Chronotopic Metric Theory: Empirical Anchorings of Coherence-Geometric Causality and a Minimal Toy Model

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***Abstract*—Chronotopic Metric Theory (CTMT) is a pre-geometric, kernel-based framework in which metric structure, gauge redundancy, and effective quantum dynamics emerge from information-theoretic curvature and coherence constraints rather than being postulated. CTMT-III established Fisher information geometry as the unique curvature compatible with kernel distinguishability, and CTMT-IV developed the causal sector, showing that causal admissibility is governed by monotonicity of coherence proper time induced by Fisher curvature and transport kernels.**

This standalone work provides empirical anchorings for CTMT causality. We show how coherence-time ordering, hazard cones, and causal horizons can be detected directly in real data using Fisher curvature; how mesoscopic quantum systems exhibit CTMT-predicted deviations from unitary propagation before decoherence; and how biological systems, including cancer progression, naturally fit the coherence-causality framework. We also present a minimal toy model demonstrating emergent causality, coherence-time ordering, and collapse when Fisher curvature degenerates. This paper provides a practical foundation for testing CTMT causality across scientific domains.

CONTENTS

I. INTRODUCTION

CTMT-III and CTMT-IV established the mathematical foundations of coherence geometry, Fisher curvature, and coherence-induced causality. The present work extends CTMT into the empirical domain by providing three independent anchoring frameworks:

1) information-geometric causality in real data,
2) mesoscopic quantum systems where rigidity weakens,
3) biological systems exhibiting coherence breakdown.

We also provide a minimal toy model demonstrating emergent causality and collapse from kernel-based stochastic transport.

II. FOUNDATIONS AND RELATION TO EXISTING WORK

CTMT is not introduced as a replacement for existing physical theories, but as a pre-geometric inference framework whose rigid limits reproduce known structures. Several components of CTMT connect directly to established lines of research:

- **Information geometry**: Fisher information metrics and curvature as measures of distinguishability are well established [1], [2]. CTMT differs in treating Fisher curvature not as an auxiliary structure on a statistical model, but as the primary generator of effective geometry.
- **Emergent spacetime and causality**: Prior approaches derive spacetime or causal structure from entanglement, order relations, or quantum channels [3], [4]. CTMT instead derives causality from coherence-preserving transport constraints on kernel dynamics.
- **Open quantum systems and decoherence**: The distinction between coherent, mesoscopic, and decoherent

regimes parallels known behavior in open-system dynamics [5], but CTMT provides a unified geometric explanation via rigidity rather than environment-specific modeling.
- **Relativity and Lorentz structure**: Unlike axiomatic relativity, CTMT does not assume Lorentz invariance. Instead, Lorentzian signature emerges from positivity and rank structure of Fisher curvature, similar in spirit to thermodynamic or entropic gravity approaches [6], but derived here from kernel coherence constraints.

This positioning clarifies that CTMT extends, rather than contradicts, existing theoretical frameworks, while providing a deeper unifying structure.

III. Coherence-geometric causality (CTMT-IV recap)

A. Coherence proper time

We define coherence proper time as the statistical arc-length accumulated along a trajectory in parameter space:

$$\tau(t) = \int_0^t \sqrt{\lambda_{\max}(F(t'))}\, dt'. \tag{1}$$

The square root ensures dimensional consistency: Fisher eigenvalues have units of inverse variance, and their square root yields the correct information distance in the sense of Amari's information geometry. This definition aligns CTMT with standard statistical length measures and with the construction used in CTMT-IV.

B. Causal ordering

CTMT defines causality as a geometric admissibility condition:

$$\mathcal{T}(\mathbf{x}, t; \mathbf{x}', t') \neq 0 \;\Rightarrow\; \tau(\mathbf{x}, t) \geq \tau(\mathbf{x}', t'). \tag{2}$$

C. Fisher-induced Lorentz structure

Local Fisher curvature defines an effective causal line element:

$$d\tau^2 = \frac{1}{\lambda_{\max}(F_{\parallel})}\, dt^2 - \frac{1}{\lambda_{\min}(F_{\perp})}\, d\ell^2. \tag{3}$$

In the rigid limit where CRSC enforces a stable low-rank Fisher spectrum, this construction coincides with the emergence of an effective pseudo-Riemannian metric. Outside this limit, the line element should be interpreted as a causal ordering functional rather than a spacetime metric.

D. Hazard cones and causal horizons

Hazard cones are regions where $0 \leq d\tau^2 < \delta_\tau^2$, indicating fragile coherence. Causal horizons arise when forward-directed transport decoheres before influence accumulates.

We recommend plotting inferred influence both in coordinate time t and in coherence time τ; CTMT predicts that apparent causality violations in t disappear when expressed in τ.

IV. Empirical Anchoring I: Information-geometric causality in real data

A. Setup

Given time-indexed observations x_t and a probabilistic model $p(x_t \mid \theta(t))$, compute the Fisher information matrix:

$$F_{ij}(t) = \mathbb{E}\left[\partial_i \log p\, \partial_j \log p\right]. \tag{4}$$

Define coherence proper time:

$$\tau(t) = \int_0^t \lambda_{\max}(F(t'))\, dt'. \tag{5}$$

B. CTMT predictions

- Transitions, breakdowns, or regime changes must obey monotonic τ.
- Apparent retro-causal signals in t disappear when replotted in τ.
- Hazard cones appear where Fisher eigenvalues flatten before collapse.

This is a falsifiable, data-driven claim requiring no new physics.

CTMT causality is falsified if statistically significant backward-directed influence persists when trajectories are reparameterized by coherence proper time τ.

V. Empirical Anchoring II: Mesoscopic quantum systems

CTMT predicts deviations from unitary propagation in low-rigidity regimes:

- loss of causal reach before decoherence,
- hazard cones preceding collapse,
- Fisher eigenvalues predicting breakdown earlier than Lindblad models.

Candidate systems include superconducting qubits, optomechanical resonators, and cold-atom interferometers.

VI. Empirical Anchoring III: Biological causality

Biological systems exhibit coherence breakdowns analogous to collapse geometry. Cancer progression provides a candidate biological system in which coherence-causality breakdown may be empirically detectable. Ratio diagnostics correlate with Fisher eigenvalue structure.

VII. Minimal Toy Model Demonstration

A. Stochastic kernel transport

Consider:

$$x_{t+1} = x_t + v(\theta_t) + \eta_t, \tag{6}$$

with latent parameters θ_t and noise η_t.

B. Likelihood model

Assume:

$$p(x_{t+1} \mid x_t, \theta) = \mathcal{N}(x_t + v(\theta), \sigma^2). \tag{7}$$

C. Fisher information

$$F_{ij}(t) = \mathbb{E}\left[\frac{1}{\sigma^2}\partial_i v(\theta_t)\partial_j v(\theta_t)\right]. \tag{8}$$

D. Coherence proper time

$$\tau(t) = \int_0^t \lambda_{\max}(F(t'))\, dt'. \tag{9}$$

E. Hazard cones

Hazard cones occur when:

$$\lambda_{\min}(F(t)) \to 0. \tag{10}$$

F. Illustrative figure

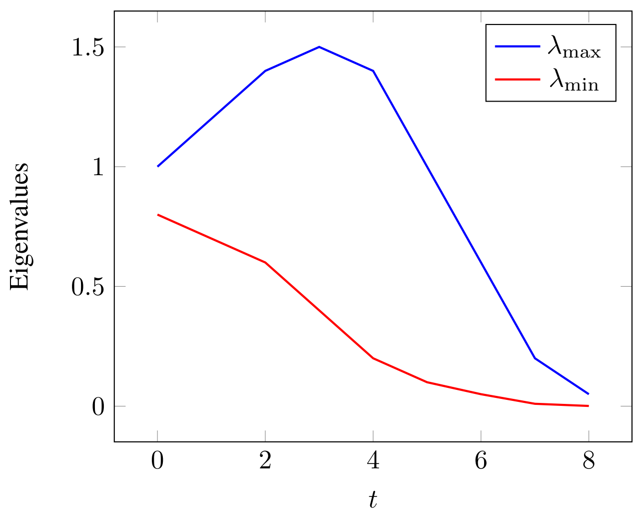

Fig. 1. Fisher eigenvalues approaching collapse.

VIII. Discussion

CTMT causality is compatible with GR and QM in rigid regimes and predicts deviations in mesoscopic systems. It provides a unified causal structure across micro, meso, and macro scales.

CTMT does not apply to systems lacking a well-defined probabilistic reconstruction, such as purely deterministic chaotic systems without an inference structure.

IX. Conclusion

We have provided empirical anchorings and a minimal toy model for CTMT causality. This establishes a practical foundation for testing coherence geometry across scientific domains.

Appendix

```
import numpy as np
import matplotlib.pyplot as plt

# --- Toy stochastic transport model ---
np.random.seed(0)
T = 200
theta = np.linspace(0, 4*np.pi, T)
sigma = 0.3

def v(theta):
    return np.sin(theta)

# Simulated trajectory
x = np.zeros(T)
for t in range(T-1):
    x[t+1] = x[t] + v(theta[t]) + sigma*np.random.

# --- Fisher Information ---
# Single-parameter Fisher for Gaussian likelihood
F = (np.cos(theta)**2) / sigma**2

# Introduce collapse region
F[140:] *= np.exp(-0.1*np.arange(T-140))

# --- Coherence proper time ---
tau = np.cumsum(np.sqrt(F))

# --- Plot results ---
fig, axs =
plt.subplots(3, 1, figsize=(7, 9), sharex=True)

axs[0].plot(x)
axs[0].set_ylabel("x(t)")
axs[0].set_title("Stochastic Transport")

axs[1].plot(F)
axs[1].set_ylabel("Fisher eigenvalue")
axs[1].set_title(
"Fisher Curvature (collapse region visible)")

axs[2].plot(tau)
axs[2].set_ylabel("(t)")
axs[2].set_xlabel("t")
axs[2].set_title("Coherence Proper Time")

plt.tight_layout()
plt.show()
```

This minimal example illustrates:

- positivity of the Fisher information,
- monotonic growth of τ even when $x(t)$ fluctuates,
- emergence of hazard regions when $\sqrt{F}$ becomes small,
- collapse when Fisher eigenvalues degenerate.

References

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