

Super-Momentum Coherence as a Diagnostic Probe of Causality from Asymmetric Decoherence

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We derive from first principles the proposition that causality emerges as the phenomenology of asymmetric convergence in decoherence processes. Starting from the pre-causal correlation structure C_{prim} where no preferred basis exists, we show that the interaction Hamiltonian structure $H_{\text{int}} = \hat{x} \otimes \hat{E}$ generically selects position as the pointer observable, creating an asymmetry between position-decoherence and momentum-coherence. This asymmetry, quantified by the convergence polarization tensor Π , drives the accumulation of redundant records $R(t)$ at an irreversible rate γ_{irr} . We prove that causal structure—branch distinguishability, temporal ordering, and embedded observerhood—emerges if and only if decoherence converges asymmetrically ($\Pi \rightarrow 1$). The complementary sector coherence ("super-momentum") remains off-resonant with environmental monitoring, providing an experimental probe of the rendering process itself. This yields the Principle of Asymmetric Convergence: the most informative probes of effective rendering come from complementary-sector coherence, as these reveal the polarized conversion of nonclassical organization into irreversible branch memory.

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I. INTRODUCTION: THE CAUSALITY-DECOHERENCE PROBLEM

The quantum-to-classical transition is typically described as decoherence: environmental entanglement suppresses interference in the reduced density matrix [1]. However, this description leaves a critical question unanswered: *why does causality emerge?*

Standard decoherence theory explains the *selection* of a pointer basis but not the *directedness* of time or the *hardness* of causal relations. We propose that these features are not additional postulates but necessary consequences of *asymmetric convergence*—the directional accumulation of environmental records in a preferred basis.

Our central claim is triadic:

$$\text{Causality} \leftrightarrow \text{Asymmetric Convergence} \leftrightarrow \text{Decoherence Resolution} \quad (1)$$

These three phenomena are not separate but aspects of the same rendering process, viewed from within the effective classical sector B_{eff} .

II. FIRST PRINCIPLES: THE PRE-CAUSAL DOMAIN

A. The Fundamental Level: C_{prim}

At the deepest level, which we denote C_{prim} (primary correlation structure), the total quantum state evolves unitarily:

$$|\Psi(t)\rangle = \hat{U}(t, t_0) |\Psi(t_0)\rangle, \quad \hat{U}^\dagger \hat{U} = \mathbb{I} \quad (2)$$

Principle 1 (No Preferred Basis): At the level of C_{prim} , no basis is ontologically privileged. The density operator $\rho = |\Psi\rangle\langle\Psi|$ can be decomposed in any orthonormal basis $\{|a\rangle\}$:

$$\rho = \sum_{a, a'} \rho_{aa'} |a\rangle\langle a'| \quad (3)$$

with $\rho_{aa'} = \langle a|\rho|a'\rangle$. All bases are equivalent under unitary transformation.

Corollary 1 (Pre-Causality): Without a preferred basis, there is no operational notion of:

- Definite events (which basis elements?)

- Temporal ordering (with respect to what pointer?)
- Causal influence (between which distinguishable states?)

B. The Total Coherence Conservation

Unitary evolution preserves the purity $\mathcal{P} = \text{Tr}(\rho^2) = 1$. More generally, the *total coherence*—quantified by the off-diagonal elements in any basis—is conserved:

$$\sum_{a \neq a'} |\rho_{aa'}|^2 = \text{constant} \quad (4)$$

This is not decoherence but *reallocation*. Coherence moves from system to system-environment correlations.

III. THE EMERGENCE OF ASYMMETRY

A. Interaction Structure and Pointer Selection

Consider a system S interacting with environment E . The total Hamiltonian is:

$$\hat{H}_{\text{tot}} = \hat{H}_S \otimes \mathbb{I}_E + \mathbb{I}_S \otimes \hat{H}_E + \hat{H}_{\text{int}} \quad (5)$$

Physical Motivation: Most fundamental interactions depend on *position*, not momentum. This is because:

1. Field couplings are local in spacetime: $\mathcal{L}_{\text{int}}(x) \propto \phi(x)\psi(x)\bar{\psi}(x)$
2. Gauge interactions (electromagnetic, strong, weak) couple to charges at points
3. Gravity couples to stress-energy, which is position-localized

Therefore, generically:

$$\hat{H}_{\text{int}} = \hat{x} \otimes \hat{E} \quad (6)$$

where \hat{x} is the system position operator and \hat{E} is an environment operator (field amplitude, etc.).

B. The Commutator Criterion

The key asymmetry emerges from the commutator:

$$[\hat{x}, \hat{H}_{\text{int}}] = 0, \quad [\hat{p}, \hat{H}_{\text{int}}] = i\hbar\hat{E} \neq 0 \quad (7)$$

Proposition 1 (Pointer Basis Selection): The interaction Hamiltonian $\hat{H}_{\text{int}} = \hat{x} \otimes \hat{E}$ commutes with \hat{x} but not with \hat{p} . Therefore:

- Position eigenstates $|x\rangle$ are *stable* under H_{int} (pointer states)
- Momentum eigenstates $|p\rangle$ are *unstable* under H_{int} (decohere rapidly)

Proof: For a position eigenstate $\rho_S = |x\rangle\langle x|$:

$$[\hat{x}, \rho_S] = 0 \implies \text{no evolution under } H_{\text{int}} \text{ (stable)} \quad (8)$$

For a momentum eigenstate $\rho_S = |p\rangle\langle p|$:

$$[\hat{p}, \rho_S] = 0 \text{ but } [\hat{p}, H_{\text{int}}] \neq 0 \implies \text{evolution under } H_{\text{int}} \text{ (unstable)} \quad (9)$$

□

C. Reduced Dynamics and Master Equation

Tracing out the environment, the system evolves under:

$$\frac{d\rho_S}{dt} = -\frac{i}{\hbar}[\hat{H}_S, \rho_S] + \mathcal{L}[\rho_S] \quad (10)$$

where \mathcal{L} is the Lindbladian superoperator. For position-decoherence:

$$\mathcal{L}[\rho_S] = -\gamma_{\text{dec}}[\hat{x}, [\hat{x}, \rho_S]] \quad (11)$$

This suppresses off-diagonal elements $\rho_S(x, x')$ at rate $\gamma_{\text{dec}} \propto |x - x'|^2$.

IV. IRREVERSIBILITY AND RECORD FORMATION

A. The Environmental Phase Space

The environment has enormous Hilbert space dimension $\dim \mathcal{H}_E \gg \dim \mathcal{H}_S$. After interaction, the total state is:

$$|\Psi_{SE}\rangle = \sum_a c_a |a\rangle_S \otimes |E_a\rangle_E \quad (12)$$

where $\{|E_a\rangle\}$ are environment states correlated with system states $\{|a\rangle\}$.

Proposition 2 (Orthogonality of Records): For distinct position eigenstates $x \neq x'$:

$$\langle E_x|E_{x'}|E_x|E_{x'}\rangle \approx \delta(x - x') \quad (\text{for macroscopic environment}) \quad (13)$$

Proof: The overlap $\langle E_x|E_{x'}|E_x|E_{x'}\rangle = \exp(-N\epsilon)$ where N is the number of environmental subsystems and $\epsilon \propto |x - x'|^2$. For $N \rightarrow \infty$, $\langle E_x|E_{x'}|E_x|E_{x'}\rangle \rightarrow 0$ exponentially.

□

B. Irreversible Rate γ_{irr}

The decoherence rate is not arbitrary but derives from environmental spectral density:

$$\gamma_{\text{irr}} = \int_0^\infty d\omega J(\omega) \coth\left(\frac{\hbar\omega}{2k_B T}\right) \quad (14)$$

where $J(\omega)$ is the spectral density. This is *irreversible* because:

1. Poincaré recurrence time $\tau_P \sim e^N$ is infinite for $N \rightarrow \infty$
2. The environment is never perfectly reversed in practice
3. Coherence is dispersed into $\dim \mathcal{H}_E$ degrees of freedom

C. Redundancy Accumulation

Following Zurek's Quantum Darwinism [2], the information about x is copied into multiple environmental fragments:

$$R(t) = \text{number of environmental subsystems containing } I_{\text{class}} \text{ about } x \quad (15)$$

This grows as:

$$\frac{dR}{dt} = \Gamma_R \cdot \Theta(\gamma_{\text{irr}} t - 1) \quad (16)$$

where Γ_R is the redundancy production rate.

V. THE CONVERGENCE POLARIZATION TENSOR

A. Definition

We define the **convergence polarization** $\Pi[\psi; \mathcal{B}]$ as the overlap between the system's coherence structure and the environment's monitoring basis \mathcal{B} :

$$\Pi[\psi; \mathcal{B}] = \frac{\sum_{b \in \mathcal{B}} |\langle b|\psi\rangle|^4}{\left(\sum_{b \in \mathcal{B}} |\langle b|\psi\rangle|^2\right)^2} = \sum_b p_b^2 \quad (17)$$

where $p_b = |\langle b|\psi\rangle|^2$.

Properties:

- $\Pi = 1$ for $\psi \in \mathcal{B}$ (aligned, pointer state)
- $\Pi = 1/d$ for uniform superposition over d basis states (maximally misaligned)
- Π is basis-dependent and frame-dependent

B. Effective Decoherence Functional

The total effective decoherence is polarization-weighted:

$$\mathcal{D}_{\text{eff}}(t) = \int_0^t dt' \gamma_{\text{irr}}(t') \cdot \Pi[\psi(t'); \mathcal{B}_{\text{env}}] \cdot R(t') \quad (18)$$

This is the key quantity. It depends on:

1. The irreversible rate γ_{irr} (thermodynamic arrow)
2. The polarization Π (alignment with monitoring basis)
3. The redundancy R (how many records exist)

VI. DERIVATION OF THE ASYMMETRIC CONVERGENCE PRINCIPLE

A. Theorem: Causality from Asymmetric Convergence

Theorem 1: Causal structure (branch distinguishability, temporal ordering, embedded observerhood) emerges in B_{eff} if and only if $\mathcal{D}_{\text{eff}}(t)$ converges with $\Pi \rightarrow 1$.

Proof:

(\Rightarrow) Assume causality emerges. Then:

1. Definite events exist \implies pointer states are distinguishable
2. Pointer states are stable under H_{int} (Proposition 1)
3. Stability requires $[\hat{x}, \rho_S] = 0 \implies \rho_S$ diagonal in position basis
4. Therefore $\Pi[\psi; \text{position}] = 1$

(\Leftarrow) Assume $\Pi \rightarrow 1$ and $\mathcal{D}_{\text{eff}} \gg 1$:

1. $\Pi = 1 \implies \psi$ is pointer state (position eigenstate)
2. $\mathcal{D}_{\text{eff}} \gg 1 \implies$ redundant records exist in environment
3. Redundant records enable multiple observers to agree on state (objectivity)
4. Objectivity + pointer stability \implies definite events \implies causality

□

B. Corollary: Symmetric Decoherence = No Causality

Corollary 2: If decoherence proceeds symmetrically ($\Pi \approx$ constant for all bases), no causal structure emerges.

Proof: Symmetric decoherence implies no preferred basis. Without preferred basis, no pointer states. Without pointer states, no definite events. Without definite events, no causal relations. □

C. The "Super-Momentum" Regime

Consider coherence prepared in the *complementary* sector to \mathcal{B}_{env} :

$$\psi_{\text{super-mom}} = \int dp \phi(p) |p\rangle, \quad \phi(p) \text{ localized} \quad (19)$$

For position-monitoring environment:

$$\Pi[\psi_{\text{super-mom}}; \text{position}] \ll 1 \quad (20)$$

Proposition 3 (Process Visibility): When $\Pi \ll 1$, the system coherence does not contribute to \mathcal{D}_{eff} initially. The rendering process is "frozen" for this component, revealing the *dynamics* of convergence rather than its outcome.

As $\psi_{\text{super-mom}}$ evolves under H_{tot} :

$$\frac{d\Pi}{dt} = \gamma_{\text{irr}}(1 - \Pi) + \mathcal{O}(\Pi^2) \quad (21)$$

The coherence "rotates" into the pointer basis at rate γ_{irr} , contributing to \mathcal{D}_{eff} only as $\Pi \rightarrow 1$.

VII. THE PRINCIPLE OF ASYMMETRIC CONVERGENCE

Principle 1 (Asymmetric Convergence). *In a branch-local position-decohering environment, the most informative probes of effective rendering come from states whose coherence is prepared in a complementary sector, such as momentum, because the observable signal is generated not by static classical agreement with the environment but by the polarized conversion of nonclassical organization into irreversible branch memory.*

Physical Motivation:

1. **Interaction structure:** $H_{\text{int}} = \hat{x} \otimes \hat{E}$ selects position as pointer
2. **Complementarity:** Momentum is the conjugate variable, maximally non-commuting
3. **Process visibility:** Off-resonant coherence reveals the conversion mechanism
4. **Embedded observer:** We are constituted by converged records, so only pre-converged coherence reveals the process

VIII. EXPERIMENTAL CONSEQUENCES

A. The Activation Law

Effective gravitational sourcing depends on \mathcal{D}_{eff} :

$$T_{\text{eff}}^{\mu\nu}(x, t) = \int_{-\infty}^t dt' K_{\text{act}}(t - t') g[\mathcal{D}_{\text{eff}}(t')] T_{\text{ref}}^{\mu\nu}(x, t') \quad (22)$$

with activation function:

$$g(\mathcal{D}) = \frac{\mathcal{D}^n}{\mathcal{D}^n + \mathcal{D}_*^n} \quad (23)$$

B. Super-Momentum Onset Dynamics

For a source prepared with momentum coherence:

$$\mathcal{D}_{\text{eff}}(t) = \mathcal{D}_0 + \int_0^t \gamma_{\text{irr}}(t') \Pi(t') R(t') dt' \quad (24)$$

with $\Pi(0) \ll 1$.

Prediction: The gravitational response shows **delayed activation** compared to position-coherent sources, with the delay time τ_{delay} encoding the convergence rate γ_{irr} .

C. Falsifiability

The framework is falsified if:

1. No trigger-correlated temporal structure is observed
2. Momentum-coherent and position-coherent sources show identical onset
3. The delay time τ_{delay} is inconsistent with γ_{irr}^{-1}

IX. RELATION TO EXISTING FRAMEWORKS

A. Zurek's Decoherence Theory

Our framework extends Zurek's by:

- Making the *asymmetry* explicit (convergence polarization Π)
- Identifying *causality* as the phenomenology of convergence
- Proposing *complementary-sector coherence* as experimental probe

B. Consistent Histories

Griffiths-Omnè [4] decoherence functional:

$$D(\alpha, \alpha') = \text{Tr}(P_{\alpha_n}(t_n) \cdots P_{\alpha_1}(t_1) \rho P_{\alpha'_1}(t_1) \cdots P_{\alpha'_n}(t_n)) \quad (25)$$

Our \mathcal{D}_{eff} is the *accumulated* version, with explicit dependence on irreversibility and redundancy.

C. Semiclassical Gravity

Standard: $G_{\mu\nu} = 8\pi G \langle \hat{T}_{\mu\nu} \rangle$ (unconditional)

Ours: $G_{\mu\nu} = 8\pi G T_{\text{eff}}^{\mu\nu}[\mathcal{D}_{\text{eff}}]$ (history-dependent)

X. CONCLUSION

We have derived from first principles the proposition that causality is not fundamental but emerges as the phenomenology of asymmetric convergence in decoherence processes. The key steps were:

1. At C_{prim} , no preferred basis exists (Principle 1)
2. Interaction structure $H_{\text{int}} = \hat{x} \otimes \hat{E}$ selects position as pointer (Proposition 1)
3. Irreversible record formation at rate γ_{irr} with redundancy $R(t)$
4. Convergence polarization Π quantifies alignment with monitoring basis
5. Causality emerges iff $\mathcal{D}_{\text{eff}} = \int \gamma_{\text{irr}} \Pi R dt'$ converges with $\Pi \rightarrow 1$ (Theorem 1)
6. Complementary-sector coherence ($\Pi \ll 1$) reveals the rendering process (Proposition 3)

This yields the Principle of Asymmetric Convergence: the most informative probes of effective rendering come from "super-momentum" coherence, as these states reveal the polarized conversion of nonclassical organization into irreversible branch memory that constitutes our causal world.

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