Dimension and Space as Emergent Properties of Distance in a Cause-Effect Model of the Emergence of Time

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1 One-Sentence Summary

Dimension and space emerge from causal distances inside a single stable Node, via approximate metric embeddings.

2 Abstract

We extend a previously introduced framework in which time and distance arise from internal causal relations within a single stable Node. In this work we clarify that no metric, geometric structure, or fixed dimensionality is assumed at the fundamental level. The Node is an abstract collection of subnodes linked by causal influence, and any notion of "space" arises only from the distances induced by causal chains. We show that observers may assign an effective spatial dimension whenever these causal distances can be approximately embedded into a D-dimensional space with low distortion. Crucially, no particular dimension D is preferred or fundamental: the same causal structure may support multiple effective dimensional interpretations, and the true underlying dimensionality is undefined. This liberates spatial dimension from preconceived geometric constraints and treats it as an emergent, observer-dependent property of causal relations rather than a fixed feature of spacetime.

3 Keywords

emergent spacetime, causal sets, relational physics, dimension, embeddings, metric structure

4 Introduction

Standard physics assumes that spacetime possesses a fixed number of spatial dimensions. Even in discrete or relational approaches, approaches typically begin with a target dimension or with structures designed to reproduce a chosen geometry, or expected behavior. In contrast, the Node framework introduces no geometric background, no predefined dimensionality, and it's agnostic to any behavior encoded in the causal network: a single stable Node N contains subnodes related by a causal order. Time emerges as the experience of this ordering, and distance arises from causal-chain length. Beyond this, no metric axioms, symmetry requirements, or geometric constraints are imposed.

In this work we examine how spatial dimension can itself emerge from the causal structure. We do not define a new metric, nor do we restrict the causal network to mimic any specific geometry. Instead, we allow the induced distance function to be arbitrary, possibly asymmetric, and shaped solely by the causal behavior of subnodes. When observers attempt to represent these distances within $\mathbb{R}^D$, the success or failure of low-distortion embeddings determines the effective dimensionality they assign to the system. This dimensionality is not fundamental but reflects the perceptual or operational fit between causal relations and manifold-like structures.

Thus the Node framework removes the assumption that space must possess a single fixed dimension. A causal structure may be compatible with multiple dimensional embeddings, or with none. Dimension becomes an emergent and potentially non-unique property reconstructed by observers, rather than a fundamental attribute of the underlying system.

5 Recap of the Node Framework

5.1 Structure of the Node

- Stable Node: a single entity N with fixed total property (e.g., energy).
- Subnodes: a set $\{n_i\}i \in I$ of internal components.
- Causality: a partial order $\succ$ where $n_i \succ n_j$ means causal influence.

5.2 Distance from Minimal Chains

For subnodes n_i, n_j, a causal chain of length k is:

$$n_i \succ n_{a_1} \succ \cdots \succ n_{a_{k-1}} \succ n_j$$

Distance $d(n_i, n_j)$ is the minimal k for which such a chain exists. If none exists, the distance may be infinite or undefined.

The choice of minimality as a notion of distance is clearly arbitrary.

5.3 Time as an Ordering of Events

The relation $n_i \prec n_j$ expresses causal precedence. Recurrent cycles allow local "clock" definitions: the count of causal steps gives a measure of duration.

6 Formalizing Emergent Dimension

6.1 Metric-Like Properties

The distance function d behaves like a graph distance. It may not be symmetric, but when finite it provides a metric-like structure.

Proposition (Pseudo-Metric) If the causal relation is acyclic and well-defined, d induces a pseudo-metric on pairs with finite causal connection.

6.2 Approximate Embeddings and Effective Dimension

At large scales, if causal distances embed faithfully into $\mathbb{R}^D$, the perceived geometry is D-dimensional.

Definition (Effective Dimensionality) Let $\mathbf{N}$ be the set of subnodes with distance d. A finite subset $S \subset \mathbf{N}$ embeds in $\mathbb{R}^D$ with fidelity $\epsilon \geq 0$ if there exists

$$\Phi : S \to \mathbb{R}^D$$

such that for all $n_{i_p}, n_{i_q} \in S$:

$$\big| \|\Phi(n_{i_p}) - \Phi(n_{i_q})\| - d(n_{i_p}, n_{i_q}) \big| \leq \epsilon.$$

If arbitrarily large subsets embed with arbitrarily small ϵ, the system is effectively D-dimensional.

6.3 Non-Unique Dimensionality

The Node framework places no requirement that a single dimension describe the entire causal structure. Different regions may admit embeddings into different Euclidean spaces.

Theorem (Non-Uniqueness of Effective Dimension)

Let $(\mathbf{N}, d)$ be the causal pseudo-metric defined by minimal causal chains. If there exist two subsets $S_1, S_2 \subset \mathbf{N}$ and integers $D_1 \neq D_2$ such that each admits arbitrarily low-distortion embeddings

$$\Phi_k : S_k \to \mathbb{R}^{D_k}, \qquad k = 1, 2,$$

then the Node has no single effective dimension. Dimension is not a property of the causal structure itself but of the embedding chosen by the observer.

Corollary (Dimensional Degeneracy)

If an observer samples only a subsystem whose causal distances embed well into $\mathbb{R}^D$, the observer will infer dimension D even when the full Node admits no finite-dimensional embedding.

This makes clear why different theoretical frameworks may assign dimensions such as 3, 4, 7, 10, or 11 without contradiction: each describes a different effective embedding of a different causal sector.

6.4 Connections to Manifold-Like Behavior

Discrete causal structures often approximate manifolds at large scales. Our definition captures this without assuming smoothness. If embeddings exist with small distortion for $D = 3$ or 4, the system is effectively 3D or 4D.

7 Discussion

The key implication of this extension is that spatial dimension is not a primitive feature of the Node. The causal structure alone determines the distances between subnodes, and any geometric interpretation is secondary. Observers may assign an effective D only when the induced distances admit a low-distortion embedding into $\mathbb{R}^D$. Different regions or different coarse descriptions may support different dimensional interpretations, and no single "true" dimension exists at the fundamental level.

This view separates the Node framework from causal-set or quantum-gravity approaches that aim to reproduce general relativity or assume a target dimensionality. We do not require acyclicity, Lorentzian structure, or metric conditions, and we allow causal loops. Distance asymmetry may occur, and if such asymmetry prevents low-distortion embedding, that simply reflects that the underlying causal relations do not support a geometric interpretation in that domain.

What emerges is space as an effective construct: a manifold-like representation chosen by observers because large causal regions admit faithful metric embeddings. Dimension is therefore not fundamental, not unique, and not guaranteed. It is an attribute of an embedding, not of the Node itself.

7.1 Beyond Geometry: Matter and Fields

Additional physical properties (mass, charge, fields) might also emerge if incorporated into the causal structure. Future work may define embeddings preserving additional attributes, leading to emergent gauge fields or matter excitations.

8 Conclusions

Dimension arises rather than being postulated. Effective dimensionality follows from approximate embeddings of causal distances into $\mathbb{R}^D$. Thus time, distance, space, and dimension emerge from deeper causal relations within a single stable Node.

Observers impose geometry because large causal regions admit faithful metric embeddings.

9 About Author(s)

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10 References

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