Observer-Conditioned Path Integrals and the Scrambling of Localized Memory in Causal Sets

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Abstract

The gravitational path integral in Causal Set Theory is pathologically dominated by highly connected, 3-level Kleitman-Rothschild (KR) posets, which overwhelm the manifold-like configurations required to recover classical spacetime. Rather than seeking purely dynamical suppression, we introduce an observer-conditioned selection principle. We demonstrate that KR posets and non-manifold expander graphs are fundamentally incompatible with the existence of localized observers. By requiring the persistence of a local memory register over a macroscopic timeline, the observer-conditioned partition function algebraically annihilates the $\exp(\mathcal{O}(N^2))$ KR multiplicity due to its insufficient temporal depth ($H = 3$). Furthermore, high-connectivity non-manifold posets function as topological expanders that rapidly scramble local quantum information in $\mathcal{O}(\ln N)$ steps, preventing memory survival. This strict observer-realizability constraint dynamically selects for low-dimensional, low-expansion causal substrates. We conclude by offering an ontological interpretation where 4D macroscopic Lorentzian spacetime emerges not as the objective bulk, but as the anthropic decoding interface (Virtual Machine) required to render the selected low-dimensional substrate.

1 The Observer-Conditioned Path Integral

Let Ω_N be the ensemble of causal sets of cardinality N. The standard discrete gravitational partition function evaluates the Benincasa-Dowker action $S_{\mathrm{BD}}(\mathcal{C})$ [2]. However, this unconstrained sum is overwhelmingly dominated by the $\exp(\mathcal{O}(N^2))$ Kleitman-Rothschild (KR) posets, which bear no resemblance to continuous Lorentzian manifolds. While Loomis and Carlip demonstrated that the complex phase of the action suppresses a large class of 2-level non-manifold sets [7], the 3-level KR orders remain a persistent theoretical obstacle.

Instead of searching for a purely objective dynamical suppression, we condition the physically relevant ensemble on observer-realizability. We define the Observer-Conditioned Path Integral as a restricted sum over the observer-compatible subspace $\Omega_{\text{obs}} \subset \Omega_N$:

$$Z_{\text{obs}} = \sum_{\mathcal{C} \in \Omega_{\text{obs}}} \exp\left(iS_{\text{BD}}(\mathcal{C})\right) \tag{1}$$

where Ω_{obs} is the strict subset of causal sets that can support an observer $\mathcal{O}$. To formalize this, an observer $\mathcal{O}$ is mathematically modeled as a localized causal sub-graph bounded by a Markov Blanket $\partial\mathcal{O}$ [4]. For $\mathcal{O}$ to experience a continuous temporal evolution, it must possess a persistent memory register capable of bounding error and resisting thermalization for at least T discrete sequential updates, where $T \gg 1$.

2 Temporal Depth Annihilation and Memory Scrambling

The 3-level KR posets contain approximately $N/2$ elements in the middle layer, forming a tripartite structure with a maximum proper time (height) of exactly $H = 3$ [6]. This extreme temporal shallowness provides an immediate, exact mathematical resolution to the entropy trap. Because an observer requires $T \gg 1$ sequential causal updates to maintain a memory register, the causal sets with maximum height $H < T$ cannot support an observer, meaning they are excluded from Ω_{obs}. This hard constraint algebraically annihilates the entire $\exp(\mathcal{O}(N^2))$ KR multiplicity in the path integral, resolving the primary counting paradox without requiring fine-tuned dynamical suppression.

For the remaining subset of non-manifold causal sets that do possess sufficient temporal depth ($H \geq T$), the observer conditioning imposes a second rigorous filter: quantum information scrambling. If we model the causal set as a tensor network where causal edges represent local unitary channels acting on subset Hilbert spaces, high-connectivity non-manifold posets function as topological expanders. For a causal network with Cheeger constant (expansion) h, the unitary scrambling time τ_{scr} scales logarithmically with cardinality [8]:

$$\tau_{\text{scr}} \sim \frac{1}{h} \ln N \tag{2}$$

For highly connected expander graphs, an $\mathcal{O}(1)$ expansion ensures the causal structure acts as an ultra-fast scrambler. Any localized state injected into the network is globally entangled and decohered in $\mathcal{O}(\ln N)$ steps. Because the observer requires persistent local state isolation ($\tau_{\text{scr}} \gg T$), expander topologies are excluded from the observer-compatible subspace Ω_{obs}.

Therefore, both shallow KR traps and deep topological expanders are aggressively eliminated from the restricted path integral, leaving them physically unexperienceable.

3 Dimensional Suppression and Emergent Holography

The requirement for local memory survival (that the scrambling time is much greater than the required survival time, $\tau_{\text{scr}} \gg T$) acts as a strict topological filter, eliminating high-expansion graphs and selecting for geometries with low connectivity and strict locality. Such localized diffusion strictly favors low-dimensional geometries.

Furthermore, following the theorem of Bombelli, Henson, and Sorkin, a Lorentz-invariant discrete substrate behaves statistically as a Poisson sprinkling [3]. If we project a Poisson sprinkling into a 4D continuous bulk, the resulting configurational entropy scaling risks diverging beyond the physical Bekenstein-Hawking thermodynamic bounds for finite regions [1]. To preserve both discrete Lorentz invariance and exact holographic bounds without divergence, the fundamental objective topology must be restricted to a lower-dimensional surface, specifically $d \leq 2$.

Because the objective 2D causal substrate lacks 4D Lorentzian geometry, 4D macroscopic spacetime cannot be an objective bulk container. Drawing on the interface theory of perception [5], we offer the ontological interpretation that 4D Minkowski space acts as an exact geometric data structure—a "Virtual Machine" interface—synthesized by the biological observer to encode the 2D causal data stream. Observer-realizability thus dynamically selects a low-dimensional physical network, while rendering 4D spacetime as an adaptive evolutionary reality.

References

[1] Jacob D Bekenstein. Black holes and entropy. *Physical Review D*, 7(8):2333, 1973.

[2] Dionigi MR Benincasa and Fay Dowker. The scalar-tensor theory of gravity in the causal set approach. *Physical Review Letters*, 104(18):181301, 2010.

[3] Luca Bombelli, Joe Henson, and Rafael D Sorkin. Discreteness without symmetry breaking: a theorem. *Modern Physics Letters A*, 24(32):2579–2587, 2009.

[4] Karl Friston. Life as we know it. *Journal of the Royal Society Interface*, 10(86):20130475, 2013.

[5] Donald D Hoffman, Manish Singh, and Chetan Prakash. The interface theory of perception. *Psychonomic bulletin & review*, 22(6):1480–1506, 2015.

[6] Daniel J Kleitman and Bruce L Rothschild. Asymptotic enumeration of partial orders on a finite set. *Transactions of the American Mathematical Society*, 205:205–220, 1975.

[7] S Loomis and Steven Carlip. Suppression of non-manifold-like sets in the causal set path integral. *Classical and Quantum Gravity*, 35(1):015009, 2018.

[8] Yasuhiro Sekino and Leonard Susskind. Fast scramblers. *Journal of High Energy Physics*, 2008(10):065, 2008.