Abstract

Modern fundamental physics struggles with the background-independence problem, frequently relying on space and time as axiomatic priors. The Hierarchical Causal Structure Network (HCSN) offers a radical alternative: a pre-geometric, simulation-first framework where the universe is fundamentally treated as a computational substrate. Modeled purely as a discrete directed hypergraph (Axiom 0), HCSN replaces the classical spacetime manifold with probabilistic, local rewrite rules that strictly preserve causal consistency. Time is eliminated as an external parameter, emerging operationally as algorithmic rewrite depth. Through empirical simulation, we demonstrate that the network's structural evolution exhibits distinct phases governed by an emergent order parameter, hierarchical closure (Ω). In the supercritical regime ($\Omega > 1.2$), the system naturally generates topological defects—localized, self-regulating violations of closure balance. As these defects form persistent worldlines, they satisfy strict operational criteria for physical identity, momentum coherence, and inertial stability. Ultimately, HCSN derives stable, interacting, particle-like behavior entirely from the probabilistic evolution of pure causal logic, proving that physical matter and dynamics can be fully operationalized without assuming the prior existence of space or time.

1. Introduction

Most modern fundamental physics models inherently assume space and time as a fixed, pre-existing background manifold. HCSN addresses this background-independence problem by starting from absolute minimal assumptions: no space, no time, no metric tensor, and no predefined symmetries.

Instead, the framework treats the universe as a computational substrate, exploring the testable hypothesis that the universe does not just contain computation, but *is* computation. Therefore, any geometry, dimensionality, or physical law must emerge operationally from the system's internal relational history.

2. Methodology

2.1. Foundational Substrate: Axiom 0

The HCSN framework strictly eschews any pre-existing background manifold. Instead, the universe is modeled purely relationally as a computational substrate. Formally, this substrate is defined by **Axiom 0**, which posits that the universe is a finite but unbounded directed hypergraph:

$$\mathcal{H} = (\mathcal{V}, \mathcal{E}, \preceq) \tag{1}$$

Where $\mathcal{V}$ represents a set of discrete events, $\mathcal{E}$ represents hyperedges acting as causal relations, and $\preceq$ denotes a strict partial causal ordering.

Under Axiom 1 (Causal Consistency), the relation $\preceq$ is inherently irreflexive and transitive, guaranteeing that the underlying topology is a Directed Acyclic Graph (DAG). Because there is no external space, "distance" is operationally extracted from the network via causal interval size.

2.2. Operational Mechanics of Rewrite Dynamics

Physical dynamics in HCSN are defined strictly by the algorithmic transformation of the network topology itself. The system evolves via a discrete rewrite flow governed by transformation functions acting on bounded subgraphs:

$$\mathcal{H}_{t+1} = \Phi(\mathcal{H}_t, \text{rule}_i) \tag{2}$$

Every proposed rewrite is probabilistically evaluated against the system's global regulatory tension, hierarchical closure (Ω). If a local rewrite induces a discontinuous fluctuation ($\Delta\Omega$) that threatens the stability of the hierarchy, its acceptance probability drops exponentially:

$$P(\text{rewrite}) \propto e^{-\gamma|\Delta\Omega|} \tag{3}$$

Stable structures are simply regions where the rewrite dynamics have found statistically persistent configurations that survive this computational sieve.

2.3. Time as Rewrite Depth

A defining theoretical departure of HCSN is the complete elimination of time as an external parameter. Time is defined operationally as *rewrite depth*. The local temporal coordinate of any specific event v is its causal depth, calculated as the maximum causal chain length extending from the absolute past:

$$v_{\text{depth}} = \max\{u_{\text{depth}} + 1 \mid u \preceq v\} \tag{4}$$

This operational definition ensures that temporal ordering and finite signal speeds emerge organically as structural artifacts of the network's processing history.

3. Results: Phase Transitions & Emergence

3.1. Phase Structure of Hierarchical Closure (Ω)

Simulation tracking identified that hierarchical closure (Ω) acts strictly as an order parameter. It modulates the network's transport capacity without transporting information itself. Data revealed distinct phase regimes:

- **Subcritical ($\Omega < 1.0$):** Unstable. Defect lifetimes are short ($\tau < 100$ steps).
- **Critical ($\Omega \approx 1.1$):** Marginal structural stability with fluctuating effective dimensions.
- **Supercritical ($\Omega > 1.2$):** Stable. Persistent transport fields propagate, and structural persistence ($\tau > 10^4$) is reliably observed.

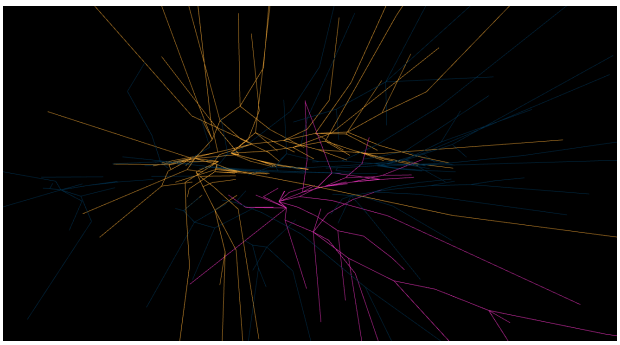


Figure 1: Visualization of the HCSN discrete causal hypergraph, demonstrating the underlying network topology before geometric emergence.

3.2. Topological Defects and Particle Emergence

In the supercritical regime, localized violations of the closure balance naturally occur. We operationally define a defect event as a discontinuous fluctuation satisfying $|\Delta\Omega(t)| > \epsilon$.

Persistent defect worldlines form "proto-objects". A defect worldline is formally classified as an emergent particle when it meets criteria for persistence, momentum coherence, and inertial stability. Momentum ($\mathbf{p}$) manifests as a statistical rewrite imbalance, while mass (m) emerges inversely proportional to momentum variance:

$$m \propto \frac{1}{\mathrm{Var}(\mathbf{p})} \tag{5}$$

Interactions occur not via predefined force fields, but through asymmetric rewrite competition for computational resources from the surrounding Ω-regulated environment.

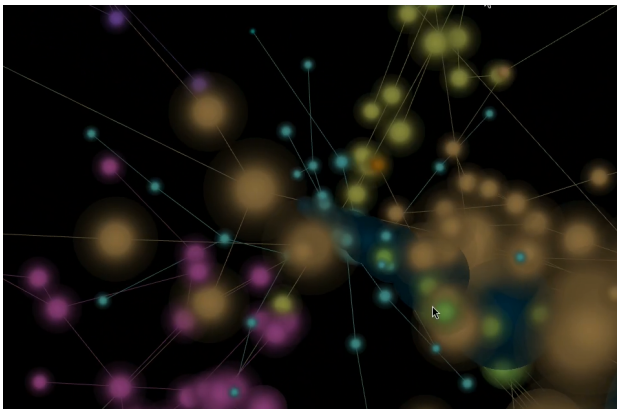


Figure 2: Emergence of localized topological defects. The clustered nodes represent stable proto-particles competing for rewrite resources within the supercritical phase.

4. Discussion and Future Work

4.1. Dimensional Selection and Scaling Limits

While HCSN proves that stable transport can exist prior to geometric emergence, a complete analytic mechanism for how the network selects a stable effective dimension (e.g., macroscopic 3D space) remains an open problem. Because conservation laws within this framework are statistical approximations rather than fundamental constants, tracing the exact transition from microscopic discrete graph topology to a continuous geometric limit requires observing phase transitions at immense scales.

4.2. Computational Bottleneck

The primary barrier to mapping this dimensional stabilization is purely computational. Simulating long-time scaling behaviors asymptotically beyond $t \sim 10^5$ rewrites becomes prohibitively expensive on local hardware. The immediate roadmap for the HCSN project requires a transition to high-performance compute clusters. By scaling the engine's throughput, we aim to map the full emergence of macroscopic symmetries from the network and prove that our universe is, at its core, a self-rewriting causal system.

Data Availability and Code

The simulation engine, visualizer, and full canonical documentation are open-source and available at hcsn.tech.