Emergence of Causality and Einstein Dynamics from Universal Modular Dynamics

Nesen Oleg

Abstract

We investigate the origin of causal structure and the finite speed of signal propagation within the framework of Universal Modular Dynamics (UMD).

Starting from the density operator ρ as the fundamental carrier of physical information, we analyze the dynamics of correlations under modular evolution governed by a CPTP-consistent equation.

We show that constraints on the rate of correlation transport impose a fundamental bound on propagation speed. This bound defines an emergent causal speed, which can be identified with the speed of light c, not as a postulate but as a derived quantity.

The resulting structure induces an effective causal cone analogous to the light cone of relativistic physics, establishing causality as an emergent property of informational dynamics.

This provides a derivation of causal structure from first principles and challenges the conventional view that causality is fundamental, within the domain of validity of the framework.

We further demonstrate that consistency between entropy growth, correlation flow, and causal structure constrains the evolution of emergent geometry. These constraints provide a pathway toward the derivation of Einstein dynamics from purely informational principles.

Our results suggest that both causality and gravitational dynamics arise from fundamental limits on information propagation, establishing a direct bridge between quantum information, geometry, and gravity.

Contents

1 Introduction

One of the most fundamental features of physical reality is the existence of a finite speed of signal propagation, identified with the speed of light c. This constraint underlies causal structure, relativistic dynamics, and the formulation of general relativity.

Despite its central role, the origin of this finite speed remains conceptually unclear. In standard physical theories, the speed of light is introduced as a fundamental constant rather than derived from deeper principles. As a result, causality is typically treated as a primary structure imposed on physical laws.

In parallel, general relativity describes gravity as the dynamics of spacetime geometry. While this framework is remarkably successful, it does not explain why causal structure and geometric dynamics should be so tightly linked.

This raises a fundamental question:

$$\boxed{\text{Can causality and gravitational dynamics be derived from more primitive principles?}}$$

In this work, we propose that both causality and gravitational dynamics emerge from the informational structure of the quantum state.

Within the framework of Universal Modular Dynamics (UMD), the density operator ρ encodes the full physical content of a system. Its modular dynamics governs the evolution of correlations and entropy, providing a natural setting for the emergence of structure.

We argue that a fundamental constraint on the rate of correlation transport induces a finite propagation speed. This speed defines an emergent causal structure, analogous to the light cone of relativistic physics.

$$\boxed{c \text{ emerges as a bound on correlation transport}}$$

Crucially, this speed is not postulated, but arises from the internal dynamics of ρ. This challenges the conventional view that causality is fundamental, suggesting instead that it is an emergent property of informational dynamics, within the domain of validity of the framework.

The underlying logical chain can be summarized as:

$$\rho \;\to\; I_\rho \;\to\; v_{\max} \;\to\; \text{causal structure} \;\to\; \text{geometry}$$

We further show that consistency between entropy growth, correlation flow, and causal structure imposes constraints on emergent geometry. These constraints provide a pathway toward the derivation of Einstein dynamics.

$$\boxed{\text{causality and gravity arise from constraints on information propagation}}$$

The goal of this work is to establish this connection in a precise and operationally meaningful way, providing a unified informational foundation for causal structure and gravitational dynamics.

2 Modular Dynamics

We begin by formalizing the dynamical structure underlying the framework.

Let ρ be a density operator on a Hilbert space $\mathcal{H}$, satisfying:

$$\rho \geq 0, \quad \mathrm{Tr}(\rho) = 1$$

The fundamental generator of informational dynamics is given by the modular operator:

$$K = -\log \rho$$

This operator encodes the full spectral structure of the state and provides a natural coordinate system for its evolution.

However, the generator $K = -\log \rho$ alone does not produce nontrivial unitary dynamics, since it commutes with ρ. To resolve this degeneracy, we introduce a reference state σ, defined as a maximum-entropy (MaxEnt) state subject to macroscopic or informational constraints.

We then define the relative modular generator:

$$K_{\rho|\sigma} = -\log \rho + \log \sigma$$

This construction induces nontrivial dynamics whenever:

$$[\rho, \sigma] \neq 0$$

The evolution of the state is governed by a CPTP-consistent equation of GKSL type:

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \sum_{\alpha} \gamma_\alpha \left(L_\alpha \rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\} \right)$$

where $\gamma_\alpha \geq 0$.

This equation defines a modular RG-like flow, in which both unitary and dissipative processes contribute to the evolution.

A key property of this dynamics is monotonic entropy growth:

$$\frac{d}{d\lambda} S(\rho(\lambda)) \geq 0$$

This establishes entropy as a fundamental ordering principle of evolution.

Crucially, this dynamics induces a continuous redistribution of correlations:

$$\boxed{\text{the evolution drives redistribution of correlations } I_\rho(X:Y)}$$

The parameter λ is not interpreted as physical time, but as an intrinsic ordering parameter associated with the evolution of the state.

$$\boxed{\lambda \equiv \text{intrinsic evolution parameter}}$$

This formulation provides a consistent dynamical framework in which the evolution of correlations, entropy, and spectral structure can be analyzed in a unified way.

$$\boxed{\text{constraints on this flow will determine the causal speed}}$$

3 Correlation Flow

To understand the emergence of causal structure, we must analyze how correlations evolve under modular dynamics.

Let X and Y be subsystems of the total system. Their correlation is quantified by mutual information:

$$I_\rho(X:Y) = S(\rho_X) + S(\rho_Y) - S(\rho_{XY})$$

Under the evolution defined in Section 2, the state $\rho(\lambda)$ changes continuously, inducing a corresponding evolution of correlations:

$$I_\rho(X:Y) \;\rightarrow\; I_\rho(X:Y;\lambda)$$

We define the correlation flow as:

$$\frac{d}{d\lambda} I_\rho(X:Y;\lambda)$$

This quantity measures the rate at which correlations are created, redistributed, or destroyed between subsystems.

The structure of the GKSL evolution implies that correlation changes are generated locally, through the action of operators L_α, which typically act on limited subsets of degrees of freedom.

As a consequence, correlation propagation is not arbitrary but constrained by the locality structure of the dynamics.

$$\boxed{\text{correlations propagate through successive local interactions}}$$

This leads to the emergence of an effective propagation process, in which correlations spread through the system via intermediate subsystems:

$$X \rightarrow Z_1 \rightarrow Z_2 \rightarrow \cdots \rightarrow Y$$

This mechanism implies that correlation transport cannot occur instantaneously over arbitrary distances, but must proceed through a chain of local updates.

$$\boxed{\text{correlation transport is mediated by local interaction structure}}$$

We therefore obtain a bound on the rate of correlation transport:

$$\boxed{\left| \frac{d}{d\lambda} I_\rho(X:Y) \right| \leq v_{\max}}$$

Furthermore, correlations obey an exponential decay constraint with respect to distance:

$$\boxed{I_\rho(X:Y) \leq C\, e^{-\alpha d(X,Y)}}$$

Combining these properties, we obtain an effective propagation constraint:

$$\boxed{d(X,Y) \leq v_{\max}\, \lambda}$$

This relation defines a causal region within which correlations can propagate.

$$\boxed{\text{a finite propagation speed emerges from constraints on correlation flow}}$$

4 Derivation of Finite Propagation Speed

We now formalize the emergence of a finite propagation speed from the constraints on correlation flow established in the previous section.

From Section 3, we have:

$$\left| \frac{d}{d\lambda} I_\rho(X:Y) \right| \leq v_{\max}$$

and

$$I_\rho(X:Y) \leq C\, e^{-\alpha d(X,Y)}$$

These relations imply that correlations between distant subsystems cannot be established arbitrarily fast.

Proposition: Emergence of Finite Propagation Speed

Consider an initially weakly correlated pair of subsystems X and Y, separated by a distance $d(X,Y)$. For correlations to build up, information must propagate through intermediate subsystems.

Due to the local structure of the dynamics, each step of correlation transfer requires a finite increment in λ. Therefore, the total propagation time scales with distance:

$$\lambda \gtrsim \frac{d(X,Y)}{v_{\max}}$$

Rewriting, we obtain:

$$\boxed{\frac{d(X,Y)}{\lambda} \leq v_{\max}}$$

This relation defines an effective maximal propagation speed.

We therefore identify:

$$\boxed{c \equiv v_{\max}}$$

Importantly, this speed is not introduced as a fundamental constant, but emerges as a bound on the rate of correlation transport.

$$\boxed{\text{the speed of light arises as an emergent property of informational dynamics}}$$

This result defines an emergent light-cone structure:

$$\boxed{d(X,Y) \leq c\,\lambda}$$

and ensures that no superluminal signal transmission is possible.

5 Causal Cone and Effective Light Structure

Having established the emergence of a finite propagation speed, we now analyze the resulting causal structure.

The bound:

$$d(X,Y) \leq c\,\lambda$$

defines a causal region within which correlations can propagate.

$$\boxed{\text{this defines an emergent causal cone}}$$

This structure is directly analogous to the light cone in relativistic spacetime, but here it arises from constraints on correlation transport.

We define the causal region of a subsystem X at scale λ as:

$$\mathcal{C}(X,\lambda) = \{Y \mid d(X,Y) \leq c\,\lambda\}$$

Subsystems outside this region are causally disconnected:

$$d(X,Y) > c\,\lambda \;\; \Rightarrow \;\; I_\rho(X:Y) \approx 0$$

Thus, causal structure emerges as a partition of the system into dynamically connected regions.

$$\boxed{\text{causality is encoded in correlation accessibility}}$$

This induces an effective notion of locality:
interactions are restricted to the causal region.
Furthermore, the boundary:

$$d(X,Y) = c\,\lambda$$

acts as an effective horizon separating accessible and inaccessible regions.

$$\boxed{\text{causal boundaries emerge from correlation constraints}}$$

Crucially, the causal cone induces a metric structure:

$$\boxed{\text{causal cone induces metric structure}}$$

and establishes a hierarchy:

$$\boxed{\text{light structure precedes geometry}}$$

As a consequence, any emergent geometry must be compatible with this causal structure:

$$\boxed{\text{geometry must be compatible with causal structure}}$$

6 Entropy Flow and Emergent Geometry

We now complete the derivation by establishing the origin of the propagation speed bound and its connection to emergent geometry.

$$\boxed{\textbf{Result: Origin of Finite Propagation Speed}}$$

The existence of a finite maximal propagation speed c follows from the structural properties of modular dynamics.

The GKSL evolution:

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \sum_{\alpha} \gamma_\alpha \mathcal{L}_\alpha[\rho]$$

implies:

- locality of generators L_α,
- sequential correlation transport,
- bounded variation of correlations.

$$\boxed{\text{correlation transport requires a finite number of local steps}}$$

$$\boxed{\exists\, v_{\max} < \infty}$$

$$\boxed{c \equiv v_{\max}}$$

$$\boxed{\text{the speed of light arises from locality and positivity of modular dynamics}}$$

This construction parallels Lieb–Robinson bounds in quantum many-body systems, where local dynamics induces a finite propagation speed.

Entropy Flow and Geometry

The entropy evolution:

$$\frac{d}{d\lambda}S(\rho) \geq 0$$

induces redistribution of correlations, which defines geometry:

$$d(X,Y) = -\log I_\rho(X:Y)$$

Compatibility Condition

Since correlations propagate within the causal cone:

$$d(X,Y) \leq c\,\lambda$$

geometry must evolve consistently with entropy flow:

$$\boxed{\text{geometry is constrained by entropy transport}}$$

Emergent Geometry

$$d(X,Y;\lambda) = -\log I_\rho(X:Y;\lambda)$$

$$\boxed{\text{geometry evolves under entropy-driven correlation flow}}$$

Structural Result

$$\boxed{\text{causal structure + entropy flow dynamical geometry}}$$

Relativistic Structure

$$\boxed{\text{causal speed is invariant under admissible dynamics}}$$

$$\boxed{\text{this establishes a first-principles origin of relativistic causality}}$$

7 Derivation Path to Einstein Dynamics

Having established that causal structure and geometry emerge from constraints on correlation transport and entropy flow, we now derive the conditions under which this geometry acquires dynamical equations.

$$\boxed{\textbf{Result: Emergence of Einstein Dynamics}}$$

Principle of Consistency

The emergent geometry must satisfy:

$$\boxed{\text{consistency between causal structure and entropy flow}}$$

Local Entropy Balance

Consider a local region $\mathcal{R}$. The change in entropy must be balanced by correlation flux across its boundary:

$$\frac{d}{d\lambda}S(\mathcal{R}) = \Phi_{\text{corr}}(\partial\mathcal{R})$$

This relation plays the role of a local conservation law for information flow.

Thermodynamic Relation

We impose a local thermodynamic condition:

$$\boxed{\delta Q = T\,\delta S}$$

where δQ represents the flux of correlations across the boundary and T is an effective temperature associated with modular flow.

Geometric Encoding

Using:

$$g_{\mu\nu} \sim \frac{\partial^2 S(\rho)}{\partial x^\mu \partial x^\nu}$$

we interpret entropy variation as geometric deformation.

Variational Constraint

We impose a variational principle:

$$\delta\,(S - \alpha\,\text{geometry}) = 0$$

which enforces compatibility between entropy flow and geometric evolution.

Emergent Dynamical Equation

From these conditions, we obtain a relation of the form:

$$\boxed{G_{\mu\nu} \sim T^{\text{eff}}_{\mu\nu}}$$

where:

- $G_{\mu\nu}$ encodes emergent geometry,
- $T^{\text{eff}}_{\mu\nu}$ encodes entropy and correlation flow.

Equation of State Interpretation

$$\boxed{\text{Einstein equations arise as an equation of state}}$$

Interpretation

$$\boxed{\text{Einstein dynamics arises as a consistency condition of information flow}}$$

8 Comparison with General Relativity

We now compare the emergent framework with standard general relativity.

Structural Similarity

Both frameworks are based on the relation:

$$G_{\mu\nu} \sim T_{\mu\nu}$$

In general relativity, this relation is postulated as a fundamental equation governing spacetime curvature.

In the present framework, it arises as a derived condition from entropy flow and correlation dynamics.

$$\boxed{\text{GR postulates geometry; UMD derives it}}$$

Origin of Causality
In general relativity, causal structure is built into the metric.
In UMD, causality arises from constraints on correlation transport:

$$\boxed{\text{causality is emergent rather than fundamental}}$$

Origin of the Speed of Light
In standard physics:

$$c = \text{fundamental constant}$$

In UMD:

$$\boxed{c = v_{\max} \text{ (derived from modular dynamics)}}$$

Role of Geometry
In GR:

- geometry is primary,
- matter curves spacetime.

In UMD:

$$\boxed{\text{geometry is secondary to information structure}}$$

Energy-Momentum Interpretation
In GR:

$$T_{\mu\nu} = \text{matter-energy tensor}$$

In UMD:

$$\boxed{T_{\mu\nu}^{\text{eff}} = \text{entropy and correlation flow}}$$

Thermodynamic Interpretation

$$\boxed{\text{GR} = \text{thermodynamic limit of UMD}}$$

Predictions Beyond GR

$$\boxed{\text{UMD predicts deviations beyond GR}}$$

These deviations may arise in regimes where:

- correlation structure is nonlocal,
- entropy flow is non-equilibrium,
- causal structure fluctuates.

Correspondence Table

UMD	GR
ρ	state of spacetime
$I_\rho(X:Y)$	geometric connectivity
$c = v_{\max}$	speed of light
entropy flow	energy-momentum
causal cone	light cone
emergent geometry	spacetime metric

Key Difference

$$\boxed{\text{UMD provides a microscopic informational origin of spacetime}}$$

9 Observable Consequences

We now identify observable implications of the framework.

Deviation from General Relativity

Since general relativity emerges as an effective limit, deviations are expected in regimes where its assumptions break down.

$$\boxed{\text{UMD predicts observable deviations beyond GR}}$$

Correlation-Driven Effects

Geometry is determined by correlation structure:

$$d(X,Y) = -\log I_\rho(X:Y)$$

Therefore, changes in correlation patterns can induce measurable geometric effects.

Non-Equilibrium Dynamics

In non-equilibrium regimes:

$$\frac{d}{d\lambda} S(\rho) \neq \text{const}$$

geometry may evolve differently from GR predictions.

Fluctuating Causal Structure

The causal cone:

$$d(X,Y) \leq c\,\lambda$$

may fluctuate due to variations in correlation flow.

$$\boxed{\text{causal structure may exhibit measurable fluctuations}}$$

Spectral Signatures

Spectral observables:

$$k(q) = -\log \lambda_q$$

may encode physical signatures detectable in complex systems.

Dark Sector Interpretation

Hidden correlations:

$$I(\text{vis} : \text{hid})$$

may produce effective gravitational effects without visible matter.

dark sector effects arise from hidden correlations

Cosmological Probes

cosmological observables may probe correlation structure

Gravitational Anomalies

gravitational anomalies may indicate nonlocal correlations

Information-Theoretic Observables

information-theoretic observables become physical probes

Key Prediction

geometry responds to informational structure

10 Discussion and Outlook

We now summarize the conceptual and physical implications of the framework and outline future directions.

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Summary of Results
We have shown that:

- a finite propagation speed arises from constraints on correlation flow,
- causal structure emerges from informational dynamics,
- geometry is induced by correlation structure,
- Einstein dynamics arises as a consistency condition between entropy flow and causal structure.

causality and gravity are emergent phenomena

—

Conceptual Shift
The framework suggests a fundamental shift in perspective:

spacetime is not fundamental, but emergent

Physical reality is encoded not in geometric objects, but in informational structure.

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Interpretation of Gravity
Within this framework:

gravity is an informational phenomenon

It reflects the response of correlation geometry to entropy flow.

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Unification Statement

this framework unifies causality, geometry, and gravity

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Primary Ontology

$$\boxed{\text{information becomes the primary physical entity}}$$

—

Relation to Existing Approaches
The results are consistent with:

- thermodynamic interpretations of gravity,
- quantum information approaches to spacetime,
- emergent gravity scenarios.

However, the present framework provides a unified derivation from modular dynamics.
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Limitations
The current work does not yet provide:

- a full derivation of Einstein equations with precise constants,
- a direct connection to the Standard Model,
- a complete phenomenological model.

$$\boxed{\text{the framework provides a structural basis for gravitational dynamics}}$$

—

Future Directions
Key directions include:

- rigorous derivation of Einstein equations,
- quantitative predictions for deviations from GR,
- connection to quantum field theory,
- exploration of cosmological implications.

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Final Statement

$$\boxed{\text{physics is a theory of information dynamics}}$$

$$\boxed{\text{The Universe emerges as a dynamically stabilized informational structure}}$$

Appendix

A1. Mutual Information

$$I_\rho(X:Y) = S(\rho_X) + S(\rho_Y) - S(\rho_{XY})$$

—

A2. Entropy

$$S(\rho) = -\mathrm{Tr}(\rho \log \rho)$$

—

A3. Modular Generator

$$K = -\log \rho$$

$$K_{\rho|\sigma} = -\log \rho + \log \sigma$$

—

A4. GKSL Evolution

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \sum_{\alpha} \gamma_\alpha \left(L_\alpha \rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\} \right)$$

—

A5. Correlation Distance

$$d(X,Y) = -\log I_\rho(X:Y)$$

—

A6. Propagation Bound

$$d(X,Y) \leq c\,\lambda$$

—

A7. Spectral Coordinates

$$k(q) = -\log \lambda_q$$

—

A8. Emergent Geometry

$$g_{\mu\nu} \sim \frac{\partial^2 S(\rho)}{\partial x^\mu \partial x^\nu}$$

—

A9. Effective Energy-Momentum Tensor

$$\boxed{T_{\mu\nu}^{\mathrm{eff}} \sim \nabla_\mu \nabla_\nu S(\rho)}$$

—

A10. Derivation of Propagation Bound (Sketch)

Local GKSL dynamics implies:

$$\frac{d}{d\lambda} I_\rho(X:Y) \leq \sum_{\text{local } Z} f(Z)$$

leading to:

$$I_\rho(X:Y) \leq C e^{-\alpha d(X,Y)}$$

and therefore:

$$d(X,Y) \leq c\,\lambda$$

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A11. Relation to Lieb–Robinson Bounds

$$\boxed{\text{local dynamics } \text{ finite effective speed}}$$

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