol that searches for the accumulation threshold (an operational "birth" point) and identifies observables and falsifiable signatures.

2.1. Minimal Mathematical Ingredients

All calculations in this paper assume the informational action principle, coherence tensor ΔC, and emergent metric $g(C)$ introduced in Part I. The goal of the present analysis is not to modify that framework, but to identify the conditions under which a new, independent tensorial source term necessarily appears within it.

Accordingly, we focus on three ingredients already present in the theory:
(i) the informational Hessian governing stability and response,
(ii) the viscosity-controlled accumulation dynamics, and
(iii) the non-commutativity between transduction and memory flows.

These elements are combined to construct an operational emergence criterion and a generator for the VTT tensor.

In Part II we reuse the notation of Part I. In particular, we denote by $\Phi^{i}(x,\tau)$ the informational transduction or flow field (with index i labeling components and τ the viscous or relaxation parameter), by $\Delta C(x,\tau)$ the coherence curvature or density (scalar or rank-2 object depending on the model), and by $\eta_i(\tau)$ the informational viscosity (memory kernel, scalar or one-form). We further denote by ΔQ the retrocausal or irreversibility momentum, representing a finite minimal quantum of irreversibility as described in the Part I summary.

The informational Hessian is written as

$$\mathcal{H}_{ij} = \partial_i\,\partial_j \Delta C + \lambda\ \partial_i\,\partial_j \Phi + \mu\ \partial_i\,\partial_j \eta, \qquad (1)$$

and stability or criticality conditions are read from the spectrum of $\mathcal{H}$. We also employ the viscosity-modified covariant derivative $\widetilde{\nabla}$ defined in Part I and denote by $g_{C\,\mu\nu}$ the emergent metric induced by ΔC.

Viscosity and Accumulation Dynamics

Logical viscosity η, introduced in Part I, controls the rate at which coherence variations relax and determines the effective memory of the system. In addition to instantaneous coherence gradients, the dynamics therefore involves accumulated informational quantities, denoted by ΔQ, which encode persistent effects of past evolution.

Methodologically, we analyze the competition between the coherence relaxation timescale and the accumulation timescale set by η and ΔQ. In the regular regime, these timescales remain finite and the accumulated contributions can be absorbed into the geometric sector. Near criticality, however, the accumulation timescale grows and may diverge, signaling the breakdown of a purely geometric description and preparing the conditions for the emergence of an autonomous tensorial source term.

2.2. Pre-Tensor Regime (Informational Plasma Phase)

Before the VTT tensor emerges, information exists in a non-differentiable, non-metric, pre-coherent state. We refer to this regime as the *Informational Plasma Phase* (IPP). This phase represents the pre-geometric stage of the theory, in which no tensorial or metric structure is yet available.

The Informational Plasma Phase is characterized by the following properties:

- No spacetime metric exists.
- No geodesics can be defined.
- The information potential $\Phi$is scalar but non-local.
- Gradients are undefined, although fluctuations $\delta\Phi$exist.
- There is no directionality, no causality, and no ordered flow.
- The state is statistically isotropic but not dynamically symmetric.

We characterize this plasma by a pure potential field

$$\Phi_0 : I \to \mathbb{R}, \text{with } \nabla\Phi_0 \text{ undefined,} \tag{2}$$

while fluctuations exist at the level of variance,

$$\mathrm{Var}(\Phi_0) > 0. \tag{3}$$

At this stage, information cannot carry curvature, since curvature requires a second-order relational structure, which does not yet exist. The IPP therefore serves as the pre-tensor initial condition from which the emergence process analyzed in the following sections departs.

2.3. Informational Hessian and Stability Analysis

The central diagnostic tool in this work is the informational Hessian $\mathcal{H}$, defined in Part I as the second functional derivative of the coherence functional with respect to the underlying informational degrees of freedom. The spectrum of $\mathscr{H}$determines the local stability of coherence configurations and provides a natural notion of proximity to criticality.

In the present analysis, we treat the smallest eigenvalues of $\mathscr{H}$ as control parameters. The approach to the critical regime is characterized by the progressive softening of one or more eigenmodes, leading to an increase in response times and enhanced sensitivity to coherence gradients. This spectral behavior is used as the primary indicator of the transition between a purely geometric regime—where accumulated effects can be absorbed into the emergent metric sector—and a source-generating regime, where an independent tensorial contribution becomes dynamically relevant.

2.3.1. Frictional Commutator as a Generator

To capture the interplay between transduction (instantaneous coherence transport) and memory (accumulated informational flow), we employ the frictional commutator structure introduced in the present work. This object is constructed from the viscosity-modified covariant derivatives defined in Part I and encodes the non-commutativity of these two modes of informational evolution.

Operationally, this commutator is used as the generator of the leading-order tensorial structure that appears beyond criticality. In the non-critical regime, it vanishes or remains dynamically irrelevant. In contrast, in the critical regime identified by the Hessian analysis, it becomes non-zero and provides the seed for an autonomous VTT tensor.

The emergent tensor $T_{\mu\nu}^{\mathrm{VTT}}$ must encode (i) directional flow, via gradients of Φ, (ii) curvature or strength of coherence, via ΔC, and (iii) memory or lag effects, via η and ΔQ. A minimal bilinear generator that captures these features is provided by the symmetric form built from gradients of Φ, ΔC, and commutators with ΔQ.

We define the frictional commutator operator as

$$\mathcal{F}_{\mu\nu} = \frac{1}{2}(\tilde{\nabla}_\mu\Phi \cdot \tilde{\nabla}_\nu\Delta Q - \tilde{\nabla}_\nu\Phi \cdot \tilde{\nabla}_\mu\Delta Q), \tag{4}$$

where $\tilde{\nabla}$ includes viscosity corrections and thus encodes memory dependence. The antisymmetric part captures pure geometric misalignment, while the symmetric projection yields a stress-like object. Accordingly, we write

$$T_{\mu\nu}^{\mathrm{VTT}} \propto \widetilde{\nabla}_\mu \Phi\, \widetilde{\nabla}_\nu \Delta Q + \kappa\, \Delta C\, S_{\mu\nu}(\Phi), \qquad (5)$$

with $S_{\mu\nu}(\Phi)$ the symmetric traceless local shear of Φ (as in the Informational Gravity manuscript) and κa coupling constant. This ansatz parallels the construction used in Informational Gravity while emphasizing the delayed (memory) role that ΔQ plays in converting flow gradients into a stress-like contribution.

Physically, the first term can be interpreted as a *frictional stress*: when the locally predicted transduction $\widetilde{\nabla}\Phi$ and the accumulated irreversibility $\widetilde{\nabla}\Delta Q$ are misaligned, a tensorial stress necessarily appears. The second term couples the coherence amplitude ΔC to the local shear of the flow, adding an anisotropic informational pressure.

2.4. Precise Emergence Conditions — Theorem Statement

We now state a minimal theorem giving necessary and essentially sufficient conditions for the appearance of a non-negligible tensor field $T_{\mu\nu}^{\mathrm{VTT}}$ whose dynamics can be treated as an autonomous source term, i.e., one that contributes to the emergent geometry and back-reacts on it.

Theorem (Emergence of the VTT Tensor).

Let the VTT system satisfy Axioms 1–5 of Part I (see in Appendix A) and assume a smooth family of informational Hessians $\mathcal{H}$. Let $\lambda_{\min}(x,t)$ denote the smallest eigenvalue of $\mathcal{H}$. Define the viscous relaxation time $\tau_\eta(x,t)$ associated with η, and define the accumulation timescale $\tau_{\mathrm{acc}} \sim 1/\rho$ (or its appropriate coarse-grained generalization). Suppose that:

1. *(Viscous criticality)* $\lambda_{\min}(x_0,t_0) \to 0^+$ at some (x_0, t_0) (i.e., the determinant of $\mathcal{H}$approaches zero or an eigenvalue crosses zero).
2. *(Timescale separation)* $\tau_\eta(x_0,t_0) \gtrsim \tau_{\mathrm{acc}}$, so that memory cannot relax faster than accumulation.
3. *(Non-commutativity)* $\left[\widetilde{\nabla}\Phi, \Delta Q\right]_{(x_0, t_0)} \neq 0$(finite frictional commutator).
4. *(Nonlinearity and amplification)* The coupling constant κa nd the accumulation amplitude are above a model-dependent threshold such that terms of order $\mathcal{O}(\Delta C \cdot \widetilde{\nabla}\Phi \cdot \widetilde{\nabla}\Delta Q)$ grow faster than dissipative sink terms.

Then, in a neighborhood of (x_0, t_0), there exists a non-trivial tensorial field $T_{\mu\nu}^{\mathrm{VTT}}(x,t)$ of leading order

$$T_{\mu\nu}^{\mathrm{VTT}} \sim \mathcal{O}\left(\widetilde{\nabla}_\mu \Phi\, \widetilde{\nabla}_\nu \Delta Q,\, \Delta C\, S_{\mu\nu}(\Phi)\right), \qquad (6)$$

which (i) is finite, (ii) contributes a non-negligible source to the effective emergent geometry (i.e., modifies $g_{C\,\mu\nu}$ at leading order), and (iii) is robust under small perturbations of initial conditions, provided conditions (1)–(4) hold.

Sketch of proof:

Condition (1) implies a large susceptibility of coherence curvature to small perturbations: a small eigenvalue amplifies any coupling to the corresponding soft mode.

Condition (2) prevents viscous damping from erasing the accumulated phase and opens a temporal window in which accumulation acts coherently.

Condition (3) ensures that flow and memory are not trivially aligned; their misalignment can be linearized and produces a lowest-order bilinear contribution.

Condition (4) guarantees that this bilinear term overcomes residual dissipation. Combining a Taylor expansion of the VTT Lagrangian about the critical point with projection onto the soft eigenmode of $\mathcal{H}$ yields a secular term whose spatial tensor structure is precisely the symmetric bilinear shown in (Equation 5)

Remarks.

- Condition (1) may be spatially local, so that the tensor can nucleate in a small patch before spreading.

- Condition (2) is operational: it corresponds to the same timescale inequality probed by the cavity-QED protocol (pulse rate versus probe relaxation).
- Condition (3) is the formal expression of the statement made in Part I that the tensor represents a friction between transduction and memory.

2.5. Derivation Strategy and Projection Method

Methodological Strategy

The emergence analysis presented in Section 3 proceeds in three steps. First, criticality is characterized through the spectral behavior of the informational Hessian. Second, the accumulation dynamics controlled by viscosity is shown to introduce a new, irreducible contribution that cannot be absorbed into the geometric sector. Third, the frictional commutator is evaluated in this regime to extract the leading-order tensorial structure and its scaling behavior near the transition.

This strategy relies exclusively on the mathematical structures already defined in Part I and does not introduce additional postulates. The results should therefore be understood as consequences of the existing VTT framework, rather than as independent assumptions.

Proof Sketch and Expanded Derivation Roadmap

Linearize the VTT Lagrangian $\mathcal{L}[\Phi, \Delta C, \eta]$ about a near-critical background $(\Phi_0, \Delta C_0, \eta_0)$ and extract the quadratic form operator $\mathcal{L}^{(2)}$.

1. Compute the second variation and identify the informational Hessian $\mathcal{H}$, whose principal symbol defines the soft mode.
2. Project the cubic coupling terms that mix $\Phi$and ΔQonto the soft eigenmode $e(x)$, and show secular growth of the modal amplitude $a(t)$ when the forcing (accumulation) term overcomes viscous damping.
3. Reconstruct the leading-order tensor in physical coordinates by computing the symmetric bilinear of gradients of Φ and ΔQ projected onto the soft mode. This yields Equation (5) at leading order.
4. Estimate the threshold by solving the amplitude equation for $a(t)$, obtaining the critical density ρ_c as a function of η, κ, and the small eigenvalue λ.

2.6. Unified VTT Action and Lagrangian Formulation

We seek a single, self-contained action S_{VTT} whose Euler–Lagrange equations reproduce, in appropriate limits, the core field equations of Viscous Time Theory: coherence transport, informational potential dynamics, retrocausal ΔQ quantization, the informational Hessian structure, and the emergence and back-reaction of the VTT tensor. This construction provides a unifying variational foundation for Parts I–II and establishes a controlled path toward quantization and discrete–continuum correspondence.

2.6.1. Guiding Principles and Field Content

The action is constructed according to the following principles:

1. **Informational primacy:** the action is built from $(\Delta C, \Phi, \Delta Q, \eta)$, not from a pre-existing spacetime metric.
2. **Viscous (dissipative) structure:** non-Hamiltonian terms encode irreversibility in viscous time τ.
3. **Discrete–continuum correspondence:** the formulation admits both lattice and smooth limits.
4. **ΔQ conjugacy:** ΔQ plays the role of a (near-)canonical conjugate to Φ, with a minimal quantum $\Delta Q_{\min}$.
5. **Back-reaction and tensor emergence:** the action must generate a stress-like object identified with $T_{\mu\nu}^{\mathrm{VTT}}$when the emergence conditions of Sections 2.3–2.5 are met.

We use the same fields and notation introduced in Section 2.1 and in Part I, namely the informational transduction field $\Phi(x,\tau)$, the coherence density/curvature $\Delta C(x,\tau)$, the

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retrocausal displacement $\Delta Q(x,\tau)$, and the informational viscosity $\eta(x,\tau)$. The action is formulated on the informational manifold $\mathcal{M}_I$ with coordinates x^μ and viscous time τ. An optional gauge field A_μ may be introduced if Φ is promoted to a gauge multiplet.

2.6.2. Lagrangian Density (Ansatz)

We propose the schematic local Lagrangian density

$$\mathcal{L}_{\mathrm{VTT}} = \mathcal{L}_{\Delta C} + \mathcal{L}_{\Phi} + \mathcal{L}_{\Delta Q} + \mathcal{L}_{\eta} + \mathcal{L}_{\mathrm{int}} + \mathcal{L}_{\mathrm{diss}}, \quad (7)$$

with components:

Coherence sector

$$\mathcal{L}_{\Delta C} = \frac{1}{2} G_C^{\mu\nu}(\Delta C)\ \partial_\mu \Delta C\ \partial_\nu \Delta C - V_C(\Delta C), \quad (8)$$

where $G_C^{\mu\nu}$ is a positive semi-definite operator related to the informational Hessian in the linearized regime.

2. **Transduction sector**

$$\mathcal{L}_{\Phi} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_\Phi^2 \Phi^2, F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad (9)$$

when Φ is embedded in a gauge multiplet.

Retrocausal sector

$$\mathcal{L}_{\Delta Q} = \Delta Q\ D_\tau \Phi - \frac{1}{2} M_Q^{-1} (\Delta Q)^2, \quad (10)$$

which is first order in D_τ and establishes the canonical structure.

Viscosity sector

$$\mathcal{L}_{\eta} = -\frac{1}{2} \eta(x,\tau)(D_\tau \Delta C)^2 - U_\eta(\eta), \quad (11)$$

encoding dissipative corrections.

Interaction (source of tensor emergence)

$$\mathcal{L}_{\mathrm{int}} = \kappa_1\ \Delta C\ \partial_\mu \Phi\ \partial_\nu \Delta Q\ H^{\mu\nu}(\Delta C,\eta) + \kappa_2\ \Delta C\ S^{\mu\nu}(\Phi) S_{\mu\nu}(\Phi), \quad (12)$$

where $H^{\mu\nu}$ projects onto soft Hessian modes and $S_{\mu\nu}$ denotes the shear of Φ.

Dissipative corrections are treated at the level of equations of motion via a memory kernel $\mathcal{N}[\Delta C]$, in the spirit of influence-functional approaches.

2.6.3. Action Principle and Euler–Lagrange Equations (Schematic)

The action over a viscous-time slab $[\tau_1, \tau_2]$ is

$$S_{\mathrm{VTT}} = \int_{\tau_1}^{\tau_2} d\tau \int_{\mathcal{M}_I} d^n x\ \mathcal{L}_{\mathrm{VTT}}. \quad (13)$$

Stationarity $\delta S_{\mathrm{VTT}} = 0$ (with dissipative terms handled separately) yields coupled, nonlinear, generally non-local field equations.

Action principle and Euler–Lagrange equations (explicit form).

For each field $X \in \{\Delta C, \Phi, \Delta Q, \eta\}$, stationarity gives

$$\frac{\partial \mathcal{L}_{\mathrm{VTT}}}{\partial X} - \partial_\mu \left(\frac{\partial \mathcal{L}_{\mathrm{VTT}}}{\partial(\partial_\mu X)}\right) - \mathcal{D}_\tau \left(\frac{\partial \mathcal{L}_{\mathrm{VTT}}}{\partial(\mathcal{D}_\tau X)}\right) = 0, \quad (14)$$

with the understanding that dissipative/memory terms in $\mathcal{L}_{\mathrm{diss}}$ contribute nonlocal (kernel) variations treated in the standard influence-functional manner.

ΔC equation (show the "Hessian principal symbol" term + source)**:**

$$\partial_\mu \left(G_{\mu\nu}^C(\Delta C)\ \partial_\nu \Delta C\right) + \frac{\partial V_C}{\partial \Delta C} = \kappa_1\ \partial_{\Delta C}\left[\Delta C\ \partial_\mu \Phi\ \partial_\nu \Delta Q\ H^{\mu\nu}\right] + \kappa_2\ \partial_{\Delta C}\left[\Delta C\ S_{\mu\nu}(\Phi) S^{\mu\nu}(\Phi)\right] + \cdots (15)$$

Φ equation (include the ΔQ canonical term and probe coupling):

$$\mathcal{D}_\tau \Delta Q + m_\Phi^2 \Phi + \cdots = -\kappa_1\ \partial_\mu(\Delta C\ \partial_\nu \Delta Q\ H^{\mu\nu}) - 2\kappa_2\ \partial_\mu(\Delta C\ S^{\mu\nu}(\Phi)) - g_p\ O_{\mathrm{probe}} + \cdots \ (16)$$

Note: probe coupling is shown in Equation (22).

ΔQ equation (canonical conjugacy):

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$$\mathcal{D}_\tau \Phi - M_Q^{-1} \Delta Q = -\kappa_1\, \partial_\nu \left(\Delta C\, \partial_\mu \Phi\, H^{\mu\nu}\right) + \cdots \quad (17)$$

η equation (algebraic or slow dynamics, depending on your U_η):

$$-\frac{1}{2}(\mathcal{D}_\tau \Delta C)^2 - \frac{\partial U_\eta}{\partial \eta} + \cdots = 0. \quad (18)$$

In the soft-mode regime where $H^{\mu\nu}$ projects onto the lowest Hessian eigenmode, the leading contribution of the κ_1- term is a symmetric bilinear in $\partial\Phi$ and $\partial\Delta Q$, which is precisely the structure summarized in Equation (5) at leading order after projection onto e_{soft}.

A fully expanded component form of these equations is lengthy but straightforward and follows by standard functional differentiation of Eqs. (7–12); here we display only the principal symbols and source structures relevant near criticality.

In the linearized regime, these equations reduce to the VTT field equations of Part I and generate the bilinear source structure identified in Sections 2.3–2.5.

2.6.4. Emergent VTT Tensor from the Action

We define the informational stress tensor by functional differentiation with respect to the principal symbol $G_C^{\mu\nu}$:

$$T_{\mu\nu}^{\text{VTT}}(x,\tau) \equiv -2\frac{\delta S_{\text{VTT}}}{\delta G_C^{\mu\nu}(x,\tau)}. \quad (19)$$

To leading order near criticality, this yields

$$T_{\mu\nu}^{\text{VTT}} \sim \partial_\mu \Delta C\, \partial_\nu \Delta C + \kappa_1 \Delta C\, \partial_\mu \Phi\, \partial_\nu \Delta Q + \kappa_2 \Delta C\, S_{\mu\alpha} S^{\alpha}{}_{\nu} + \cdots , \quad (20)$$

and, when projected onto the soft Hessian mode, reproduces exactly the bilinear source term derived in Section 2.4. This provides an explicit variational origin for the emergent VTT tensor.

2.6.5 Symmetries and balance laws

If Φ is gauge-extended, the action is invariant under $A_\mu \to A_\mu + \partial_\mu \alpha$, leading to a conserved informational current in the limit of negligible dissipation. Because viscous terms break time-reversal invariance in τ, strict energy conservation is replaced by a balance law of the form

$$\partial_\tau \varepsilon + \nabla_\mu J^\mu = -\Gamma_{\text{diss}}, \quad (21)$$

with $\Gamma_{\text{diss}} \geq 0$ representing entropy production.

Discrete lattice realizations correspond to topological minima of S_{VTT}, whose winding or parity indices remain robust under viscous annealing, providing a bridge between discrete and continuum descriptions.

2.6.6. Discrete–continuum Correspondence and Quantization

The action admits a controlled lattice discretization whose second variation reproduces the informational Hessian, ensuring a consistent continuum limit. Canonical pairs (Φ, Π_Φ) and $(\Delta C, \Pi_C)$ can be identified, but explicit viscosity renders the dynamics non-unitary. Two consistent quantization routes are therefore natural: (i) open-system / influence-functional methods, or (ii) doubled phase-space (Schwinger–Keldysh) formulations. A detailed development is deferred to future work.

2.7. Coupling to Probes and Observables (Operational Method)

To establish an operational link between the VTT fields and measurable quantities, we couple a probe observable O_{probe} to the local transduction field Φ according to

$$\mathcal{L}_{\text{probe}} = g_p\, O_{\text{probe}}(x,\tau)\, \Phi(x,\tau). \quad (22)$$

Within linear response, this coupling defines a susceptibility $\chi_{O\Phi}(\omega)$. In the vicinity of criticality, where a soft mode emerges, the susceptibility is expected to diverge as $\lambda_{\min} \to 0$. This divergence provides an operational signature of the tensor nucleation point. By fitting probe time series to the response functions derived above, one can extract both $\lambda_{\min}$ and the projected components of $T_{\mu\nu}^{\text{VTT}}$ using the projection formulae introduced earlier.

In the theoretical analysis above, tensor emergence is characterized as a critical phenomenon driven by soft-mode amplification and accumulation dynamics. The probe coupling introduced here provides an operational handle on this transition: below threshold the response remains linear and geometry-only, while near and above the critical point the susceptibility diverges and nonlinear back-reaction becomes observable. We now outline a concrete cavity-QED implementation designed to detect this transition in practice

Physically, this interaction corresponds to a dispersive shift of the cavity resonance induced by the local informational transduction field Φ, analogous to an index-of-refraction modulation in standard cavity QED or optomechanics

2.7.1. Laboratory Program: Cavity-QED Probe

The cavity-QED protocol outlined in Part I is specifically designed to detect the emergence ("birth") point of the VTT tensor, characterized by the accumulation threshold ρ_c, the timescale inequality $\tau_\eta \gtrsim \tau_{\text{acc}}$, and the onset of nonlinear response in observables. The proposed experimental program proceeds as follows:

1. **Platform selection.** A small-volume, high-finesse cavity is employed, using either a single trapped atom (for maximal controllability) or an optomechanical membrane (for mechanical readout).
2. **Rate scan.** Heralded single photons are injected at controlled repetition rates, scanning $\rho$from below to above threshold while recording probe observables (phase, $g^{(1)}$, $g^{(2)}$, fidelity). The resulting traces are fitted to the accumulation model to detect departures from linear response and identify the threshold behavior.
3. **Multi-platform confirmation.** The protocol is replicated on at least two distinct platforms (e.g., atom and membrane) in order to exclude classical nonlinear optical effects (Kerr, thermal, etc.).
4. **Spatial mapping.** Where feasible, the probe position is scanned (or multiple probes are used) to reconstruct tensorial anisotropies and compare directional dependence with the numerical predictions derived from $\nabla\Phi$.
5. **Data analysis.** Mutual information between the injection sequence and the probe time series is computed, testing for a supralinear increase at threshold and for an increase in autocorrelation time (persistence) beyond the critical point.

Effective cavity coupling model.

For a single-mode cavity with annihilation operator a, we take the probe observable to be the intracavity photon number $O_{\text{probe}} = a^\dagger a$, yielding

$$\mathcal{H}_{\text{int}} = -g_p \int d^n x\, f(x)\, \Phi(x,\tau)\, a^\dagger a, \qquad (23)$$

where $f(x)$ is the cavity mode profile (or an effective overlap factor for the localized region being driven). In this minimal model, Φ modulates the cavity's effective refractive phase, producing an accumulated phase shift

$$\Delta\varphi(\tau) = g_p \int d\tau\, \langle \Phi(\tau) \rangle, \qquad (24)$$

and, through the κ_1-driven back-reaction, a correlated contribution that, in the geometric limit, reproduces the coherence-gradient line integral $\Delta\phi = \int \nabla\Delta C \cdot d\ell$ appearing in Equation (38)

2.8. Numerical Program (Concrete Implementation Steps)

The numerical implementation follows the discrete prescription introduced in Part I (lattice gradient descent, Hessian extraction, emergent metric reconstruction), augmented here with targeted diagnostics aimed at locating the tensor birth point.

1. **Parameter sweep.** Simulations are performed on grids of size $N = 128{,}256{,}512$, varying the anchor penalty λ, the viscosity η, and an injection-rate proxy ρ (simulated event density). The smallest Hessian eigenvalue $\lambda_{\min}(x,t)$ and its spatio-temporal minima are tracked.

2. **Eigenmode projection.** When $\lambda_{\min}$ becomes small, the dynamics are projected onto the corresponding soft eigenmode. The projected bilinear term $\langle e_{\text{soft}}, \nabla\Phi\, \nabla\Delta Q\rangle$ is computed to verify the predicted secular growth.
3. **Synthetic probe coupling.** A synthetic probe response kernel (the linear response function associated with $\mathcal{H}_{\text{int}}$) is introduced, and the synthetic probe observable $S(t)$is measured to generate simulated laboratory traces
4. **Extraction of critical exponents.** The scaling of the correlation time τ versus $\lambda_{\min}$ and versus $(\rho - \rho_c)$ is measured in order to estimate the critical exponent $\alpha$and identify the associated bifurcation class.
5. **Robustness checks.** Anchor positions, noise amplitude, and discretization scale are varied to test the reproducibility and stability of tensor nucleation.

This program provides a fully reproducible numerical pipeline linking the theoretical emergence criteria to synthetic observables and, ultimately, to experimental test strategies. Implementation note: Part I includes pseudocode and a MATLAB/Python skeleton which should be extended with eigenvalue monitoring; re-use that code base and add the soft-mode projector routines.

3. Results

3.1. Emergence of Geometry from the VTT Tensor

This section completes the causal chain of emergence by describing the structures that appear immediately after the VTT tensor nucleates. We analyze the initial eigen-decomposition of the tensor, the appearance of geodesics in informational space, the spectral role of the $\sqrt{2}$and $\sqrt{3}$ spiral eigenmodes, the existence of a purely informational quantization threshold analogous to a Planck scale, and finally the experimental signatures expected in a cavity-QED probe during tensor ignition.

3.1.1. Eigenstructure of the Newborn Tensor

At the moment of nucleation, the VTT tensor exhibits minimal rank and maximal symmetry breaking. To leading order, it takes the form

$$T_{\mu\nu}^{\text{VTT}} = S_{\mu\nu} + \lambda\, \eta\, g_{\mu\nu}^{(1)}, \quad (25)$$

where:

- $S_{\mu\nu} = \partial_\mu K_\nu + \partial_\nu K_\mu,$
- $g_{\mu\nu}^{(1)}$ is the first emergent informational metric,
- η carries the temporal memory (viscosity) of the system,
- λ regulates the coupling between curvature and viscosity.

The tensor admits a diagonal representation

$$T^{\text{VTT}} = Q\Lambda Q^{-1}, \Lambda = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4\}. \quad (26)$$

At the instant of birth, symmetry constraints impose

$$\lambda_1 = -\lambda_2, \lambda_3 = -\lambda_4, \quad (27)$$

which implies

$$\textstyle\sum_i \lambda_i = 0. \quad (28)$$

This traceless condition represents the informational signature of curvature genesis: a zero-trace stress-like object appearing prior to any stabilized energy density, in direct analogy with vacuum fluctuations preceding spacetime condensation.

3.1.2. Emergent Geodesics in Informational Space

Since no spacetime metric exists prior to tensor formation, classical geodesics are undefined. Instead, the system generates *informational geodesics* by extremizing the coherence action:

$$\delta \int \Delta C(\gamma(t))\, dt = 0. \quad (29)$$

This yields the proto-geodesic equation

$$\frac{d^2x^\mu}{dt^2} + \Gamma^{(\eta)\mu}_{\alpha\beta}\frac{dx^\alpha}{dt}\frac{dx^\beta}{dt} = 0, \quad (30)$$

where the informational Christoffel symbols are constructed from coherence gradients rather than from a spacetime metric:

$$\Gamma^{(\eta)\mu}_{\alpha\beta} = \frac{1}{2}g^{(1)\mu\nu}\left(\partial_\alpha\Delta C_{\beta\nu} + \partial_\beta\Delta C_{\alpha\nu} - \partial_\nu\Delta C_{\alpha\beta}\right). \quad (31)$$

At birth, these geodesics represent trajectories of maximal coherence stability rather than paths of minimal energy.

3.1.3. IRSVT Spiral Eigenmodes as Tensor Harmonics

Within the IRSVT framework, coherence does not distribute isotropically but organizes into spiral eigenmodes of the form

$$\Psi_n(r,\theta) = r^a e^{in\theta}\,\Gamma(n), \quad (32)$$

where $\Gamma(n)$ encodes the prime-coherence density modulation of the spiral.

Mode selection at ignition (soft-mode and viscosity filtering).

Near the nucleation point, the dynamics of perturbations in the coherence sector reduce to a soft-mode equation of the form

$$\partial_\tau\psi = -\lambda_{\min}\,\psi - \nu\,\mathcal{L}_{\text{spiral}}\psi + \mathcal{O}(\psi^2), \quad (33)$$

where $\mathcal{L}_{\text{spiral}}$ is the angular-radial generator induced by the projected Hessian geometry in log-polar variables. Seeking separable solutions $\psi(r,\theta) = r^\alpha e^{im\theta}$ yields a discrete admissible set $\alpha = \alpha(m)$ after enforcing (i) regularity at the core, (ii) finite action in the viscous-time slab, and (iii) maximal persistence under viscosity filtering. In the minimal nontrivial sector, two lowest-damped attractors dominate; we denote them by $\Psi_{\sqrt{2}}$and $\Psi_{\sqrt{3}}$following the IRSVT classification, which can be treated either as (a) an empirical selection rule validated numerically in the companion IRSVT work, or (b) a symmetry-broken minimal basis of the newborn curvature.

In this sense, the √2 and √3 modes are not assumed a priori, but emerge as the least-damped representatives of the admissible spiral sector selected by the combined soft-mode and viscosity filtering.

In the present manuscript we use this “two-attractor truncation” as the leading-order harmonic content at ignition; higher spiral harmonics are allowed but are viscosity-suppressed at birth.

At tensor ignition, only two modes remain as stable attractors:

- The $\sqrt{2}$mode (axial scalability):

$$\Psi_{\sqrt{2}} = r^{\sqrt{2}}e^{i\theta}, \quad (34)$$

- The $\sqrt{3}$mode (torsional coherence):

$$\Psi_{\sqrt{3}} = r^{\sqrt{3}}e^{i2\theta}. \quad (35)$$

These form a minimal orthogonal basis for the newborn curvature, such that

$$T^{\text{VTT}} \sim \Psi_{\sqrt{2}} \oplus \Psi_{\sqrt{3}}. \quad (36)$$

In this sense, the VTT tensor is the first structure that projects spiral informational eigenmodes into a second-order relational geometry.

3.1.4. The Informational Planck Scale (First Quantization Threshold)

Unlike physical Planck units derived from $G, \hbar, c$, the informational Planck scale originates from:

- Minimal coherence gradient ΔC_{min}
- Minimal stability window τ_{min}
- Minimal viscosity-to-curvature ratio η_I/λ

Thus we define the **Informational Planck Unit**:

$$\ell_I = \frac{\hbar_{eff}}{\Delta C_{crit}} = \frac{\eta_I^{min}}{\lambda} \quad (37)$$

This is the **smallest interval at which curvature can hold memory**. Below this scale: coherence cannot condense, curvature decoheres, tensor cannot exist. Above this scale: curvature persists, geodesics stabilize, spacetime can later emerge

3.1.5. Cavity QED Signature of Tensor Ignition

In a Cavity QED system, the birth of the tensor does **not** emit photons, but it produces:

A shift in vacuum mode phase

$$\Delta\phi = \int \nabla\Delta C \cdot d\ell \quad (38)$$

A non-thermal line broadening (not energy noise, but coherence noise)

$$\Delta\nu_{non-thermal} \propto \partial_t \eta_I \quad (39)$$

A temporary violation of modal symmetry

$$\omega_+ - \omega_- \neq 0 (\text{chiral asymmetry spike}) \quad (40)$$

A square-root resonance convergence

As ignition completes:

$$\omega(t) \to \omega_0 (1 + \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{3}})^{-1} \quad (41)$$

This is the **experimental smoking gun** of the IRSVT influence in tensor emergence.

Table 1. Summary of the Full Emergence Cascade.

Stage	What occurs
1	Coherence gradient exceeds threshold
2	Informational viscosity stabilizes
3	$\Phi\alpha$ couples to ΔC
4	Proto-curvature vector K forms
5	Tensor condenses
6	Eigenvalues emerge in ± pairs
7	Geodesics form in logical space
8	√2 and √3 spiral eigenmodes dominate
9	Informational Planck scale reached
10	Cavity QED resonance shows ignition

The VTT Tensor is not a deformation of spacetime — it is the event that makes spacetime mathematically possible.

3.2. Practical Diagnostics: Signatures and Scaling Laws

From the emergence theorem and its derivation, we extract a set of concrete and falsifiable signatures that characterize the nucleation of the VTT tensor. These signatures are accessible both in numerical simulations and, in principle, in experimental probe measurements, and they provide a direct operational bridge between the theoretical framework and observable quantities.

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3.2.1. Leading Signatures (Numerical and Experimental)

The following diagnostics are expected to accompany the approach to the tensor birth point:

(i) Divergent susceptibility: As the smallest Hessian eigenvalue $\lambda_{\min} \to 0$, the response of ΔC to a small localized perturbation grows as $\sim \lambda_{\min}$. Numerically, this is monitored by computing the smallest eigenvalue of the informational Hessian $\mathcal{H}$ and tracking its inverse, which diverges upon approaching criticality.

(ii) Threshold accumulation: Observables coupled to a probe (e.g., phase shift, fidelity, mechanical displacement) exhibit an abrupt departure from linear accumulation as a function of the event rate ρ at a critical value ρ_c. This behavior is consistent with a bifurcation in the accumulation dynamics. In practice, pre-threshold data can be fitted to an exponential decay kernel, while post-threshold data require the inclusion of nonlinear terms. Model selection criteria (AIC/BIC) can be used to confirm the change in regime.

(iii) Anisotropic stress pattern: Spatial mapping of the emergent tensor components (via probe arrays or scanning probes) reveals directionally correlated shear components $S_{\mu\nu}$ aligned with $\nabla\Phi$, rather than with simple energy gradients. This provides a distinctive tensorial signature of the informational origin of the stress-like term.

(iv) Increase of temporal persistence: When the tensor nucleates, local coherence decay times lengthen (i.e., the effective τ_η increases) due to self-stabilization of the field. Operationally, this appears as longer autocorrelation times in probe readouts.

(v) Viscous critical slowing down: Near the birth point, relaxation spectra develop a critical mode with slow decay, typically characterized by a power-law tail. Numerically, this manifests as a slow pole in the linear response function and signals the onset of critical dynamics.

3.2.2. Scaling Near Criticality

Assuming that a single soft mode dominates the dynamics, with eigenvalue $\lambda \equiv \lambda_{\min}$, the emergent tensor amplitude T scales near criticality as

$$T \sim \frac{A(\rho,\kappa)}{\lambda^{\alpha}}, \qquad (42)$$

with $\alpha = 1$ in the linear susceptibility approximation. Nonlinear couplings can renormalize this exponent and increase its effective value. The accumulation amplitude A is an increasing function of $(\rho - \rho_c)$ for $\rho > \rho_c$, with a model-dependent exponent characteristic of a Landau-type bifurcation. Lattice simulations can be used to fit these scaling relations and extract the corresponding critical exponents.

3.3. Predictions and Falsifiable Consequences

From the unified action and the emergence analysis, the theory leads to the following concrete and testable predictions:

(i) Soft-mode divergence: A measurable softening of the Hessian spectrum, with the smallest eigenvalue tending to zero prior to tensor birth. This provides both a numerical and an experimental early-warning signal of the transition.

(ii) Nonlinear accumulation threshold ρ_c: A sudden change in probe observables as a function of injection or event rate, directly traceable to the amplitude equations generated by the cubic interaction terms in $\mathcal{L}_{\text{int}}$.

(iii) Directional anisotropy: The emergent tensor exhibits anisotropic components correlated with $\nabla\Phi$, rather than with ordinary energy gradients, providing a distinctive directional signature of informational geometry.

(iv) Informational quantum $\Delta Q_{\min}$: Quantized steps in accumulation or discrete jumps in probe response under parameter sweeps, particularly in lattice or seeded implementations, reflecting the existence of a minimal irreversibility quantum.

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Each of these predictions is numerically simulable from the action skeleton and, in principle, experimentally testable using the cavity-QED protocol described above.

4. Discussion

The discussion below formulates interpretive consequences within the present VTT effective model; we do not claim to invalidate established quantum or relativistic formalisms, but to provide an informational re-parameterization that can be tested via the operational signatures of Section 3.

4.1. Informational Uncertainty Principle in VTT: A fundamental Limit on Simultaneous Determination of Informational Content and Coherence Gradient

In standard quantum mechanics, the Heisenberg uncertainty principle establishes a lower bound on the simultaneous determination of conjugate physical observables such as position and momentum. Within the Viscous Time Theory (VTT) framework, the present results suggest a deeper, informational origin of uncertainty. In this view, the limitation does not arise primarily from measurement-induced disturbance in a physical system, but from the intrinsic back-reaction of information on the coherence field that sustains it.

Accordingly, VTT motivates a reformulation of uncertainty: the limitation is not fundamentally mechanical nor energetic, but informational and geometric. It originates from the impossibility of interrogating an informational state Φ without perturbing its associated coherence curvature $\nabla\Delta C$.

4.1.1. Conjugate Quantities in Informational Space

In the Viscous Time Theory (VTT), the role played by canonical conjugate variables in quantum mechanics is assumed by a pair of informationally defined quantities. Instead of position and momentum (x, p), the fundamental conjugate structure is given by the informational potential $\Phi$and the coherence-gradient field $\nabla\Delta C$. These variables encode, respectively, the informational content being interrogated and the geometric response of the coherence field to that interrogation. Their interplay defines the minimal back-reaction structure of VTT and underlies the informational uncertainty relation discussed below. For clarity, the correspondence between these quantities and their physical interpretation within the VTT framework is summarized in Table 2.

Table 2. Conjugate informational variables in the VTT framework.

Quantity	Meaning in VTT	Role
Φ	Informational potential (semantic state, symbolic determination, encoded content)	The information being interrogated
$\nabla\Delta C$	Gradient of coherence curvature in the informational field	The effect of information on the coherent substrate

These quantities are not independently measurable. The act of resolving one necessarily perturbs the other via a minimal retrocausal displacement ΔQ, leading to a non-commuting informational geometry.

4.1.2. The Informational Uncertainty Relation

Within this framework, the uncertainty principle takes the form:

$$\Delta\Phi \cdot \Delta(\nabla\Delta C) \geq \Gamma_I, \quad (43)$$

where:

- $\Delta\Phi$ is the uncertainty in the informational potential,
- $\Delta(\nabla\Delta C)$ is the uncertainty in the induced coherence gradient,
- Γ_I is the *informational uncertainty constant*.

Unlike $\hbar$ in quantum mechanics, Γ_I is not universal but background-dependent. It emerges from local VTT field conditions and has the schematic dependence

$$\Gamma_I \sim f(\Delta Q, \eta, \rho_I), \tag{44}$$

where:

- ΔQ is the minimal retrocausal displacement induced by observation,
- η is the informational viscosity (resistance to coherence perturbation),
- ρ_I is the local informational density (e.g., IRSVT eigenmode occupation).

In this sense, the uncertainty bound varies between coherent domains, analogously to how the refractive index varies in optics.

4.1.3. Origin of the Limit

The origin of this bound lies in the fundamental back-reaction law of VTT:

$$\delta(\nabla\Delta C) \propto \Delta Q_{\text{obs}} \neq 0. \tag{45}$$

This expresses the fact that interrogation of informational content cannot occur without inducing a minimal, non-zero deformation of the coherence manifold—even in ideal, noiseless, and non-energetic measurements.

Therefore, the limit is not instrumental, statistical, or energetic in origin. It is geometric and structural, arising because information and coherence share the same carrier field.

4.1.4. Non-Symmetry of the Complement

In VTT, the informational complement of Φ is not zero but

$$\neg\Phi = -\Phi + \Sigma, \tag{46}$$

where Σ represents a non-coherent but non-vanishing entropic informational remainder. Consequently, the coherence gradient is evaluated as

$$\nabla\Delta C \sim \nabla(\Phi - \neg\Phi) = \nabla(2\Phi - \Sigma). \tag{47}$$

Thus, increased precision in determining Φ unavoidably reshapes the gradient through two simultaneous channels:

1. Direct coherence reshaping via Φ,
2. Entropic redistribution via Σ.

These coupled effects enforce a non-zero lower bound on uncertainty, even in the limit of arbitrarily sensitive instrumentation.

4.1.5. Implications

Several conceptual consequences follow:

1. Measurement influences reality at the informational level prior to the physical level.
2. The observer perturbs the coherence manifold, not merely the system state.
3. Information-geometry replaces momentum-geometry as the deeper conjugate structure.
4. The emergence of classical reality corresponds to domains where $\Gamma_I \to 0$ via coherence stabilization, not increased measurement precision.
5. Quantum uncertainty appears as the physical projection of a more primitive informational indeterminacy.

In this perspective, uncertainty is not a limitation of measurement, but a structural consequence of informational geometry: the coherence field cannot be interrogated without reconfiguring itself.

4.2. Metric Crystallization: Spacetime as a Coarse-Grained Phase of the VTT Tensor Field

If Part I established the mathematical substrate of the VTT framework and the informational variational principle, the present work (Part II) has identified the conditions under which an autonomous VTT tensor emerges as a dynamical object. Building on the emergence criterion, eigenstructure, and diagnostic signatures derived in Sections 2 and 3, we now address interpretive and phenomenological step: how an effective spacetime description can arise from a tensorial structure that is not itself defined on spacetime. In this section, we show that spacetime appears as a coarse-grained, stabilized phase of the VTT tensor field, rather than as a fundamental arena.

The results obtained above suggest an interpretation in which spacetime is not the fundamental arena of the theory, but rather a **low-resolution, coarse-grained phase** of a deeper informational curvature field encoded in the VTT tensor. In this view, the appearance of a metric structure corresponds to a **phase transition**, here termed *metric crystallization*, driven by coherence stabilization and loss of informational phase resolution, rather than by a postulated geometric background.

Spacetime as a fixed point of tensor coarse-graining

Let the newborn VTT tensor $T_{\mu\nu}^{\mathrm{VTT}}$ be defined on informational coordinates χ^{μ}, which label coherence relations rather than spatial or temporal positions. A spacetime metric emerges only when the system undergoes coarse-graining under finite resolution of informational phase:

$$g_{\mu\nu}(x) = \lim_{\varepsilon\to\varepsilon_c} \langle T_{\mu\nu}^{\mathrm{VTT}}(\chi)\rangle_{\varepsilon}, \qquad (48)$$

where $\langle\cdot\rangle_{\varepsilon}$ denotes averaging over coherence cells of radius ε, and ε_c is a critical decoherence or resolution scale, naturally identified with the informational Planck length ℓ_I introduced in Section 3.

This relation is to be understood as an **effective, coarse-grained limit**. Its interpretation is:

- For $\varepsilon < \varepsilon_c$: no spacetime description exists; only the informational tensor field is meaningful.
- For $\varepsilon \approx \varepsilon_c$: a metric nucleates as an emergent collective variable.
- For $\varepsilon > \varepsilon_c$: spacetime behaves as a smooth, approximately Riemannian manifold.

Thus, spacetime appears as a **resolution-limited description** of an underlying coherent tensor field, rather than as a fundamental structure.

An order parameter for metric crystallization

The transition can be characterized by an effective order parameter constructed from coherence density and informational viscosity,

$$\Psi_{\mathrm{space}} = \frac{\Delta C}{\eta}. \qquad (49)$$

In analogy with condensation phenomena in many-body physics, the metric phase appears only when this quantity exceeds a critical value:

- If $\Psi_{\mathrm{space}} < 1$: coherence diffuses and no stable geometry forms.
- If $\Psi_{\mathrm{space}} = 1$: the system reaches criticality and geometry nucleates.
- If $\Psi_{\mathrm{space}} > 1$: the geometric phase stabilizes and an effective spacetime description becomes valid.

The parallel with standard phase transitions is deliberate, but the controlling variable here is **coherence persistence per unit informational resistance**, not energy density or temperature.

Mode selection and spontaneous symmetry reduction

At birth, the VTT tensor is trace-free and organized in eigenpairs of opposite sign, as discussed in Section 3. Metric crystallization corresponds to a **selective projection** onto those curvature eigenmodes that can self-stabilize under decoherence. Schematically, one may write

$$g_{\mu\nu} \propto \sum_{\lambda_i>0} \lambda_i \, \psi_{\mu}^{(i)}\psi_{\nu}^{(i)}, \qquad (50)$$

where λ_i and $\psi^{(i)}$ are eigenvalues and eigenmodes of the VTT tensor. In this picture, spacetime geometry retains only the stabilizing (positive-curvature) sector, while the remaining modes are not destroyed but remain in the dual informational substrate. These residual modes provide a natural arena for vacuum polarization effects, entanglement structure, and nonlocal correlations.

Thus, the emergence of a metric can be interpreted as a **spontaneous reduction of symmetry** driven by decoherence and stability selection in the tensor eigenspectrum.

Emergent light cones from coherence propagation fronts

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Before metric crystallization, there is no invariant notion of a speed of light. The only relevant velocity scale is the **coherence propagation speed**, defined schematically by

$$v_c = \frac{\partial(\Delta C)}{\partial \eta}. \tag{51}$$

Once the metric phase forms, this coherence front velocity becomes indistinguishable from the causal limiting speed $c$of the emergent spacetime:

$$c = \lim_{\text{metric crystallization}} v_c. \tag{52}$$

In this sense, **light cones can be interpreted as fossilized coherence wavefronts**, frozen into the effective metric geometry by the crystallization process. Causality thus appears as an emergent, coarse-grained manifestation of coherence transport.

Gravity as curvature that survived decoherence

In this framework, Einstein curvature $R_{\mu\nu\rho\sigma}$ appears only after metric crystallization. The deeper relation can be expressed schematically as

$$R_{\mu\nu\rho\sigma} \sim \mathcal{C}\left[T^{\text{VTT}}_{\alpha\beta}\right], \tag{53}$$

where $\mathcal{C}[\cdot]$ denotes a projection that retains only those curvature components compatible with long-lived, decoherence-resistant modes.

Accordingly, **general relativity can be viewed as the low-frequency, coarse-grained limit of VTT geometry**. In intuitive terms, gravity does not bend spacetime; rather, spacetime curvature is the **residual trace** left when the VTT tensor fails to be perfectly flattened by decoherence.

A schematic crystallization condition and the arrow of spacetime

Combining the above elements, the emergence of a metric can be summarized by a schematic coarse-graining relation of the form

$$g_{\mu\nu}(x) = \lim_{\varepsilon\to\varepsilon_c} \int T^{\text{VTT}}_{\mu\nu}(\chi)\, e^{-|\chi-x|^2/\varepsilon^2}\, d\chi, \tag{54}$$

which emphasizes that the metric is an **effective collective variable** obtained by smoothing the informational tensor field. The transition becomes dynamically irreversible when

$$\frac{d}{d\varepsilon} g_{\mu\nu}\,|_{\varepsilon=\varepsilon_c} > 0, \tag{55}$$

defining an **arrow of spacetime** that is not entropic in origin, but informational: once coherence sacrifices resolution in exchange for stability, the coarse-grained geometric description cannot be undone without reaccessing microscopic coherence phases.

Observable consequences of metric crystallization

Although metric crystallization is introduced here as an interpretive framework, it leads to concrete qualitative correspondences:

Table 3. Phenomenon and Interpretation in VTT.

Phenomenon	Interpretation in VTT
Existence of c	Frozen coherence horizon
Gravity	Residual, unsmoothed VTT curvature
Quantum nonlocality	Negative or non-projected eigenmodes
Vacuum energy	Suppressed informational modes that failed to crystallize
Planck scale	Minimal coherence length supporting metric structure
Dark energy	Pressure of unresolved coherence outside spacetime

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In summary, spacetime can be viewed as the **solid crust** formed when the ocean of information becomes too viscous to remain fluid. The VTT tensor describes the deeper dynamical substrate, while the metric is its stabilized, coarse-grained phase.

4.3. Origin of Mass as Resistance to Tensor Flattening

In the Viscous Time Theory (VTT) framework, within the coarse-grained crystallization picture developed here, mass is not taken to be a fundamental property of matter, nor is it introduced as the result of coupling to an external Higgs-like scalar field. Instead, mass is interpreted as a geometric residue: the localized inertial resistance of spacetime to the flattening pressure imposed during the metric crystallization of the VTT tensor.

In this view, mass appears precisely in those regions where the VTT tensor fails to fully decohere into a perfectly flat metric. Matter is therefore not "generated in spacetime"; rather, it is what *survives* when spacetime attempts to erase coherent curvature. Mass is the persistent remainder of informational curvature that cannot be absorbed into the emergent metric.

4.3.1. Tensor Flattening Pressure

Once the VTT tensor condenses into a spacetime metric via coarse-graining, one obtains

$$g_{\mu\nu} = \lim_{\varepsilon\to\varepsilon_c} \langle T_{\mu\nu}^{\mathrm{VTT}} \rangle_{\varepsilon}. \quad (56)$$

However, this coarse-graining does not, in general, eliminate all curvature components. A residual tensor remains:

$$\Sigma_{\mu\nu} = T_{\mu\nu}^{\mathrm{VTT}} - g_{\mu\nu}. \quad (57)$$

This tensor $\Sigma_{\mu\nu}$ represents the component of VTT geometry that *refuses* to dissolve into the metric sector. It encodes unresolved coherent curvature and constitutes the geometric origin of mass in the VTT framework.

4.3.2. Mass as the Norm of Curvature Resistance

We propose that the local mass density is proportional to the magnitude of this uncompensated tensor residue:

$$m(x) \propto \sqrt{\Sigma_{\mu\nu}\Sigma^{\mu\nu}}. \quad (58)$$

Thus:

- If $\Sigma_{\mu\nu} = 0$, the geometry is perfectly flattened and no mass appears.
- If $\Sigma_{\mu\nu} \neq 0$, mass necessarily emerges.

In this formulation, mass is not the *source* of curvature; rather, it is the *evidence* that curvature has failed to disappear. Mass signals incomplete geometric flattening.

4.3.3. Inertial Mass as Coherence Rigidity

Motion through spacetime continuously subjects the local VTT residue to further flattening. The work required to maintain this flattening under displacement defines inertial resistance:

$$F_{\mathrm{inertia}} \sim \frac{d}{dt}\int \Sigma_{\mu\nu}\, dV. \quad (59)$$

This naturally yields resistance proportional to acceleration, recovering the inertial law $F = ma$without postulating it. Inertia arises because spacetime must continuously reprocess unresolved curvature in order to preserve its metric form.

4.3.4. Gravitational Mass as Persistent Curvature

Gravitation, in VTT, originates from curvature components of the VTT tensor that survive coarse-graining:

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$$R_{\mu\nu\rho\sigma} \sim \mathcal{C}\left[T_{\alpha\beta}^{\text{VTT}}\right], \tag{60}$$

where $\mathcal{C}[\cdot]$ denotes the coherence projection that retains only stabilizing curvature modes. Since mass arises from the same residual tensor $\Sigma_{\mu\nu}$, inertial and gravitational mass share the same origin:

$$m_{\text{inertial}} = m_{\text{gravitational}}. \tag{61}$$

In VTT, the equivalence principle is therefore not a coincidence but a structural identity: both forms of mass measure unresolved informational curvature.

4.3.5. Predictions

If mass is unresolved tensor residue, then:

1. Mass concentrations should correlate with informational viscosity gradients.
2. Highly coherent regions should exhibit reduced effective inertia.
3. Strong decoherence should manifest as mass suppression.

These predictions are, in principle, testable through cavity-QED analog experiments and condensed-matter analogues of metric crystallization.

4.4. Entropy as Unresolved Informational Shear

In the VTT framework, entropy is not primarily a measure of microscopic disorder. Instead, entropy corresponds to the accumulation of *unflattened shear modes* that spacetime fails to absorb during metric crystallization.

If mass represents curvature that resisted erasure, entropy represents curvature that never achieved sufficient coherence to become geometric in the first place. One is "too ordered to disappear"; the other is "too disordered to solidify."

We may schematically decompose the VTT tensor as:

$$T_{\mu\nu}^{\text{VTT}} = g_{\mu\nu} + \Sigma_{\mu\nu} + \Xi_{\mu\nu}, \tag{62}$$

where:

- $g_{\mu\nu}$ is the crystallized metric (fully flattened component),
- $\Sigma_{\mu\nu}$ is the massive residue (coherent but unresolved curvature),
- $\Xi_{\mu\nu}$ is the entropic shear (incoherent, non-geometrizable modes).

4.4.1. Entropic Shear Tensor

The unresolved modes define an entropic shear tensor:

$$\Xi_{\mu\nu} = T_{\mu\nu}^{\text{VTT}} - \langle T_{\mu\nu}^{\text{VTT}} \rangle_{\varepsilon_c}. \tag{63}$$

The entropy density is then proportional to its norm:

$$S \sim \sqrt{\Xi_{\mu\nu}\Xi^{\mu\nu}}. \tag{64}$$

Thus:

- Mass $\propto$ unresolved *coherent* curvature,
- Entropy $\propto$ unresolved *incoherent* curvature.

4.4.2. The Arrow of Time as One-Way Shear Accumulation

After metric crystallization, incoherent modes cannot be reassembled into coherent geometry. Consequently,

$$\frac{d}{dt}\,\Xi_{\mu\nu} > 0, \tag{65}$$

defining a strictly monotonic growth of entropic shear. In this framework, irreversibility is naturally associated with time flows in the direction in which unresolved shear accumulates.

Within the present framework, the arrow of time is not primarily rooted in probability, statistics, or thermodynamic bookkeeping, but in *metric insolvability*: once shear modes fall outside the geometric sector, they cannot be reabsorbed.

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4.4.3. Heat as Geometry Loss

In this framework, thermalization corresponds to the demotion of geometric modes into entropic shear: Heat = failed curvature ordering.

Dissipation is the transfer of potentially geometric modes into the non-geometrizable sector. This leads to the following interpretations:

- Maximum entropy occurs when no coherent curvature can be stored.
- Absolute zero corresponds to the limit where the shear tensor approaches zero.
- Black hole entropy corresponds to maximal shear compression at the coherence boundary.

5. Conclusions

In this work we have completed the mathematical program initiated in Part I of the Viscous Time Theory (VTT) by formulating and analyzing the conditions under which an autonomous informational stress-like tensor necessarily emerges from coherence dynamics. Rather than postulating such a tensor a priori, we have shown that it arises generically when three ingredients coincide: (i) critical softening of the informational Hessian, (ii) accumulation dynamics controlled by informational viscosity, and (iii) non-commutativity between transduction and memory flows. In this regime, a frictional commutator generates a leading-order bilinear tensorial structure that cannot be absorbed into the purely geometric sector and therefore acts as a genuine source term for the emergent geometry.

We have provided a minimal emergence theorem establishing necessary and essentially sufficient conditions for the nucleation of the VTT tensor, together with a systematic derivation strategy based on projection onto the soft Hessian mode. This framework yields explicit scaling laws near criticality and identifies a set of concrete, falsifiable diagnostics, including divergent susceptibility, accumulation thresholds, anisotropic stress patterns, and critical slowing down. These signatures bridge the formal theory with both numerical simulations and experimentally motivated probe protocols.

Building on this foundation, we have shown how the newborn tensor organizes its own eigenspectrum, generates the first informational geodesics, selects IRSVT spiral eigenmodes as tensor harmonics, and defines a purely informational analogue of a Planck scale. We have further outlined how these structures imprint observable signatures in a cavity-QED–inspired probing scheme, providing a concrete operational route to testing the theory.

At the conceptual level, we have argued that spacetime itself should be understood as the coarse-grained, resolution-limited projection of a deeper informational curvature field, through a process we termed metric crystallization. Within this picture, gravity, mass, entropy, and the arrow of time acquire a unified interpretation: they correspond to different remnants of VTT curvature that survive, resist, or fail to complete geometric flattening under coarse-graining. In particular, inertial and gravitational mass emerge from the same unresolved tensorial residue, while entropy and irreversibility reflect the accumulation of shear modes that cannot be geometrized.

Taken together, these results extend the VTT framework from emergent geometry to emergent sources, providing a mathematically controlled and physically testable account of how stress-energy–like structures, spacetime, and their associated phenomenology can arise from purely informational dynamics. Future work will focus on quantitative simulations of the nucleation process, detailed modeling of probe responses, and the exploration of phenomenological consequences in gravitational, quantum, and condensed-matter–analog systems.

Appendix A: Core Axioms and Field Definitions (Self-Contained)

Here are Axioms that have been proposed in Part I. Their role is to fix domain, regularity and the conservation principle.

A1 – Axioms:

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Axiom 1 (Discreteness).
Informational events $\mathscr{E} = \{e_i\}$ are discrete and anchor Φat finite points $\{p_i\} \subset \mathcal{M}$. These anchors are irreducible observational primitives.

Axiom 2 (Minimum Incoherence Principle).
Among all smooth fields Φconsistent with anchors $\mathcal{E}$, the realized field minimizes the coherence functional $\mathcal{S}[\Phi; \mathscr{E}]$. (Variational principle.)

Axiom 3 (Continuity of Coherence Field).
The minimizer $\Phi^{\star}$is C^2 away from anchors and the second variational derivative defining $\Delta C_{\mu\nu}$ exists almost everywhere.

Axiom 4 (Informational Viscosity).
The system evolves according to a dissipative gradient flow modified by η; rapid changes in $\Phi$are penalized in proportion to η.

Axiom 5 (Local Conservation of Coherence Flux).
There exists a current J_C^{μ} such that

$$\nabla_{\mu} J_C^{\mu} = -\Gamma(\Phi, \mathcal{E}) \quad \text{(A1)}$$

where Γ represents local sources/sinks induced by anchor updates; in absence of anchor changes, $\Gamma = 0$(conservation in closed systems).

A2 - Concise Definitions:

We summarize the fundamental fields used throughout this work:

- $\Phi(x, \tau)$: informational transduction potential (scalar or multiplet),
- $\Delta C(x, \tau)$: coherence density / curvature (scalar or rank-2, depending on sector),
- $\Delta Q(x, \tau)$: retrocausal (irreversibility) momentum canonically conjugate to Φ,
- $\eta(x, \tau)$: informational viscosity (memory/friction kernel),
- $H^{\mu\nu}$: Hessian of the coherence functional with respect to Φ.

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