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Concept Paper

The Correlationhedron: Spacetime as Projections of Quantum Correlations

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Abstract: We propose a unified geometric framework in which space and time emerge as observer-dependent projections of quantum correlations embedded in the universal wavefunction. In this approach, we formulate six axioms (including a duality between entanglement and time) that establish a correspondence between correlation structures and effective spacetime geometry. We introduce the *correlationhedron*, a convex geometric object representing the set of all permissible correlation vectors of a given state, and show how different observer “slicings” (modeled by projection maps) yield distinct emergent spacetimes from this object. An emergent metric is defined on each observer’s spacetime via the second derivative of a correlation density (analogous to a Fisher information metric), linking gradients in quantum entanglement to curvature. This paper establishes the conceptual foundations of this approach as the first in a planned series of investigations. We illustrate the framework with conceptual and quantitative examples, including an explicit calculation of the emergent geometry for a two-qubit system in both separable and entangled states. Connections to holography (AdS/CFT) [1,2], tensor networks [3], and relational quantum approaches [4] are discussed, along with experimental signatures (such as curvature variations with entanglement) that could support the theory. Finally, we outline the limitations of the framework, particularly regarding dynamics and observer-dependent causality, to guide future investigations. This kinematic framework establishes the conceptual skeleton of emergent spacetime; detailed constructions, proofs of smoothness, and dynamical laws will appear in forthcoming work.

Keywords: Quantum correlations; Emergent spacetime; Correlationhedron; Entanglement-time duality; Quantum geometry; Observer-dependent reality; Information geometry; Holographic principle; Tensor networks; Quantum foundations

1. Introduction

1.1. Motivation and Overview

The nature of space and time remains one of the central puzzles in modern physics. In the prevailing paradigm, general relativity treats spacetime as a dynamical continuum curved by energy and momentum, whereas quantum mechanics relies on the wavefunction to describe probabilistic outcomes of measurements. An emerging perspective—fueled by insights from quantum gravity and quantum information—posits that space and time are not fundamental but instead *emerge* from deeper quantum correlations[5]. In this work, we propose that the universal wavefunction ψ contains a high-dimensional web of quantum correlations, and classical space and time arise as observer-dependent projections of this underlying structure. This paper presents the foundational framework and conceptual machinery for this approach, establishing a program for further investigation that we intend to develop in subsequent work. We introduce the concept of a *correlationhedron* (denoted K_ψ): a convex set encompassing all physically consistent correlation vectors derivable from ψ . We show how different “slicings” of K_ψ —corresponding to different observers or reference frames—recover familiar aspects of spacetime geometry (such as locality and curvature). This observer-dependent perspective is reminiscent of the *Heisenberg cut* in quantum mechanics – the notional boundary between the observer and the system. In our context, each choice of observer effectively places such a cut,

isolating a subset of the universal correlations as that observer's experienced spacetime. Drawing parallels with ideas from information geometry and entanglement renormalization, our aim is to unify quantum mechanical and gravitational phenomena under a common, correlation-centric framework.

Notably, while our correlationhedron shares a geometric spirit with concepts like the entanglement polytope from quantum information theory, it differs significantly in scope, structure, and applicability. The entanglement polytope (e.g., [6]) describes the set of possible one-body marginal eigenvalues (entanglement spectra) achievable by states within a given entanglement class, whereas K_ψ captures the full range of correlation patterns (including multi-partite and temporal correlations) for a fixed state ψ . In other words, K_ψ is a state-specific, high-dimensional object encompassing much richer information than the limited local marginals summarized by entanglement polytopes. Moreover, K_ψ is utilized here to derive an emergent spacetime geometry for each observer. This is an application beyond the purview of entanglement polytopes, which have primarily been used to classify entanglement types. This distinction underscores the novelty of the correlationhedron concept within our framework.

1.2. Recent Developments

Our proposal builds on a variety of modern approaches linking geometry and quantum correlations. For instance, the AdS/CFT correspondence¹[1] demonstrates how entanglement entropy can be used to reconstruct higher-dimensional geometry[2,7]. Tensor-network descriptions like MERA²[8,9] highlight how renormalization-group flow encodes emergent spatial structure. Notably, Van Raamsdonk has argued that progressively increasing entanglement between two halves of a divided quantum system causes their dual spacetime regions to join together, whereas removing entanglement can tear spacetime apart – a dramatic illustration that entanglement is the “glue” of spacetime[10,11]. At a more combinatorial level, geometric objects such as the *amplituhedron* provide striking examples of how scattering amplitudes can be organized in a purely geometric fashion[12].

It remains an intriguing open question whether the amplituhedron itself can be realized as a *state-specific* correlationhedron. Concretely, one would seek a quantum state ψ (for instance, the planar $\mathcal{N} = 4$ SYM vacuum) and a set of operators whose two-point or higher correlators furnish precisely the momentum-twistor data of the amplituhedron. If the allowed region of these correlators coincided with the amplituhedron and the push-forward of the natural volume on K_ψ reproduced the canonical form of the amplituhedron, then scattering amplitudes would emerge directly from quantum-state correlations. We view this as a promising direction for future work.

Finally, studies of entanglement area laws in many-body systems[13] and relational quantum gravity models[14] lend support to the notion that classical spacetime can arise from underlying quantum informational degrees of freedom.

The framework presented in this paper should be understood as a conceptual foundation rather than a complete theory. We establish the basic mathematical structures and relationships while identifying the key questions that must be addressed in developing a full theory of emergent spacetime from quantum correlations. Subsequent work will focus on expanding the mathematical rigor, addressing dynamical aspects, and exploring more complex systems beyond the toy models presented here.

1.3. Completeness and Positivity

- **Axiom A1 (Completeness):** All physically realizable correlations of the universal wavefunction can be embedded in the correlationhedron K_ψ . This echoes the holographic idea that every degree of freedom of the state is encoded in its correlation structure [15].

¹ Anti-de Sitter/Conformal Field Theory correspondence relating a gravitational bulk to a boundary quantum field theory.

² Multiscale Entanglement Renormalization Ansatz, a tensor network whose hierarchical structure encodes a discrete hyperbolic geometry.

- **Axiom A2 (Positivity):** Quantum correlations are derived from positive semidefinite operators. For example, for any observables A_i and A_j ,

$$\text{Cov}(A_i, A_j) = \langle A_i A_j \rangle - \langle A_i \rangle \langle A_j \rangle ,$$

which implies that the covariance matrix $[\text{Cov}(A_i, A_j)]$ is positive semidefinite. This ensures that K_ψ is a convex set [16].

1.4. Observer Slicability and Locality Emergence

- **Axiom A3 (Observer Slicability):** An observer, by choosing a set of measurements, projects K_ψ onto a lower-dimensional manifold M_θ . This projection, denoted π_θ , is determined by the observer's frame (e.g., their velocity or measurement basis) and is responsible for the emergence of effective spacetime [7].
- **Axiom A4 (Locality Emergence):** In sufficiently localized regions of K_ψ , correlations cluster such that an approximate notion of locality arises. This is in accord with area-law behaviors observed in low-energy states [16].

1.5. Curvature from Gradients and Entanglement–Time Duality

- **Axiom A5 (Curvature from Gradients):** Variations in the quantum correlation density induce effective curvature in the emergent spacetime. Steep gradients in the correlation distribution act analogously to mass-energy in classical general relativity, curving the effective geometry (requires $\rho_{\text{clock}}(x) \in C^2$ and $\ln \rho_{\text{clock}}$ bounded in local patches).
- **Axiom A6 (Entanglement–Time Duality):** Temporal ordering and quantum entanglement are two complementary manifestations of the same underlying correlation structure (strictly holds when ψ factorizes as clock \otimes system; see Page–Wootters [17]). For example, in the Page–Wootters mechanism³[17], entanglement between a clock and a system gives rise to time evolution. Here, the observer's projection can turn entanglement into an emergent temporal ordering. For instance, consider a global state of the form

$$|\Psi\rangle = \sum_t c_t |t\rangle_{\text{clock}} \otimes |\psi_t\rangle_{\text{system}} .$$

An observer with access only to the system (but not the clock) perceives the sequence $\{|\psi_t\rangle\}$ as a time-ordered evolution. Thus π_θ transforms the clock-system entanglement into an emergent time coordinate t .

These axioms establish the idea that the full set of quantum correlations (encoded in K_ψ) can be partitioned by an observer into an emergent spacetime, where the structure and geometry are intimately tied to the state's correlation patterns.

While this initial framework primarily addresses kinematic aspects, it provides the necessary foundation for exploring dynamical features in future developments. The axioms themselves suggest natural extensions to temporal evolution that will be explored in subsequent work.

2. Mathematical Framework

In this section we translate the axioms into a concrete mathematical construction. We define the correlationhedron K_ψ more formally, describe how an observer's projection π_θ produces an effective spacetime manifold, and derive an emergent metric on that manifold.

To formalize this slicing process, we introduce the notion of an observer projection:

³ A scheme in which entanglement between a clock subsystem and the rest yields effective time evolution.

Definition 2.1 (Observer Projection). An *observer projection* π_θ is a smooth map from the full correlation structure K_ψ to a lower-dimensional manifold M_θ , representing the effective spacetime experienced by an observer θ . Formally,

$$\pi_\theta : K_\psi \rightarrow M_\theta$$

This map selects the subset of observable correlations accessible to the observer, typically by restricting to a subalgebra $\mathcal{A}_\theta \subset \mathcal{A}$. The image $M_\theta = \pi_\theta(K_\psi)$ inherits coordinates corresponding to expectation values of observables in \mathcal{A}_θ , and geometric structure is induced via correlation densities on K_ψ .

2.1. Correlationhedron Definition and Convexity

Let \mathcal{H} be the Hilbert space of a closed quantum system described by the wavefunction ψ (or a density matrix $\rho = |\psi\rangle\langle\psi|$ for a pure state, generalizable to mixed states). We define the *correlation space* \mathcal{C} as the space of all possible correlation vectors $\mathbf{c} \in \mathbb{R}^N$ that can be constructed from expectation values of products of observables on the system. Each \mathbf{c} is of the form:

$$\mathbf{c} = (\langle O_1 O'_1 \rangle, \langle O_2 O'_2 \rangle, \dots, \langle O_N O'_N \rangle)$$

for some choice of N observable pairs (O_k, O'_k) (these could be, for example, all distinct pairs of a chosen operator basis on \mathcal{H}). Not all vectors in \mathcal{C} are allowed; only those obeying quantum constraints (linearity, positivity, etc.) correspond to a physical state.

For a specific state ρ (or ψ), we define the **correlationhedron**:

$$K_\psi := \{ \mathbf{c} \in \mathcal{C} \mid \mathbf{c} = \mathbf{c}(\rho) \text{ for some state } \rho \}.$$

In words, K_ψ is the set of all correlation vectors attainable by the system when it is in the state ψ (allowing variation over different measurement contexts or decompositions but not over different states) [18]. By construction, each $\mathbf{c} \in K_\psi$ arises from a positive semi-definite ρ (Axiom A2), hence K_ψ is a convex set [19].

This convexity follows directly from the linearity of expectation values in ρ . For any two states ρ_1, ρ_2 and $0 \leq \lambda \leq 1$,

$$\langle O_i O'_j \rangle_{\lambda \rho_1 + (1-\lambda) \rho_2} = \lambda \langle O_i O'_j \rangle_{\rho_1} + (1-\lambda) \langle O_i O'_j \rangle_{\rho_2},$$

so any convex combination of correlation vectors remains in K_ψ .

In this paper, for concreteness, we restrict correlation vectors to include all two-point correlators $\langle O_i O_j \rangle$ drawn from a chosen operator basis on \mathcal{H} . Extensions to higher-order and temporal correlations, while straightforward in principle, are deferred to future work.

The term “hedron” highlights that K_ψ is a geometric object (indeed, typically a convex polytope or a curved convex body) in the high-dimensional space of correlations. This construction is reminiscent of the *amplituhedron* in particle physics [20], which is a convex geometric object encoding scattering amplitudes. Likewise, K_ψ encodes quantum correlation data in a single geometric entity.

K_ψ can be thought of as living in a high-dimensional space, whose dimensionality is determined by the number of independent correlation components one considers. In practice, symmetries or selection of particular observable sets can reduce this dimensionality. For example, for a system of many qubits, one might consider the set of all two-point correlators $\langle \sigma_i^a \sigma_j^b \rangle$ (with i, j labeling qubits and $a, b \in \{x, y, z\}$ Pauli components). The collection of these for all $i < j$ gives a correlation vector. The set of all such vectors physically achievable by a given ψ would form K_ψ . By Axiom A1, K_ψ is assumed to capture all relevant correlations of the state.

Concretely, given an observer whose accessible observables are $\{O_i\}$, the projection map π_θ acts by selecting the subvector

$$c_\theta = (\langle O_i O_j \rangle)_{i,j \in I_\theta} \subset \mathbf{c},$$

where I_θ indexes the observables available to that observer. Thus

$$\pi_\theta : K_\psi \rightarrow M_\theta$$

is the restriction of correlation vectors to the observer's measurement subspace.

This construction may be viewed as a vast generalization of the classical correlation polytope studied in quantum foundations. In particular, Pitowsky's Bell-scenario polytope characterizes the set of all joint probability assignments compatible with local hidden-variable models [21], and the Tsirelson bounds constrain its quantum-mechanical analogue by imposing operator-positivity and commutation relations [22]. By contrast, the correlationhedron K_ψ encompasses *all* two-point—and, in principle, higher-order and temporal—correlations arising from a single global state ψ . Whereas the Bell polytope is carved out by linear constraints on measurement outcomes in a fixed spacelike configuration, K_ψ is defined by the full family of operator covariance relations,

$$c_{ij} = \langle O_i O_j \rangle - \langle O_i \rangle \langle O_j \rangle \quad (O_i, O_j \in \mathcal{A}),$$

and is automatically convex by positive-semidefiniteness of the density operator. Moreover, by allowing O_i to come from different times—as in temporal correlations à la Leggett–Garg—this framework extends beyond the purely spatial scenarios of Bell tests, yielding a unified geometric object for arbitrary observables and spacetime orderings.

In the following sections, we first explore how an observer's projection gives rise to an emergent spacetime (Section 2.2), then formalize the mathematical structure and admissibility conditions of these projections (Section 2.3), and finally derive how such projections yield a geometric structure (Sections 2.4–2.6).

2.2. Examples and Intuition for Observer Projections

While K_ψ represents the totality of correlations in the quantum state, an observer can only access a subset of this information. We model the perspective of a given observer by an **observer projection** π_θ **mapping**

$$\pi_\theta : K_\psi \rightarrow M_\theta, \tag{1}$$

which takes the full correlationhedron and produces a lower-dimensional “shadow” of it on an effective manifold M_θ [12]. Here M_θ is a manifold (with dimension d typically much smaller than that of K_ψ) that the observer interprets as their physical space and time. We furthermore assume $\dim M_\theta = 4$ (three spatial coordinates plus one time coordinate). In practice, Axiom A4 (locality emergence) and Axiom A6 (entanglement–time duality) guide the choice of observables so that M_θ can be interpreted as a classical 3+1-dimensional spacetime for the observer. The parameter θ denotes the observer's state (for example, θ could encode the observer's velocity, orientation, choice of measurement basis, or other contextual information).

If the observer's subalgebra A_θ has a nondegenerate reduced state $\rho|_{A_\theta}$ and its expectation values vary smoothly with the global state ρ , then there exists a smooth projection map

$$\pi_\theta : K_\psi \rightarrow \mathbb{R}^d$$

whose Jacobian has full rank almost everywhere on K_ψ .

In general, π_θ will be a many-to-one map (different points in K_ψ may look identical to a given observer if they cannot be distinguished by that observer's measurements). A simple example of a projection is to marginalize over (i.e. ignore) certain correlation components. For instance, an observer might be sensitive only to two-point correlations among a subset of particles, and blind to higher-order correlations or correlations involving other distant particles. In that case, π_θ could be a linear projection picking out those two-point correlators from the full vector $\mathbf{c} \in K_\psi$. Another example: if the observer

moves at high velocity, their notion of simultaneity changes (relativistic time dilation), which in this framework could correspond to a different slicing through correlation time-orderings in K_ψ .

Importantly, π_θ should be chosen such that the image M_θ inherits meaningful coordinates interpretable as space and time for the observer. (One might need additional structure to define a metric or geometry on M_θ , but we address that shortly.) There may not be a unique way to choose π_θ — indeed, there are many possible ways to define an observer's slice[23]. However, Axiom A3 demands that some consistent projection exists for any valid observer.

Clarification (Examples of π_θ): To build intuition, consider two extreme cases of projections. At one extreme, an “ideal” observer with access to all degrees of freedom would have π_θ as the identity on K_ψ , recovering the full structure (and thus presumably a high-dimensional, highly curved space). At the other extreme, a very limited observer who can only measure one variable might map K_ψ to a 1D manifold (just the expectation value of that variable), losing most of the structure. Realistic observers lie in between, projecting out some but not all information. The choice of π_θ can be dynamic — for instance, an accelerating observer might effectively change their projection over time.

While multiple distinct projections π_θ can map to observationally equivalent spacetimes, any physically relevant distinction must be empirically accessible through measurement outcomes.

2.3. Mathematical Structure of Observer Projections

Let \mathcal{H} be the Hilbert space of the quantum system with global state ρ (or pure state ψ). Let \mathcal{A} be the full observable algebra on \mathcal{H} , and let $\mathcal{A}_\theta \subseteq \mathcal{A}$ be the subalgebra accessible to an observer labeled by parameter θ .

Define the space of two-point correlators:

$$\mathcal{C} := \{c = (\langle O_i O_j \rangle)_{i,j} \mid O_i, O_j \in \mathcal{A}\}.$$

Define the *correlationhedron* for a fixed state ρ as:

$$K_\psi := \{c \in \mathcal{C} \mid c_{ij} = \langle O_i O_j \rangle_\rho \text{ for all } O_i, O_j \in \mathcal{A}\}.$$

We model an observer's emergent spacetime M_θ via a projection map:

$$\pi_\theta : K_\psi \rightarrow M_\theta \subseteq \mathbb{R}^d,$$

where π_θ selects a subvector of correlators $(\langle O_i O_j \rangle)_{i,j \in I_\theta}$ for some finite index set I_θ .

Definition (Admissible Projection): A projection π_θ is *admissible* if it satisfies:

1. **Positivity Preservation:** $\rho|_{\mathcal{A}_\theta}$ is positive semidefinite. 2. **Smoothness:** π_θ is at least C^2 smooth on K_ψ , i.e., all derivatives up to second order exist. 3. **Full Rank:** The Jacobian J_{π_θ} of π_θ has full rank almost everywhere.

Proposition: If ρ is a C^2 -smooth density operator and \mathcal{A}_θ is finite-dimensional with smooth matrix elements, then π_θ is admissible.

2.4. Emergent Metrics from Correlation Densities

Given a particular observer's projected manifold M_θ , we must define how this manifold inherits a notion of distance or metric from K_ψ . A natural approach is to introduce a **correlation density** $\rho_{\text{clock}}(x)$ on M_θ that captures how densely correlations from K_ψ map to different regions of M_θ .

$$g_{ij}(x) = \frac{\partial^2}{\partial x^i \partial x^j} \ln \rho_{\text{clock}}(x)^{-1} \quad (2)$$

Note that

$$\ln \rho_{\text{clock}}(x)^{-1} \equiv -\ln \rho_{\text{clock}}(x),$$

so one may equivalently write the metric as

$$g_{ij}(x) = -\frac{\partial^2}{\partial x^i \partial x^j} \ln \rho_{\text{clock}}(x).$$

See Appendix A.2 for a detailed discussion of this sign convention. By construction, the emergent metric $g_{ij}(x)$ is positive-definite, thus defining a *Riemannian* metric on M_θ . This guarantees all observer-defined distances are real; the conditions for the emergence of a Lorentzian signature (with light-cone structure) will be sketched below. The emergent metric $g_{ij}(x)$ encodes the curvature of the effective spacetime manifold through variations in the density of correlations. Regions of steep changes in correlation density correspond to higher curvature. Here $\rho_{\text{clock}}(x)$ is the density induced on M_θ by projecting the natural volume on K_ψ through π_θ , so that $\rho_{\text{clock}}(x) dV$ equals the volume of its preimage in K_ψ .

This coincides with the Fisher information metric on the statistical manifold defined by $\rho_{\text{clock}}(x)$ (see Appendix A.2 for derivation).

Intuitively, if a particular region of M_θ corresponds to many distinct points in K_ψ (i.e., many different underlying correlation configurations look the same to the observer), then $\rho_{\text{clock}}(x)$ in that region is high. Conversely, if very few configurations project to a region, $\rho_{\text{clock}}(x)$ is low.

From $\rho_{\text{clock}}(x)$, we can recover the emergent metric tensor $g_{ij}(x)$ on M_θ (see Eq. (2)), which is analogous to the Hessian of the negative log density [24]. Equivalently, $g_{ij}(x)$ is the Fisher-information metric tensor if we treat $\rho_{\text{clock}}(x)$ as defining a statistical manifold. This choice ensures several desirable properties:

- It is manifestly observer-dependent. Different π_θ yield different $\rho_{\text{clock}}(x)$ and thus different metrics. This aligns with the idea that geometry is not absolute but tied to the observer's slicing of correlations.
- It is positive-definite (so long as $\rho_{\text{clock}}(x) > 0$ in the neighborhood, ensuring no singular behavior in the log-density). This means distances computed from $g_{ij}(x)$ are real.
- It responds to correlation gradients: regions where $\rho_{\text{clock}}(x)$ changes rapidly will have a large curvature (as second derivatives are large), while flat regions of $\rho_{\text{clock}}(x)$ give flat geometry.

A key requirement for g_{ij} to serve as a Riemannian metric is that it be nondegenerate (invertible) everywhere on M_θ . This will be true if $\rho_{\text{clock}}(x)$ is smooth and nowhere vanishing on M_θ (or more precisely, $\rho_{\text{clock}}(x)$ may approach zero but not be identically zero in a patch, so that $\ln \rho_{\text{clock}}(x)^{-1}$ is well-behaved). In practice, $\rho_{\text{clock}}(x)$ might be very small or zero in some regions if certain correlation configurations are impossible or extremely unlikely for a given ψ . In those cases, the metric may become singular, signaling an “edge” to the observer's spacetime (beyond which no points from K_ψ map). Physically, this could correspond to horizons or singularities from the observer's perspective, beyond which their measurements cannot probe.

This emergent metric encapsulates how the observer perceives distances in their space in terms of underlying correlation configurations. If $\rho_{\text{clock}}(x)$ is uniform, $g_{ij}(x)$ is zero (flat space) – meaning the observer sees no curvature, as every region of their space corresponds to equally many underlying configurations. If $\rho_{\text{clock}}(x)$ is sharply peaked in one area and shallow in another, $g_{ij}(x)$ will vary across M_θ , indicating curvature (the observer might interpret that as a gravitational field or tidal force in their space). In essence, areas of high correlation density act like “mass” – they pull the geometry tight (high curvature), whereas sparse regions act like voids (flat or even effectively negative curvature in a relative sense if we allowed an analogy to negative mass).

2.5. Conditions for Lorentzian Signature

While this emergent metric is initially Riemannian (positive-definite), the structure naturally generalizes to include time-like directions and causal ordering. In particular, a Lorentzian signature may arise by partitioning correlation density into temporal and spatial components. This provides a

bridge between statistical curvature and relativistic geometry. To obtain a pseudo-Riemannian metric with one time-like direction, one can split the projection into clock and spatial pieces:

$$\pi_\theta = (\pi_{\text{clock}}, \pi_{\text{space}}),$$

then define:

$$g = -\partial_\tau^2 \ln \rho_{\text{clock}}^{-1} + \sum_{i=1}^3 \partial_{x^i}^2 \ln \rho_{\text{space}}^{-1} \quad (3)$$

This yields a $(-, +, +, +)$ signature (when ρ_{clock} and ρ_{space} satisfy differentiability and positivity conditions), consistent with the standard Lorentzian structure of spacetime, while the underlying correlation space K_ψ remains positive-definite. The negative sign associated with the temporal derivative reflects the causal distinction between time-like and space-like directions, ensuring that the emergent geometry preserves conventional causal structure. We leave the explicit construction of such a projection to future work.

In practice, identifying ρ_{clock} and ρ_{space} depends on the observer's clock-system decomposition or symmetry properties of the state, as discussed in relation to Axiom A6 and the Page-Wootters construction. This decomposition presumes that observer-accessible correlations can be naturally partitioned into temporal and spatial sectors, such as when the clock-system factorization is approximately valid or when the state exhibits symmetry under time translations. In principle, regions where the sign of the log-derivative flips could signal transitions between Riemannian and Lorentzian character—an idea reminiscent of signature change in certain quantum cosmological models.

2.6. Curvature and Observers' Perspectives

How does this formal emergent curvature relate back to known physics? If M_θ is indeed to be interpreted as an observer's spacetime, then variations in $\rho_{\text{clock}}(x)$ should mimic gravitational effects for that observer. In our construction, steep gradients in $\rho_{\text{clock}}(x)$ play the role of energy density in general relativity, curving M_θ . For example, if $\rho_{\text{clock}}(x)$ has a pronounced peak (indicating a cluster of correlations concentrated in one region of M_θ), the Hessian will be large there, meaning a strong curvature. An observer might interpret that as a massive object creating gravitational attraction in that region. Conversely, if $\rho_{\text{clock}}(x)$ is nearly flat, M_θ is nearly flat.

We emphasize that this metric is *emergent* and state-dependent. Change the quantum state ψ , and K_ψ changes, $\rho_{\text{clock}}(x)$ changes, and thus the geometry on M_θ changes. This provides a concrete implementation of the idea that spacetime (and its curvature) is not fundamental, but arises from the quantum state's correlations.

To draw a parallel, consider how in the AdS/CFT correspondence entanglement entropy in the boundary theory relates to the geometry of the bulk spacetime (via the Ryu–Takayanagi formula). In our framework, $\rho_{\text{clock}}(x)$ is a more fine-grained object than entropy – it's a distribution capturing the full spectrum of correlations, not just the entropy. Yet it plays a somewhat analogous role, dictating the emergent geometry. Where AdS/CFT uses minimal surfaces to probe bulk geometry (with areas corresponding to entropies), here we use correlation densities to directly shape the metric. Importantly, our approach does not assume any pre-existing spacetime such as AdS; it applies to an arbitrary state ψ .

Finally, one might wonder: do all choices of π_θ lead to a reasonable geometry? Perhaps not. Some projections might yield a highly singular $\rho_{\text{clock}}(x)$ or otherwise pathological metric. In such cases, the resulting M_θ fails to be a well-defined differentiable manifold. This is not unexpected – not every arbitrary slicing of correlations will correspond to a semi-classical spacetime. The hope, however, is that for “natural” choices of observables (the kind an actual physical observer might have access to), $\rho_{\text{clock}}(x)$ will be well-behaved. In the Appendix A.1, we discuss some conditions for the existence and smoothness of π_θ and how to handle cases where the emergent metric might become degenerate or singular.

In summary, the emergent metric $g_{ij}(x)$ on M_θ provides the observer's "gravitational field": it tells them how their space stretches or compresses in different regions as a function of the underlying quantum state's correlation distribution. Curvature in this space is directly tied to inhomogeneities in $\rho_{\text{clock}}(x)$ – which are, in turn, features of ψ 's correlation structure. Thus, in our approach, *gravity is nothing but the second derivative of the log correlation density*: a statement that is reminiscent of, but more general than, entropic gravity proposals.

We will next illustrate these ideas with simple toy models, to see explicitly how entanglement (or lack thereof) in ψ leads to a particular $\rho_{\text{clock}}(x)$ and $g_{ij}(x)$ for an observer.

We now extend the static picture by considering how a time-evolving quantum state $|\psi(t)\rangle$ induces a trajectory through the correlation space $K_{\psi(t)}$, leading to a time-dependent emergent geometry for the observer.

2.7. State Trajectories and Time-Dependent Correlation Geometry

So far, we have focused on static correlations and emergent geometry from a fixed state. In this section, we explore how time-evolving quantum states induce dynamics on the emergent manifold.

Let the global state $\psi(t)$ evolve unitarily:

$$\psi(t) = U(t)\psi(0), \quad U(t) = e^{-iHt},$$

for some Hamiltonian H . Then $K_{\psi(t)}$ is a time-dependent convex set.

Let $\rho_{\text{clock}}(x, t)$ be the time-dependent correlation density on M_θ defined by:

$$\rho_{\text{clock}}(x, t) := (\pi_\theta)_* \mu_{K_{\psi(t)}},$$

where $\mu_{K_{\psi(t)}}$ is a measure on $K_{\psi(t)}$ and $*$ denotes the pushforward.

Define the emergent metric at time t by:

$$g_{ij}(x, t) := -\partial_i \partial_j \ln \rho_{\text{clock}}(x, t)$$

Then the emergent Ricci tensor can be written as:

$$R_{ij}(x, t) = -\partial_i \partial_j \ln \rho_{\text{clock}}(x, t) + \text{additional curvature terms (nonlinear)}.$$

These curvature terms may include mixed partial derivatives or non-Hessian contributions, depending on the underlying geometry of $K_{\psi(t)}$.

We conjecture a dynamical law:

$$\partial_t g_{ij}(x, t) \propto T_{ij}(x, t),$$

where T_{ij} is a functional of $\rho_{\text{clock}}(x, t)$ and its derivatives, acting as an effective energy-momentum tensor from quantum correlations.

3. Conceptual Toy Models

To build intuition, we examine a few toy models that illustrate how the abstract machinery of the correlationhedron and observer projections works in simple settings. These examples highlight how locality, curvature, and entanglement–time duality manifest in concrete quantum systems.

3.1. Single-Qubit Temporal Correlations

Our first toy model is a single qubit (two-level quantum system) observed over time. Even though a single qubit has no spatial extent, it can illustrate the entanglement–time duality (A6) in a trivial setting by considering correlations in time.

Consider a qubit initially prepared in state $|\psi_0\rangle$ and then measured at two different times (by the same observer). The correlationhedron K_ψ in this case could be taken as the set of all two-time correlation values $\langle A(t_1)B(t_2) \rangle$ for observables A, B at times t_1 and t_2 . If the qubit's Hamiltonian is H , its state evolves as $|\psi(t)\rangle = e^{-iHt}|\psi_0\rangle$. Suppose the observer measures σ_z at time t_1 and σ_z at time t_2 . We can talk about a correlation $\langle \sigma_z(t_1) \sigma_z(t_2) \rangle - \langle \sigma_z(t_1) \rangle \langle \sigma_z(t_2) \rangle$ which will depend on the initial state and the time difference $\Delta t = t_2 - t_1$. In this simple case, K_ψ might be one-dimensional (since essentially one parameter Δt controls the correlation).

According to our framework, the observer (here implicitly at rest relative to the qubit) projects K_ψ onto a 1D manifold M_θ which we can identify with the time axis itself.

The correlation density $\rho_{\text{clock}}(t)$ on this time axis could be related to how correlation varies with Δt . For example:

- If $|\psi_0\rangle$ is an eigenstate of σ_z , then

$$\langle \sigma_z(t_1) \sigma_z(t_2) \rangle = 1 \quad (\forall t_2 > t_1),$$

so $\rho_{\text{clock}}(t)$ is uniform (flat emergent time).

- If $|\psi_0\rangle$ is a superposition, then

$$\langle \sigma_z(t_1) \sigma_z(t_2) \rangle = \cos(\omega(t_2 - t_1)),$$

giving a peaked $\rho_{\text{clock}}(t)$ near $\Delta t = 0$ that decays for larger Δt . The emergent metric g_{tt} then varies, producing segments of different “length.”

The main takeaway from the single-qubit example is that even temporal correlations of a single degree of freedom can be seen as defining an emergent time dimension. The entanglement–time duality is trivial here (no entanglement since one qubit, but the role of correlation in time is analogous to entanglement in space for larger systems). This sets the stage for considering space and time on equal footing as two ways of slicing correlation structures.

3.2. Two Qubits: Entangled vs. Separable

A more illuminating toy model is a two-qubit system, which we can use to explicitly demonstrate how entanglement generates curvature in the emergent geometry (A5) and how locality emerges (or fails to) depending on the state.

For our two qubits (call them A and B), consider two extreme initial states:

- A **separable state**, e.g. $|\Psi_{\text{sep}}\rangle = |0_A 0_B\rangle$, which has no entanglement between qubits A and B .
- An **entangled state**, e.g. the Bell state $|\Psi_{\text{ent}}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, which possesses maximal entanglement between A and B .

We will examine each case through the lens of our framework, determining $\rho_{\text{clock}}(x)$ on an appropriate M_θ and the resulting curvature.

For simplicity, let us define our observer's projection such that M_θ captures an effective one-dimensional “distance” between qubits A and B . Imagine the observer only measures two-qubit correlation functions that have a notion of spatial separation – for instance, they might look at correlators of the form $\langle O_A \otimes O_B \rangle$, and we interpret the strength of correlation as an inverse distance.

One way to do this is to define a proxy for distance ℓ via the correlation between spins along a certain basis. Suppose our observer measures both z - z correlations $\langle \sigma_z^A \sigma_z^B \rangle$ and x - x correlations $\langle \sigma_x^A \sigma_x^B \rangle$. Intuitively:

- If both z - z and x - x correlations are high (close to +1 or -1), it suggests the qubits are “locked together” in all measured orientations – we interpret this as the qubits being effectively at zero separation (a single combined object).
- If correlations are low or depend on orientation, the qubits behave more independently – we interpret this as some distance between them.

Let's quantify an effective separation ℓ such that $\ell = 0$ corresponds to maximal correlation in all bases, and larger ℓ corresponds to weaker or basis-dependent correlations. A brief sketch of the exact push-forward measure is as follows. Define

$$c = (c_{zz}, c_{xx}), \quad c_{zz} = \langle \sigma_z^A \sigma_z^B \rangle, \quad c_{xx} = \langle \sigma_x^A \sigma_x^B \rangle,$$

and set $\ell = \ell(c)$. Then

$$\rho_{\text{clock}}(\ell) = \int_{K_\psi} \delta(\ell - \ell(c)) d\mu(c),$$

where $d\mu(c)$ is the natural volume on K_ψ . We then adopt a Gaussian proxy

$$\rho_{\text{clock}}(\ell) \approx \exp[-(\ell/\varepsilon)^2]$$

(see Eq. 4) for intuition.

For the separable state $|\Psi_{\text{sep}}\rangle = |0_A 0_B\rangle$: - $\langle \sigma_z^A \sigma_z^B \rangle = (+1)(+1) = +1$ (since both spins are up in z). - Since the product state factorizes, one has

$$\langle \sigma_x^A \sigma_x^B \rangle = \langle \sigma_x^A \rangle \langle \sigma_x^B \rangle = 0 \times 0 = 0,$$

as each qubit in $|0_z\rangle$ satisfies $\langle \sigma_x \rangle = 0$. So in one basis the qubits appear perfectly correlated, and in another they are uncorrelated. The observer would conclude that A and B are not one single object – there is some “distance” between them that allows them to behave independently in at least one measurement basis. $\rho_{\text{clock}}(\ell)$ for the separable state might be relatively broad, reflecting that the two qubits do not share a close locality in the emergent picture.

For the Bell state $|\Psi_{\text{ent}}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$: - $\langle \sigma_z^A \sigma_z^B \rangle = (+1)(+1)/2 + (-1)(-1)/2 = +1$ (since half the time both are up, half both are down). - $\langle \sigma_x^A \sigma_x^B \rangle = +1$ as well (the Bell state is also an eigenstate of $\sigma_x^A \sigma_x^B$ with eigenvalue +1). In fact, all corresponding two-qubit correlators in orthogonal bases are +1 for this Bell state. The observer sees A and B perfectly correlated in every way they check. The natural interpretation is that $\ell = 0$: the qubits are at the same “location” in the emergent space (or even considered a single entity). The correlation density $\rho_{\text{clock}}(\ell)$ would then be sharply peaked at $\ell = 0$.

We can illustrate the effective correlation density for the two cases:

A simple ansatz for the correlation density $\rho_{\text{clock}}(\ell)$ as a function of the effective separation ℓ is

$$\rho_{\text{clock}}(\ell) \propto \begin{cases} \exp[-(\ell/\varepsilon)^2], & \text{Bell state,} \\ \text{constant,} & \text{separable state.} \end{cases} \quad (4)$$

Here, ε denotes the characteristic correlation length scale. Hence, from Eq. (2), and using the Gaussian ansatz in Eq. (4), the emergent metric component becomes

$$g_{\ell\ell} = \frac{d^2}{d\ell^2} \ln \rho_{\text{clock}}(\ell)^{-1} \sim \frac{2}{\varepsilon^2} \quad (\text{Bell}), \quad g_{\ell\ell} \approx 0 \quad (\text{separable}). \quad (5)$$

In summary, the two-qubit toy model shows that:

- When two systems are entangled, an observer's emergent space will tend to place them close together with a non-trivial geometry (possibly high curvature or even effectively identifying them as a single point for maximal entanglement).
- When two systems are not entangled, it is possible for an observer to find a frame where they appear entirely uncorrelated (far apart, no direct influence), reinforcing the emergent locality.

This provides a concrete demonstration of both locality emergence and curvature-from-correlation using the simplest non-trivial quantum system.

3.3. Observer-Dependent Outlook

Finally, we emphasize the observer-dependent aspect using a slight variation of the two-qubit scenario. Imagine two observers looking at the *same* two-qubit entangled state $|\Psi_{\text{ent}}\rangle$, but choosing different measurement contexts:

- **Observer Alice** measures $\{\sigma_z^A, \sigma_z^B\}$ correlations.
- **Observer Bob** measures $\{\sigma_z^A, \sigma_x^B\}$ correlations (mixing bases between qubits).

Alice, as we saw, finds $\langle\sigma_z^A\sigma_z^B\rangle = +1$ for the Bell state, and also $\langle\sigma_x^A\sigma_x^B\rangle = +1$ (if she also measured x - x). So in Alice's chosen basis set, A and B appear tightly bound with maximal correlation in both directions she checks.

Bob, however, measures A in z and B in x . For $|\Psi_{\text{ent}}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, what is $\langle\sigma_z^A\sigma_x^B\rangle$? One can compute this: $\langle\sigma_z^A\sigma_x^B\rangle = 0$ for this state (because the Bell state is symmetric under simultaneous rotations, but if you measure different axes, correlations can cancel out). In fact, σ_z on A and σ_x on B anticommute on the state in a way that yields zero expectation. So Bob would observe no correlation in his chosen observable pair. To Bob, it might appear that the two qubits are not directly correlated (since whenever A is up or down, B is equally likely to be $+$ or $-$ in x). Thus, Bob's emergent picture might place the qubits as more distant or even disconnected along the axis he's examining.

This situation encapsulates the relativity of correlations: The "distance" or "connection" between two subsystems in the emergent space is not absolute, but depends on how the observer probes them. Alice's projection π_{Alice} yields a geometry where A and B are at zero separation (a single coupled system), whereas Bob's projection π_{Bob} —slicing K_ψ differently—yields a geometry where A and B seem separated (at least in one direction of his space). Neither is wrong; they are simply different lower-dimensional views of the same K_ψ . Of course, if an observer has access to *all* possible measurements (full tomography of the two-qubit state), they would reconstruct the full K_ψ and recognize the state as entangled. But practical observers are limited, which is one reason different reference frames (or observers) can have different "slices" of reality.

To the extent that a shared consensus reality exists, it would emerge when observers compare notes and effectively combine their correlation data. But as long as they are looking at different cross-sections of K_ψ , their personal M_θ geometries can differ — a nod to relational quantum mechanics interpretations where facts are observer-dependent.

From the two-qubit example and this observer-dependent twist, we see how the same quantum state can give rise to different emergent spacetimes for different observers. Entanglement (or the lack thereof) informs curvature, and the choice of measured observables informs the notion of distance and connection. This paves the way for exploring larger systems where these ideas might play out in more complex and rich ways, as we will discuss in the context of holography and other paradigms.

4. Connections to Existing Paradigms

4.1. Relation to AdS/CFT and Holography

One of the strongest pieces of evidence that spacetime geometry and quantum entanglement are closely related comes from the Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence⁴[1]. In holographic duality, a $(d+1)$ -dimensional gravitational spacetime in AdS is dual to a d -dimensional quantum field theory on the boundary. Crucially, entanglement entropy in the boundary theory is connected to the area of extremal surfaces in the bulk spacetime via the Ryu-Takayanagi formula[2]. In other words, entanglement (a quantum information quantity) directly gives rise to a geometric object (an area) in a higher dimension. This has led to slogans like "Entanglement builds geometry"[7].

Our correlationhedron framework is in harmony with these ideas. Here, the entire set of correlations K_ψ plays a role reminiscent of the AdS bulk, and an observer's spacetime M_θ is like a slice or patch of that bulk corresponding to a particular "code subspace" or perspective. A large entanglement

⁴ Anti-de Sitter/Conformal Field Theory correspondence relating a gravitational bulk to a boundary quantum field theory.

between two parts of the boundary CFT (say two halves of the system) corresponds to those parts being connected in the bulk — potentially even by a wormhole if the entanglement is maximal (as conjectured in ER=EPR[10,11]). In our model, a maximally entangled pair of subsystems would appear as a single unified region in an observer's M_θ , analogous to how two black hole boundaries connected by a wormhole represent one geometry. Van Raamsdonk's thought experiment[7], where gradually reducing entanglement causes spacetime to “split” into two disconnected pieces, has a direct parallel: in the correlationhedron, if correlations between two sectors shrink, the projection for an observer can make those sectors drift apart in the emergent space (potentially becoming separate spacetimes if entanglement goes to zero).

Another point of contact is the idea of the *entanglement wedge* in holography. The entanglement structure of a region of the CFT determines a certain bulk region (its entanglement wedge). In our terms, picking a particular observer (who might correspond to having access to only a region of the full system's degrees of freedom) will project K_ψ onto a certain M_θ that might correspond only to that wedge. While our framework is more general (not relying on a pre-existing spacetime, and not limited to conformal or highly symmetric states), it is encouraging that it reproduces the qualitative dependence of geometry on entanglement seen in AdS/CFT[7,10].

In summary, the correlationhedron approach can be seen as a generalization of holographic ideas beyond AdS backgrounds: any quantum state has a “bulk” K_ψ of correlations, and any observer provides a “boundary” description M_θ (with one lower dimension) that experiences a geometry. When the state in question happens to be one like those in AdS/CFT (highly entangled, obeying area laws, etc.), K_ψ should mirror the known bulk geometry. For more general states, K_ψ defines a perhaps unusual geometry, but the mechanism — entanglement pattern dictating geometry — is analogous.

4.2. Tensor Networks and MERA

Tensor network states, especially MERA⁵ and related holographic codes, provide explicit discrete models of emergent geometry from entanglement. A MERA tensor network for a 1D critical system, for example, has a structure that looks like a discrete hyperbolic (AdS) space; distances along the network correspond to length scales in the system, and entanglement between regions corresponds to connections through the network[3].

Our framework is conceptually aligned: one could imagine constructing the correlationhedron K_ψ for a state that is represented by a tensor network. Because tensor networks encode which parts of the system are entangled (connected by bonds) and how strongly, K_ψ would be highly structured — likely consisting of clusters of correlation vectors reflecting the network connectivity. The observer's projection could act like “looking down the network” from the top, seeing an effective geometry. In fact, if one takes the continuum limit of a MERA, one might get a continuous manifold akin to our M_θ . The emergent metric we defined via correlation density is analogous to how one might define a continuum metric from a discrete network (where areas with denser tensor connections correspond to more curvature or shorter distances).

An interesting aspect is that in tensor networks, geometry is approximate and state-dependent. Similarly, our emergent geometries depend on ψ and π_θ . This means if the quantum state changes (even without dynamics, just considering a different state), the geometry can change — which is expected in a fixed network if you change the entanglement pattern (you might have to change the network or bond strengths). This underscores that spacetime here is not a fixed stage but a state-specific construct, which resonates with the idea of *It from qubit* and other paradigms where spacetime arises from quantum degrees of freedom.

One can also consider more complex networks like random tensor networks or Quantum Error Correcting Codes (QECC) that have holographic properties. The correlationhedron of such states might naturally be very symmetric and convex, potentially easier to analyze. It would be fascinating

⁵ Multiscale Entanglement Renormalization Ansatz, a tensor network whose hierarchical structure encodes a discrete hyperbolic geometry.

to identify the correlationhedron with known polytopes or geometries for solvable cases (for example, the correlationhedron for a stabilizer code state might have facets corresponding to the stabilizer constraints, etc.). This could provide a new geometric understanding of holographic codes, where the code's properties (like quantum error correction threshold) relate to the shape of K_ψ .

In short, tensor networks provide concrete examples where entanglement structure \rightarrow geometry mapping is realized, and our framework aims to provide a more general, analytical handle on that idea via the continuous geometry of K_ψ . The correlationhedron approach shares the goal of MERA and related work: to make emergent space tangible and computable from entanglement data.

4.3. Relational and Quantum Reference Frame Theories

The notion that different observers may have different “slices” of reality has analogues in relational quantum mechanics and quantum reference frame transformations. In Carlo Rovelli's relational quantum mechanics[4], the state of a system is always defined relative to another system (observer) and there is no global, observer-independent state of affairs. Likewise, here M_θ is essentially the state of spacetime as seen by observer θ . If one changes the observer (perhaps by entangling the original observer with a new system or by switching perspective to another subsystem considered as the reference), one effectively applies a transformation to π_θ .

Recent work on quantum reference frames suggests that one can transform the description of physical situations from one frame to another via certain symmetries (often entangling the original frame with the system) — a procedure that can mix what one observer calls space and another calls time[25]. This is evocative of Axiom A6: entanglement and time can swap roles depending on the frame. In a sense, switching reference frames in those formulations is akin to choosing a different way to project the underlying invariant quantum state's correlations into “personal” space and time of the new frame.

Additionally, approaches like the Page-Wootters mechanism (which we cited in A6) and the idea of “evolving constants of motion” relate to the concept of an emergent time from correlations. In Page-Wootters, a static global state yields a perception of evolution to an internal observer who correlates with a clock. This is exactly an example of how one observer's π_θ (that isolates the clock correlations) yields a time dimension, whereas another slice might not separate time at all.

Our framework can thus be seen as a concrete implementation of a relational idea: there is one quantum reality (the universal wavefunction's correlation structure), and each observer “cuts” it into their space and time. The hope is that by formalizing π_θ , we could connect with these relational ideas mathematically and perhaps define how to transform between M_θ and $M_{\theta'}$ (observers' frames) by an operation on K_ψ . While we have not delved into the transformation rules between different observers' projections, the existence of K_ψ as a containing structure hints at a possibility: a change of observer corresponds to some symmetry or linear transformation on the correlation vector space, which in turn induces a map between the emergent manifolds (could this be akin to a Lorentz transform or a diffeomorphism in the emergent setting? This remains to be fleshed out).

4.4. Experimental Outlook

A fundamental question is whether these ideas of emergent spacetime from quantum correlations can be tested or at least evidenced in laboratory systems. While directly “seeing” spacetime emerge is daunting, there are several potential experimental signatures:

- **Entanglement-Dependent Geometry in Simulators:** Quantum simulators (arrays of qubits, cold atoms in optical lattices, etc.) allow preparation of states with tunable entanglement patterns. For example, one can create a family of states ranging from product states to highly entangled states (like cluster states or GHZ states). If our framework is correct, certain geometric properties derived from correlation functions should change in predictable ways. One could attempt to measure an “emergent distance” between parts of the simulator by seeing how correlation strength decays with some notion of separation. For instance, in a 1D chain, a highly entangled state (e.g.

critical ground state) should have shorter effective distances (or more curved correlation space) between distant sites than a gapped product-like state. Practically, one could measure multi-point correlation functions or mutual information between segments as a function of system parameters. A signature of emergent geometry might be that these data can be fitted to a smooth metric space model for the entangled state but not for a less entangled one.

- **Curvature from Entanglement Distribution:** Engineering states with varying degrees of entanglement and observing how an information-theoretic notion of curvature changes. For example, define an operational proxy for curvature: take three subsystems A, B, C and measure correlation-based distances d_{AB}, d_{BC}, d_{AC} . If correlations embed into a geometric plane, distances will satisfy triangle inequalities etc., but if there's curvature, one might detect a discrepancy (similar to how in general relativity one could detect curvature via geodesic deviation). By creating states where subsystem B is entangled differently with A and C , one might see an emergent triangle inequality violation that indicates curvature. This is speculative, but one could imagine plotting an "entanglement triangle" and measuring angles via correlations.
- **Tomography of the Correlationhedron:** With small systems (few qubits), full state tomography is possible. One could reconstruct the full set of correlation vectors K_ψ for a given state. While exponentially hard in general, for say 3 or 4 qubits this is doable. Then one can analyze the geometry of K_ψ : for example, find if it indeed forms a convex polytope in certain coordinates. One could attempt to directly apply the emergent metric formula. Although with so few qubits, speaking of "smooth geometry" is a stretch, one might discretely see that a maximally entangled 4-qubit state (like a 4-qubit GHZ or cluster) has a K_ψ that is more "curved" (maybe more tetrahedron-like) than a product state whose K_ψ might be more hyper-rectangular in shape.
- **Quantum Gravity Analogues:** There are proposals to test if gravity itself might arise from quantum entanglement by observing entanglement-induced forces between masses. For instance, if two micro-mass particles become entangled through gravitational interaction (as in proposed experiments by Bose *et al.*[26] and Marletto-Vedral[27]), it would indicate that gravity (spacetime geometry) can transmit quantum information. In our context, observing gravitationally mediated entanglement would support the idea that spacetime geometry (the gravitational field) is fundamentally linked to quantum correlations. While these experiments are extremely challenging, a positive result would strongly bolster frameworks like ours where geometry is not fundamental but emergent from quantum phenomena. In essence, it would show that when we "entangle" spacetime (via masses that cause curvature), it responds quantum mechanically, aligning with the notion that spacetime is made of the same stuff as quantum correlations.
- **Tests of Entanglement–Time Duality:** One could test the interchangeability of entanglement and time in a quantum clock setup. Prepare an entangled state between a clock qubit and a system qubit (à la Page-Wootters). Verify that the system's dynamics (from the clock's perspective) slow down or speed up as the entanglement between clock and system is varied. This would be like showing experimentally that what looks like a faster flow of time can be achieved by reducing entanglement and vice versa. Some recent experiments with entangled clocks and systems (or using an ancilla as a reference) could be interpreted in this light.

In practice, demonstrating an "emergent geometry" is subtle—it's not as direct as photographing spacetime. But even observing patterns consistent with these ideas (for example, mutual information patterns that match what you'd expect if the system's states were laid out on a curved space) would be intriguing. If a quantum simulator can realize states that correspond to, say, a 2D curved space, one might measure correlation functions that match those of a quantum field on a curved space, which would be evidence that the entanglement structure is geometric.

Overall, while direct experimental confirmation of spacetime emergence is far on the horizon, incremental evidence can be gathered by studying highly entangled quantum systems in the lab and checking for consistency with geometric descriptions. The rapid progress in quantum simulation and

quantum information experiments makes us optimistic that at least some aspects of this correspondence can be tested in controlled systems in the future.

While experimental validation remains challenging, the framework presented here opens several promising theoretical avenues for further development.

4.5. Future Directions

Several key developments remain:

- **Observer transformations:** Construct explicit maps between different observer manifolds $M_\theta \rightarrow M_{\theta'}$, and recover standard relativistic transformations in regimes where classical spacetime emerges. This could further clarify the relational nature of geometry and lead to a generalized notion of observer-dependent diffeomorphisms.
- **Lorentzian signature and causality:** Section 2.5 outlines how a Lorentzian signature can emerge by partitioning correlation density into temporal and spatial components. Future work will explore concrete models of such projections, and how causal relations between events may arise from correlation patterns in K_ψ and be preserved across observers.
- **Emergent dynamics and metric flow:** Section 2.7 introduces how time-evolving quantum states $|\psi(t)\rangle$ induce trajectories on the emergent manifold, leading to a time-dependent geometry via $\partial_t g_{ij}(x)$. A key direction for future research is to formulate dynamical laws linking these metric flows to underlying unitary evolution—potentially yielding analogues of Einstein’s equations from quantum-informational principles.
- **Emergent field equations:** derive how Einstein-like field equations might emerge from the correlation structure. One approach would be to identify how correlation density gradients relate to energy-momentum distributions, potentially yielding equations of the form:

$$R_{ij}(x) - \frac{1}{2}R(x)g_{ij}(x) \propto T_{ij}[\rho_{\text{clock}}]$$

where $T_{ij}[\rho_{\text{clock}}]$ would be an effective energy-momentum tensor derived from correlation dynamics. The precise form of $T_{ij}[\rho_{\text{clock}}]$ remains to be derived, and its structure may depend on the nature of the observer slicing, time-dependence of the state, and additional assumptions. This would complete the analogy with general relativity, showing how correlation patterns not only determine geometry but also govern its evolution according to physical principles.

We view this paper as establishing the conceptual groundwork upon which these questions can be systematically addressed in subsequent investigations.

5. Conclusions and Outlook

We have presented a framework in which spacetime is an emergent construct, arising from the rich structure of quantum correlations in a global wavefunction. By introducing the correlationhedron K_ψ and a set of axioms, we showed how classical concepts — locality, dimensionality, curvature, and even the flow of time — can be interpreted as approximate, observer-dependent properties of an underlying quantum-correlation geometry.

In this revised formulation, we have clarified how the correlationhedron is defined as a convex set of correlation vectors obeying quantum constraints (Axiom A1 and A2), and how an observer’s choice (reference frame or measurement context) picks out a slice $\pi_\theta(K_\psi)$ that functions as that observer’s spacetime (A3). We expanded on how locality emerges from clustering of correlations (A4) with concrete examples, and on the intriguing duality between entanglement and time (A6) that suggests observers may trade one for the other in their description of reality. A quantitative toy example with two qubits illustrated how an entangled state yields a strongly curved emergent metric, whereas a separable state yields a flat one, capturing the idea that entanglement creates the “close-knit” fabric of spacetime. We also included schematic figures to visualize these concepts: the shape of K_ψ

together with the action of observer projections (Figure 1), and the relationship between entanglement distribution and induced curvature (Figure 2).

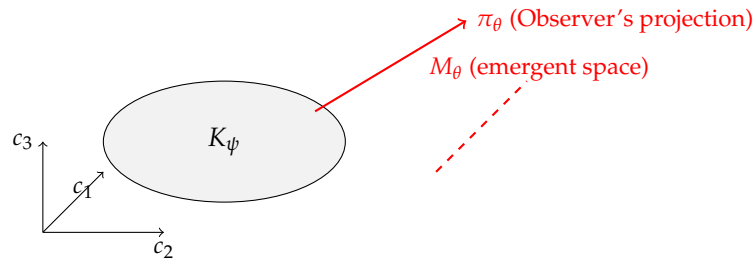


Figure 1. Schematic illustration of the correlationhedron K_ψ (high-dimensional convex set of all correlation vectors for state ψ). An observer (characterized by parameters θ) projects this structure via a map π_θ onto a lower-dimensional manifold M_θ which is interpreted as that observer's emergent spacetime. Different choices of θ (observers) yield different slices or projections of K_ψ , potentially resulting in very different effective spacetimes.

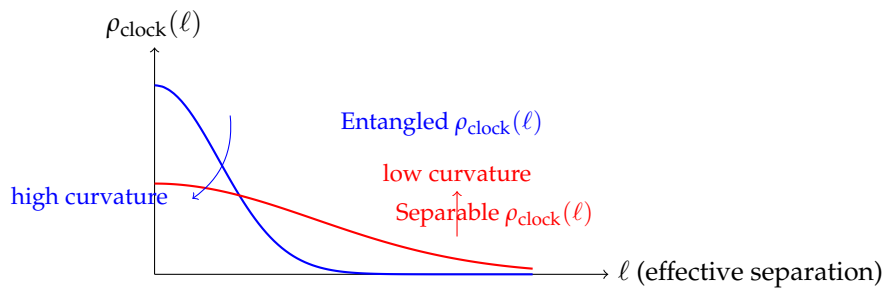


Figure 2. Illustrative correlation density $\rho_{\text{clock}}(\ell)$ as a function of emergent separation ℓ for an entangled two-qubit state (blue) versus a separable state (red). The entangled state's correlation density is sharply peaked at $\ell = 0$, indicating the two qubits are effectively at zero distance in the emergent space (strongly correlated in all bases). The separable state's $\rho_{\text{clock}}(\ell)$ is broader and flatter, suggesting the qubits are far apart or disconnected in the emergent picture. The second derivative of $\ln \rho_{\text{clock}}(\ell)$ (cf. Eq. (2) and Eq. (4)) (related to curvature) is large for the entangled case (tight peak) and nearly zero for the separable case (flat distribution), illustrating how entanglement generates curvature in the emergent geometry. Curvature is proportional to the second derivative of $\log \rho$.

The connections drawn to AdS/CFT, tensor networks, and relational quantum theories situate this work in a broader context. Notably, the common theme is that information constructs reality: whether it be the entanglement entropy dictating minimal surfaces in AdS[2], tensor network entanglement patterns encoding a holographic metric[3], or the relational viewpoint that state is observer-dependent[4], all resonate with the idea that spacetime might be an effective description arising from deeper quantum structure[11]. Our framework contributes to this discourse by providing a set of principles and a scaffold to potentially unify these ideas and apply them to arbitrary quantum states (not just highly symmetric ones).

However, many open questions and limitations remain. Most significantly, this framework in its current form is largely *kinematic*. We have not derived the dynamical laws of emergent spacetime — there is no equivalent yet of Einstein's equations or a mechanism for how $g_{ij}(x)$ back-reacts on K_ψ when ψ changes. In a fully realized theory, we would want to see how unitary evolution of the quantum state (or changes in entanglement due to, say, subsystem interactions) translates to dynamics in M_θ (perhaps emergent gravitational or cosmological behavior). Addressing this will likely require additional axioms or input, possibly relating changes in $\rho_{\text{clock}}(x)$ to energy-momentum constraints. For now, we can only speculate on the qualitative form of such emergent dynamics. If ψ evolves in time (due to unitary dynamics or interactions), then K_ψ itself deforms in correlation space, and consequently an observer's $\rho_{\text{clock}}(x)$ and metric $g_{ij}(x)$ on M_θ will change with time. Intuitively, increasing entanglement in certain degrees of freedom should concentrate $\rho_{\text{clock}}(x)$ in the corresponding region of M_θ , deepening the curvature there (akin to how added mass-energy curves spacetime in general relativity), whereas a

significant loss of entanglement would flatten out those regions or even cause the emergent spacetime to split into disjoint parts (consistent with the idea that extreme disentanglement can disconnect space[7]). One could envision an equation governing $\partial_t g_{ij}(x)$ in terms of $\partial_t \rho_{\text{clock}}(x)$ or other state parameters—analogue in spirit to Einstein’s field equations, but emerging from quantum dynamics rather than imposed as fundamental. While these ideas are admittedly speculative, they provide a glimpse of how a dynamical theory might be incorporated into our correlation-centric framework.

Another limitation is the issue of **causality**. If each observer has their own emergent time ordering (A6) from their slice of correlations, how do we ensure that different observers’ causal structures are compatible or agree where they overlap? We have an implicit assumption that when observers share information, there is a consistent translation between their spacetimes. This touches on the quantum reference frame transformations discussed in Section 4.3. A future extension of this work should formalize how to move between M_θ and $M_{\theta'}$ — in the best case, recovering something analogous to Lorentz transformations or general coordinate transformations between emergent spacetimes. Until then, the framework has an observer-relativity that, while conceptually aligned with relational quantum mechanics, needs a dictionary to compare with our usual notion of a single objective spacetime that all observers inhabit.

The **topology** of emergent space is another subtle point (addressed briefly in Appendix A.3): depending on how K_ψ is sliced, M_θ could have exotic topology (even discontinuous or fragmented). Not all such topologies may make physical sense. We might need additional constraints to exclude unphysical emergent worlds or to explain why we experience a connected, smooth 3+1 dimensional world and not, say, two disconnected 2+1 worlds. It is tantalizing to think that quantum constraints (like monogamy of entanglement or constraints from quantum error correction) might naturally enforce a reasonable topology for M_θ in realistic scenarios[23][3], but this remains speculative.

Despite these challenges, the possible payoffs are high. If successful, this line of research could provide a new lens on the quantum gravity problem: rather than quantizing geometry, it “geometrizes” quantum mechanics. It suggests that the mysteries of gravity and spacetime might be resolved not by tweaking general relativity or quantum field theory in isolation, but by understanding the information-theoretic substrate that underlies both. This framework is still in a preliminary form, but it aligns with a number of emerging threads in theoretical physics that hint we are on the right track – that spacetime and gravity are emergent from the quantum world’s fabric of correlations[14].

An intriguing implication of this framework is that gravitational effects typically attributed to dark matter could, in part, arise from the geometric imprint of entanglement. When two systems are strongly entangled, the induced correlation density $\rho_{\text{clock}}(x)$ — and thus the emergent curvature — is not necessarily localized on the systems themselves, but can be distributed across the region connecting them. If both entangled partners lie within the observer’s projection, this curvature appears as a spatial bridge or concentration between them, contributing normally to the perceived mass distribution. However, if one partner lies outside the observer’s accessible sector of K_ψ , the associated curvature becomes delocalized: the observable system appears to curve space more weakly than expected, with the “missing” curvature effectively distributed into inaccessible regions. From the observer’s perspective, this manifests as a gravitational anomaly — curvature without corresponding visible matter — mimicking the presence of dark matter. In this view, then, certain dark matter effects might be reinterpreted as geometric artifacts of entanglement with degrees of freedom that are hidden, decohered, or beyond observational reach.

In closing, we reiterate the essential vision: *spacetime is not fundamental, but an evolving mosaic pieced together by observers from the correlations within an all-encompassing quantum state.*

This paper establishes the conceptual and mathematical foundations for this perspective, deliberately focusing on the static, structural aspects of the framework. The development of dynamics, explicit calculation methods for realistic systems, and refined connections to existing quantum gravity approaches represent natural extensions that we intend to address in forthcoming work. The correla-

tionhedron framework introduced here should be viewed as a starting point for a broader research program rather than a fully realized theory.

What appears continuous and geometric is, at its core, an abstraction of quantum information links. By studying those links directly (the correlationhedron K_ψ) and understanding how different perspectives give rise to different slices of reality, we take steps toward a theory that does not just unify physics at a formal level, but conceptually explains why the world has the appearance it does to us, and how that appearance might change under extreme quantum conditions. Future work will aim to further develop the mathematical apparatus (e.g. to handle dynamical evolution and multiple observers rigorously) and to explore toy models (like quantum simulators or tabletop experiments) that could provide hints of these correlation-built spacetimes in action.

Appendix A. Mathematical Preliminaries

Appendix A.1. Existence and Uniqueness of the Projection

In constructing the map $\pi_\theta : K_\psi \rightarrow M_\theta$, we assumed that an observer's perspective can always be represented as such a projection. Here we comment on conditions for the existence and some properties of π_θ . In general, an observer is characterized by a limited set of observables or measurement outcomes. Mathematically, this can be associated with a subalgebra \mathcal{A}_θ of the full observable algebra of the system. The state ρ (or K_ψ) restricted to \mathcal{A}_θ is given by a reduced density operator (via partial trace over unobserved degrees of freedom). If this restriction yields a well-defined smooth manifold of expectation values, we identify that manifold with M_θ . In many cases, M_θ might be simply \mathbb{R}^d for some d , with coordinates corresponding to $\langle O_1 \rangle, \dots, \langle O_d \rangle$ that the observer can measure. The projection π_θ is then essentially the map $\rho \mapsto (\langle O_1 \rangle, \dots, \langle O_d \rangle)$.

However, there is not a unique choice of \mathcal{A}_θ for a given observer; different sets of observables could encode the same “view” of reality. Moreover, different π_θ mappings could potentially yield the same manifold structure M_θ up to diffeomorphism. In our framework, we do not fix π_θ uniquely, but demand that it satisfies:

- **Positivity preservation:** If $\mathbf{c} \in K_\psi$ comes from state ρ , then any reconstructed state from $\pi_\theta(\mathbf{c})$ on M_θ (for example, by maximum entropy extension) should be a valid quantum state. In practice, this means linear constraints like $\rho_{\text{clock}}(x) \geq 0$ and no negative probabilities in the observer's reduced description.
- **Smoothness:** π_θ should be a smooth map such that small changes in the state (or in \mathbf{c}) result in small changes in M_θ . This ensures the emergent metric is well-defined. If π_θ were highly discontinuous or non-differentiable, an observer's space would not appear geometric.
- **Maximal information for given observer:** π_θ should lose only the information that the observer truly cannot access. If an observer has access to certain observables, π_θ should include those correlations. In other words, M_θ should be “as large as possible” while still being a valid representation of the observer's knowledge.

Existence of π_θ is essentially guaranteed by the fact that any quantum state can be reduced to an observer's subalgebra (by partial trace). Uniqueness is not guaranteed; indeed, there could be many coordinate choices on M_θ . This is analogous to general relativity, where one can have many coordinate systems on the same manifold. We might identify a class of projections as equivalent if they are related by smooth transformations on M_θ . A deeper question is whether some natural choice of π_θ exists (e.g., perhaps the one that extremizes some entropy or information measure), but we leave this open. For our purposes, we assume an appropriate π_θ has been chosen for each observer and focus on the consequences.

Appendix A.2. Hessian-Based Metric

The emergent metric

$$g_{ij}(x) = \frac{\partial^2}{\partial x^i \partial x^j} \ln \rho_{\text{clock}}(x)^{-1}$$

has the form of a Fisher information metric on the space of correlation configurations (if we regard $\rho_{\text{clock}}(x)$ as defining a probability density). This connection to information geometry is not accidental: K_ψ can be viewed as a kind of statistical manifold (the set of correlation vectors consistent with some state). Our choice of metric ensures that if $\rho_{\text{clock}}(x)$ is Gaussian in some coordinates, those coordinates are Cartesian (flat metric), and if $\rho_{\text{clock}}(x)$ is sharply peaked, geodesic distances shrink accordingly.

One might wonder about the sign convention: why $\ln \rho_{\text{clock}}(x)^{-1}$ rather than $\ln \rho_{\text{clock}}(x)$? Both yield the same Hessian up to a minus sign (since an overall sign in the metric is immaterial for Riemannian geometry). We write $\ln \rho_{\text{clock}}^{-1}$ to emphasize that peaks in ρ_{clock} correspond to wells (i.e., positive curvature) in the emergent geometry — reminiscent of how high energy density produces positive curvature in general relativity.

There are situations in information geometry where the Hessian of a log-density is flat (not curved) even for non-trivial distributions. For instance, exponential families yield a flat information metric under certain coordinates (known as the mixture or expectation parameters). In our context, if $\rho_{\text{clock}}(x)$ happened to belong to an exponential family under some parametrization, the observer's coordinates might make the emergent space appear flat even though the distribution has structure. This is not a contradiction; it simply means those coordinates are natural for the information-geometric structure of M_θ . If an observer happens to pick such “lucky” observables that linearize ρ_{clock} , they'd see flat space.

The metric $g_{ij}(x)$ is by construction symmetric and (if $\rho_{\text{clock}}(x)$ is smooth and non-zero in a neighborhood) positive-definite as a matrix. It is also automatically compatible with the fact that $\rho_{\text{clock}}(x)$ is a probability density on M_θ (up to normalization) — $g_{ij}(x)$ is the Fisher metric, which is the only metric (up to scalar factor) that is invariant under mixture and reparameterization of distributions. These invariances correspond to a kind of gauge freedom: relabeling points in M_θ or redistributing probability under an exponential family transformation doesn't change the geometry. This is analogous to coordinate invariance in general relativity.

Appendix A.3. Topological Considerations

Global topological properties of the emergent manifold M_θ depend on how the observer slices K_ψ . Different projection choices may yield topologically distinct spaces. For instance, an observer could effectively “trace out” (ignore) certain modes or subsystems, causing what was a connected set of correlations to appear disconnected in M_θ .

Consider a situation where the universal state ψ consists of two largely unentangled sectors (e.g., two groups of particles that have almost no correlations between them). An observer who has no access to correlations between the sectors might see two separate spacetimes, one for each sector. This would mean M_θ has two disconnected components. Another example: if the observer's projection identifies (glues together) different regions of K_ψ as equivalent (perhaps by a symmetry or degeneracy in their accessible data), then M_θ could have points that are actually the same “place” in K_ψ , leading to identification of boundaries or a quotient topology (analogous to how identifying opposite edges of a square yields a torus topology).

In our framework, we have not deeply addressed topology, but we anticipate that:

- If the underlying K_ψ is “simple” (contractible, etc.) and the observer's projection is well-behaved, M_θ will likely be a single connected manifold (possibly \mathbb{R}^n or a single chart thereof).
- If K_ψ has multiple prominent correlation clusters separated by correlation gaps (very weak correlation in between), an observer focusing on one cluster might get an M_θ that covers only that cluster's effective space. In effect, parts of K_ψ can act like separate universes if they're not correlated at all.
- Situations analogous to wormholes: If ψ has two distant parts that are nevertheless highly entangled (EPR pairs across two subsystems), an observer's space might show them as adjacent or even identify them as one. This could be seen as a non-trivial topology where two distant regions are connected through a “bridge” in M_θ . Holographically, this is like the ER=EPR idea

- a quantum entangled pair creates a handle/glue between what classically would be separate regions.

We note that these topological features are not arbitrary: the quantum state's structure constrains them. For example, one cannot arbitrarily connect two regions in M_θ unless there are corresponding entanglements in K_ψ . Additionally, certain approaches to quantum gravity (like spin foam models or causal dynamical triangulations) also face the challenge of how classical topology emerges from quantum configurations [14,23]. In those approaches, summing over topologies or having a superposition of different spacetime topologies is often considered. In our approach, K_ψ is fixed for a given state, but different observers might effectively “see” different topology. We leave a detailed classification of emergent topologies for future work, but highlight that the possibility of emergent topology change in observer-space is a novel feature of our framework.

If M_θ can have multiple components, one might ask: can an observer experience those as separate worlds? If the observer has literally no access to correlations between them, then yes — they might as well be separate universes. However, if any bridging correlations are introduced, M_θ would become connected. This offers a perspective on how a multiverse-like scenario could be described in one wavefunction: truly disconnected correlation sectors yield effectively separate spacetimes for an observer. Monogamy of entanglement, which limits how entangled one subsystem can be with others, can impose a kind of cosmic speed limit on how connected different parts of K_ψ can be.

These considerations are speculative but serve to show that the framework has room to explore questions usually reserved for quantum gravity: not just the shape of spacetime, but how many components it has, whether there are handles or loops, etc., all determined by the entanglement structure of ψ and what the observer can see.

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