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A Vectorial Axiomatization of Space – Time Unity

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Abstract

This article presents a novel foundational framework for physics, grounded in a minimalist vectorial ontology. I propose that the unified fabric of reality is described by a fundamental abstract state space F, whose elements are normed vectors Ψ. From this single premise, a complete axiomatization of space-time and quantum phenomena is derived. The core innovation is the definition of space and time not as independent continua, but as complementary projections of the state vector: Ψ = (S, T). A set of nine axioms is introduced, imposing constraints on these components: their magnitudes are equal (|S| = c|T|), their directions are antiparallel (S = -T), and their evolution is a norm-preserving unitary redistribution. From these purely algebraic and geometric relations, I demonstrate the emergence of Minkowskian space-time with its Lorentzian metric, the invariant speed of light *c*, and a causal structure defined by the connectivity of F. The framework naturally incorporates quantum mechanics by identifying unitary evolution on F as the fundamental dynamical principle, with measurement and classicality arising via environmental decoherence and the dynamical selection of pointer states (Axiom IX). This work offers a path toward resolving the quantum gravity problem by suggesting that both geometry and quantum states are manifestations of a deeper vectorial substrate, thereby unifying relativity and quantum theory within a single, observer-independent mathematical structure.

Keywords: Foundational Physics, Space-Time Unity, Vectorial Axiomatics, Quantum Gravity, Emergent Geometry, Unitary Evolution, Causal Structure.

Introduction: The Need for a Unifying Substrate

The quest for a unified description of physical reality stands as the defining challenge of contemporary theoretical physics. This pursuit is fundamentally complicated by the profound conceptual and mathematical dichotomy between our two most successful frameworks: the quantum theory of fields and particles, and Einstein's general theory of relativity. The former is formulated on a fixed, pre-geometric space-time stage, treating its metric as a static background (Weinberg, 1995). The latter elegantly dynamizes this metric, identifying gravity with the curvature of a smooth, deterministic 4-dimensional manifold (Einstein, 1915). Their reconciliation into a theory of quantum gravity has proven notoriously difficult, suggesting that the problem may not merely be technical but deeply foundational (Rovelli, 2004).

A critical examination reveals a common, often unspoken, presupposition at the heart of both theories: the primacy of space-time as a continuum of events, a priori endowed with topological and geometric properties. In quantum field theory, operators are defined on this manifold; in general relativity, the manifold itself is the dynamical object. This shared premise forces quantization procedures—such as canonical quantum gravity or string theory—to quantize geometry, leading to well-known issues of non-renormalizability, the problem of time, and the measurement paradox in a gravitational context (Isham, 1993). It prompts a radical, yet increasingly compelling, question: What if space-time itself is not fundamental?

This paper advocates for a profound ontological inversion. Instead of quantizing the geometry of space-time, we propose that both the geometric and the quantum aspects of nature co-emerge from a more primitive, pre-geometric substrate. The core hypothesis is that this substrate possesses an inherently vectorial character. This is not a new idea in isolation. The central role of vector (Hilbert) spaces in quantum mechanics is axiomatic (von Neumann, 1932). Similarly, the tangent vector spaces are the building blocks of the space-time manifold in differential geometry (Misner, Thorne, & Wheeler, 1973). However, these vector structures are typically considered secondary: Hilbert space is built over space-time, and tangent spaces are attached to the manifold. We posit the reverse: that an abstract vector space, with its associated algebraic and normative structure, is the primary ontological entity.

Our approach, therefore, seeks a vectorial axiomatization. We aim to construct a minimal set of postulates centered on a fundamental state space F, from which the familiar concepts of event, manifold, metric, and even quantum state superposition can be derived as relational or phenomenological consequences. This work aligns with and seeks to formalize research programs that view space-time as emergent from quantum information processing (Lloyd, 2006), entanglement (Van Raamsdonk, 2010), or non-commutative algebraic structures (Connes, 1994). However, it distinguishes itself by placing a simple, normed vector space at the absolute starting point, prior to any notion of dimension, locality, or metric signature.

The objective of this article is to lay down the foundational layer of this axiomatic system. We begin at the "zeroth level," defining the essential mathematical architecture of the fundamental state space F. This is followed by the introduction of first-principle axioms that forge a bridge between this abstract space and the phenomenological reality of events, directions, and dynamics. These initial steps do not yet construct full general relativity or quantum field theory; rather, they aim to provide the consistent bedrock upon which such constructions may later be built, potentially bypassing the traditional contradictions.

The structure of this paper is as follows. In Section 2, we present the zeroth-level definitions, establishing the properties of the space F. Section 3 introduces the first physical axioms, linking states in F to space-time events and directional structures. Section 4 explores the axiomatic foundation for dynamics as a norm-preserving flow. Finally, Section 5 discusses the implications of this framework, its connection to existing research, and the path forward towards deriving established physics. By pursuing this axiomatic path, we hope to contribute to a framework where the unity of space-time is not an imposed condition, but a logical necessity arising from the very nature of physical state itself.

Foundational Definitions: The Fundamental State Space (Zeroth Level)

This section establishes the primitive, pre-physical mathematical framework. It defines the arena—the fundamental abstract space F—before any physical interpretation is assigned.

Definition 1. Fundamental Abstract State Space (F)

There exists a fundamental abstract space of states, denoted by F, which admits:
i. A vectorial representation, implying F is endowed with the structure of a linear space over the field of complex numbers, C. This means elements of F can be added and multiplied by scalars, fulfilling the axioms of a linear space.
ii. A norm, providing a notion of "magnitude" or "extent" for any element of F. Formally, there exists a map $|| \, . \, || : F \to R{\geq}0$ satisfying: $||\Psi|| = 0$ if and only if $\Psi = 0$; $||\alpha\Psi|| = |\alpha| \, ||\Psi||$ for any complex α; and the triangle inequality $||\Psi + \Phi|| \leq ||\Psi|| + ||\Phi||$.
iii. An operation of direction, which can be formally associated with the equivalence relation of collinearity. For any non-zero Ψ, Φ in F, a notion of "sameness of direction" is defined, typically induced by the underlying linear structure (i.e., Ψ and Φ share a direction if $\Psi = \alpha\Phi$ for some non-zero complex α).

Rationale: The choice of a vector space is minimal and powerful. It is the simplest structure that naturally incorporates the principle of superposition, a feature non-negotiable in quantum mechanics (Dirac, 1930) and implicit in the linearity of classical field equations and tangent space operations. The norm is prerequisite for any concept of measurement, scale, or probability. It introduces a topology and a concept of "size" without yet specifying what that size physically represents. The operation of direction is the abstract seed from which geometric concepts like tangent vectors, propagation, and ultimately, causal structure will grow.

Definition 2. System State

The complete state of any physical system, at a given logical instant, is represented by a vector in F. For a system S, its state is denoted by:
$\Psi\_S \in F$.

This definition is intentionally epistemic and universal. The vector Ψ_S does not yet describe a field at a point in space or a wave function in configuration space. It is the maximal mathematical representation of the system's "condition." The physical meaning of Ψ_S—whether it corresponds to a quantum state, a field configuration, or a more exotic object—will be conferred by subsequent physical axioms that act upon F and relate its elements to each other. This approach treats the state vector as the primary ontological entity, a perspective with deep roots in quantum foundations but here extended to encompass all of physics (Haag, 1992).

These two definitions constitute the inert, mathematical starting point. They contain no physics, only the potential for it. In the following section, we will breathe physical life into this structure by introducing axioms that connect F to the phenomena of events and space-time.

Axiom I: The Unity of Space and Time

The foundational definitions established a pre-geometric, normed vector space F as the ontological substrate. We now introduce the first physical axiom, which breathes life into this abstract structure by positing the precise mechanism through which the phenomenological categories of space and time arise. This axiom, termed Axiom I (Unity), constitutes the core conceptual leap of this framework.

Axiom 1 (Unity).

Space and time are not independent, pre-existing continua. They are emergent, complementary projections of a single, fundamental state vector $\Psi \in F$. This vector possesses an intrinsic structure that can be decomposed into two mutually dependent components. Formally, we denote:
$\Psi = (S, T)$
where:

- S represents the spatial component, a mathematical object encoding all structural, configurational, and locational information.
- T represents the temporal component, a mathematical object encoding the dynamic, sequential, and durational information.

Crucially, S and T are not merely added together; they are fused within the unitary object Ψ. They exist in a relationship of complementary projection. One cannot fully specify S without implicitly specifying T, and vice versa. This echoes the profound insight of Minkowski (1908), who declared that "henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality." However, while Minkowski unified space and time into a 4-dimensional continuum, Axiom 1 goes a step further by deriving this continuum itself from the decomposition of a more fundamental vector.

The axiom posits that what we perceive as a spatial separation between two events is a measure related to the difference between their associated state vectors' S-components, as conditioned by their T-components. Conversely, a temporal interval is related to the difference in T-components, as conditioned by the S-components. This interdependence is not a feature of a pre-existing manifold but the very origin of the manifold's causal and metric structure (Rovelli, 2004).

Mathematical Representation and Geometric Interpretation

The notation $\Psi = (S, T)$ requires careful interpretation. It does not imply that F is a simple Cartesian product of a "space subspace" and a "time subspace." Such a product would preserve independence, not enforce unity. Instead, we propose that F possesses a structure akin to a fiber bundle or a specific algebraic direct sum, where the S and T components are intertwined through constraints defined by the norm and the directional operation on F.

A more revealing representation utilizes the concept of a generalized phase factor. Let the norm of the state vector, $||\Psi||$, represent an invariant "world-volume" or "existence extent." The familiar 3+1 splitting of spacetime could then emerge from a polar-like decomposition of Ψ:
$\Psi = ||\Psi|| \ \exp(i (\Omega_S + \Omega_T))$,
where Ω_S and Ω_T are conjugate phase operators whose eigenvalues are linked to spatial and temporal localization, respectively. Their non-commutation, $[\Omega_S, \Omega_T] \neq 0$, would then directly give rise to the uncertainty between precise spatial location and precise temporal moment, a foundational quantum-gravitational effect hinted at in various approaches (Kempf, Mangano, & Mann, 1995). In this view, projecting onto "space" means partially fixing Ω_S, which forces a spread in Ω_T, and thus a fuzziness in temporal definition.

This formulation naturally connects to the path-integral approach, where the amplitude for a process is a sum over histories—each history being a specific pairing of spatial configuration (S) and temporal evolution (T) (Feynman & Hibbs, 1965). Axiom 1 suggests that this sum is not over external parameters but over different internal projections of the universal state vector.

Physical Consequences and Correspondence Principle

The Unity Axiom leads to several immediate conceptual consequences that align with established physics and suggest resolutions to long-standing problems.

1. The Relativity of Simultaneity as a Projection Artifact: In Special Relativity, whether two spatially separated events are simultaneous is frame-dependent. In this axiomatic system, this follows directly. A "frame of reference" corresponds to a particular choice of basis in F for separating the total information in Ψ into what is labeled "S" and what is labeled "T." A Lorentz transformation is then a change of this basis—a different "perspective" for projecting the unified Ψ onto a spatial slice and a temporal flow (Einstein, 1905). Simultaneity is not an absolute property of events but a consequence of the chosen projective decomposition.

2. The Origin of the Lorentzian Signature: The famous minus sign in the Minkowski metric ($ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2$) finds a natural origin here. It can be seen as a signature of the complementary relationship between the S and T projections. The invariant norm $||\Psi||^2$ might be given by a sesquilinear form like:
   $||\Psi||^2 = \langle\Psi|\Psi\rangle = \langle T|T\rangle - \langle S|S\rangle$,
   where the negative sign on the spatial part (or positive on the temporal, depending on convention) ensures that causal, timelike separations (dominated by T) have a positive norm, while spacelike separations (dominated by S) contribute negatively. This is not an ad hoc imposition but could arise from the requirement that physically realizable state evolutions (world-lines) preserve a positive, reparametrization-invariant norm (Hestenes, 1966).

3. A Path to Quantum Gravity: The primary obstacle in canonical quantum gravity is the "problem of time"—time disappears as a dynamical variable in the Wheeler-DeWitt equation, leading to a static universe (Isham, 1993). Axiom 1 reframes this. Time T is not a parameter on which Ψ depends; it is part of Ψ. The Wheeler-DeWitt constraint, $H\Psi = 0$, where H is the Hamiltonian constraint, can be interpreted as a condition enforcing the internal consistency of the S-T split within Ψ. Dynamics is then not evolution in time, but a correlated, unitary change in the S and T components of Ψ, from which the illusion of temporal flow emerges for internal observers described by subsystems of Ψ (Page & Wootters, 1983).

Connection to Entanglement and Holography

The unified state vector Ψ is inherently global and non-local. For a composite universe, Ψ cannot be simply factored into independent spatial and temporal parts for different regions. This suggests that the local, smooth geometry of spacetime we experience is an approximate, thermodynamic description valid only when immense numbers of fundamental degrees of freedom are entangled in a specific way.

The entanglement entropy between the degrees of freedom associated with a spatial region (a specific S-projection) and its complement has been conjectured to be related to the area of the region's boundary, a key idea in the holographic principle (Ryu & Takayanagi, 2006). In our framework, this can be reinterpreted: the entropy quantifying the entanglement between the S and T aspects of Ψ, when restricted to a volume, defines that volume's geometric boundaries. Space itself, and its metrical properties, may be a consequence of the way information in the unified Ψ is entangled and statistically organized (Van Raamsdonk, 2010).

Conclusion of Section

Axiom I, the Unity Axiom, provides the critical bridge from the abstract state space F to the phenomenology of relativity. By identifying space (S) and time (T) as complementary, inseparable projections of a single state vector Ψ, it makes their unification not a consequence of a geometric postulate, but the foundational principle itself. This move inverts the standard approach: instead of constructing quantum theory on spacetime, it derives spacetime from the structure of quantum-theoretic primitives.

The following sections will build upon this foundation. Axiom II (Direction) will elaborate how the directional operation in F gives rise to the tangent bundle and causal structure of the emergent spacetime manifold. Axiom III (Dynamics) will specify the norm-preserving flow that governs the change of Ψ, from which both the geodesic principle of general relativity and the unitary evolution of quantum mechanics must be shown to arise as effective descriptions.

Axiom II: Modular Symmetry and the Origin of the Invariant Interval

Following Axiom I (Unity), which posits that space (S) and time (T) are complementary projections of a fundamental state vector Ψ = (S, T), we must now constrain their relationship to recover the known structure of relativistic physics. The next axiom introduces a precise symmetry condition that dictates how the magnitudes of these components interrelate, leading directly to the concept of an invariant spacetime interval.

Axiom II: The Equality of Moduli

Axiom 2 (Modular Symmetry).
The magnitudes (moduli) of the spatial and temporal components of the fundamental state vector, in their native representation, are equal. Formally:
$|S| = |T|$
This equality is fundamental and invariant; it does not depend on any particular frame of reference or observational perspective.

This axiom is deceptively simple yet profoundly consequential. It asserts a deep symmetry between the "amount" of spatial structure and the "amount" of temporal structure within any given state vector Ψ. The moduli |S| and |T| are not the observable spatial and temporal intervals we measure with rods and clocks. Instead, they are more primitive quantities, the intrinsic "strengths" of the S and T projections from the unified Ψ. Their enforced equality is the linchpin that allows different observers, performing different projections (i.e., in different inertial frames), to agree on a combined, invariant quantity.

Derivation of the Invariant Interval and the Lorentz Factor

To connect this axiom to physics, we must define how an observer in a specific frame extracts measurable coordinates. An observer's frame is defined by a specific choice of basis in F that decomposes Ψ into their measured spatial displacement vector x and their measured temporal coordinate t. This process is a refinement of the general projection from Ψ to (S, T). Crucially, the observer's x and t are specific realizations of the more abstract S and T.

Let us denote the measured components in a specific frame as (S', T'), where S' corresponds to a 3-dimensional spatial vector x and T' corresponds to a scalar temporal value multiplied by a fundamental conversion constant with dimensions of velocity (which will naturally become the speed of light, *c*), i.e., T' = c t.

Axiom 2 states that the intrinsic, frame-invariant moduli are equal: |S| = |T|. However, different observers, using different bases (different frames), will assign different measured values (S', T') to these invariant objects. The relationship between the invariant moduli (|S|, |T|) and the measured values (|S'|, |T'|) in any given frame is governed by the geometry of the projection. This is analogous to how the length of a vector in Euclidean space is invariant, but its x and y components vary with the rotation of the coordinate axes.

We postulate that this relationship takes the form of a Pythagorean theorem in a space with a specific signature. For an observer at rest relative to the intrinsic orientation of Ψ (a notion that defines the "rest frame" of the event or object described by Ψ), we have a direct correspondence: |S_rest| = |S'| and |T_rest| = |T'|. In this rest frame, Axiom 2 reads: |S'_rest| = |T'_rest|.

Now, consider an observer moving with constant velocity v relative to this rest frame. Their measurement corresponds to a "rotation" in the abstract S-T space (a Lorentz boost). For this moving observer, the measured spatial modulus |S'_v| and temporal modulus |T'_v| will change, but they will be related to the invariant, rest-frame moduli by hyperbolic trigonometric functions. Standard relativistic kinematics (Einstein, 1905) dictates that these measured quantities are related by:
|T'_v|^2 - |S'_v|^2 / c^2 = |T'_rest|^2 - |S'_rest|^2 / c^2 = constant.

Since in the rest frame |S'_rest| = |T'_rest|, the constant is zero. Therefore, for any observer, the measured quantities must satisfy:
(c t)^2 - |x|^2 = 0, or |x|/t = c.
This describes the propagation of a light signal—a null interval. For a massive object or a general separation between events, the invariant constant is not zero, but the form of the invariance ($c^2\Delta t^2 - \Delta|x|^2$ = invariant) is forced upon us by the requirement to maintain the deeper, hidden symmetry |S| = |T| under all observer-induced projections. The Lorentz factor, $\gamma = 1/\sqrt{(1 - v^2/c^2)}$, emerges naturally as the hyperbolic cosine of the "rotation angle" between different projective bases.

Thus, Axiom 2 is the generative seed for the Minkowski metric and the invariance of the spacetime interval. It explains why the interval has its specific form: it is the conserved quantity that encodes the preservation of the fundamental S-T symmetry across all frames (Minkowski, 1908).

Physical Interpretation and Connection to Quantum Foundations

The equality |S| = |T| can be interpreted as a condition of balanced information. The state vector Ψ contains information about "where" and "when," and Axiom 2 states that, in their fundamental units, the informational content allocated to spatial localization and temporal sequencing is equal. This resonates with concepts in quantum information theory applied to spacetime.

For instance, consider a process governed by the quantum mechanical path integral. The amplitude is $\exp(iS/\hbar)$, where S is the classical action. For a free relativistic particle, the action is proportional to the proper time, which is precisely the invariant interval—the entity we derived from Axiom 2. The phase of the quantum amplitude thus becomes a direct measure of the "balance" between S and T components along a path. The principle of stationary phase (leading to classical trajectories) is then the condition that this balance is extremized (Feynman & Hibbs, 1965).

Furthermore, this axiom may shed light on the nature of mass. A massive particle can be viewed as a state Ψ where the intrinsic S-T symmetry is preserved ($|S| = |T|$), but the observable projections yield a timelike interval ($c^2\Delta t^2 > \Delta|x|^2$). The rest mass m can be linked to the invariant modulus itself, $m c^2 \sim \hbar/\tau$, where τ is the invariant proper time derived from |S| and |T|. In contrast, a photon would correspond to a limiting case where the projections for all observers maintain the strict equality of the measured components, leading to a null interval. This aligns with the perspective that mass arises from the coupling of a system to a background field (the Higgs mechanism) that subtly alters the projective relationship between S and T without breaking the underlying symmetry (Wilczek, 1999).

Empirical Consistency and a New Perspective on Constants

Axiom 2 is consistent with special relativity but offers a novel interpretation of the speed of light, *c*. Here, *c* is not fundamentally a "speed of light" but a universal scale conversion constant that relates the intrinsic units of the abstract temporal component T to the units of the spatial component S. Its universality is a direct consequence of the universality of the fundamental state space F and its associated norm. Light merely propagates in a manner that perfectly manifests this equality in every observational frame.

This perspective naturally invites a question about the dimensionality of F. If |S| and |T| are to be equated, they must be dimensionally consistent. The constant *c* provides this consistency, converting time into a length. This suggests that at the level of F, there may be only one fundamental dimension—that of action, entropy, or information—from which both spatial extent and temporal duration are derived as commensurate quantities (Cunningham, 1914). This aligns with modern ideas in fundamental physics suggesting the dimensionless nature of the universe (Barrow, 2002).

Implications for General Relativity and Quantum Gravity

In the curved spacetime of general relativity, the invariant interval becomes a local concept governed by the metric tensor $g_{\mu\nu}$. Axiom 2 must therefore be promoted to a local, dynamical constraint. We hypothesize that Einstein's field equations arise as the condition that preserves the local equality $|S| = |T|$ in the presence of energy-momentum distributions that warp the projective relationship between the abstract state vectors and the local tangent spaces.

In a quantum gravitational context, this axiom suggests a promising direction: the quantum states of geometry should be those that respect, in expectation value or as an eigenvalue condition, the fundamental symmetry between spatial and temporal flux operators. This could provide a clean way to incorporate the causal structure directly into the definition of quantum states, an advantage sought after in approaches like Causal Dynamical Triangulations (Ambjørn, Jurkiewicz, & Loll, 2004) or causal set theory (Bombelli, Lee, Meyer, & Sorkin, 1987).

Conclusion of Section

Axiom II, the Modular Symmetry axiom, transforms the qualitative unity of Axiom I into a precise, quantitative principle. By enforcing $|S| = |T|$, it provides the mechanism that generates the invariant spacetime interval, the Lorentz transformations, and gives a fundamental reason for the universal role of the speed of light *c*. It reinterprets relativistic invariance not as a property of spacetime itself, but as a necessary consequence of preserving a deeper symmetry within the state vector during observational projection. This moves us significantly closer to the goal of deriving the fabric of reality from the algebra of state space F. The next step, Axiom III (Dynamics), will define the law governing the evolution of Ψ, from which the geodesic principle and ultimately the Einstein field equations must emerge.

Connection to Quantum Mechanics: The Born Rule and Phase Relationships

The antiparallelism axiom offers a fascinating geometric perspective on quantum probability. In the complex vector space F, the condition $S = -T$ is likely to be represented in terms of phase relationships. If we represent the state as $\Psi = |\Psi| \exp(i\varphi)$, the S and T components could be associated with specific phase factors. Antiparallelism suggests their phases differ by π (180 degrees). This π-phase difference is the maximal quantum phase distinction.

Consider a quantum superposition. The probability according to the Born rule is given by the squared amplitude. In our framework, the probability of a projection onto a specific spatial configuration (finding S) might be related to the extent to which the internal phase relationship (the $S = -T$ condition) is preserved or disrupted during the measurement interaction. The famous minus sign in quantum interference finds a potential root here: two amplitudes contributing to an event where their internal S-T orientations are "opposite" in this sense could lead to destructive interference (Feynman, Hibbs, & Styer, 2005).

Furthermore, this provides a new angle on the concept of Wick rotation in quantum field theory, where time t is analytically continued to imaginary time it to relate quantum statistical mechanics to Euclidean field theory. The operation $t \to it$ is, in complex vector space terms, essentially a rotation by π/2. Our axiom $S = -T$, if S and T are treated as orthogonal directions in a complexified space, establishes a fixed starting relationship from which such rotations can be meaningfully defined (Hardy, 2001).

Implications for Cosmology and the Initial State

The most significant consequence of Axiom 3 may be cosmological. If every fundamental state carries an intrinsic temporal orientation ($S = -T$), then the universe as a whole, described by some universal wave function or state vector Y, must also exhibit this property. This could provide a natural explanation for the low-entropy initial condition of the Big Bang, which is the ultimate source of the observed thermodynamic arrow of time (Carroll, 2010).

The initial singularity or Planck-scale state of the universe would be one where this internal antiparallelism was globally and coherently defined. As the universe evolved and its state vector branched or decohered, this fundamental causal orientation would be inherited by all subsystems, enforcing a consistent local arrow of time. This resolves the need to postulate a special boundary condition ad hoc; it becomes a necessary feature of any physical state in this axiomatic system (Page, 1985).

Synthesis of the Axiomatic Foundation

With Axioms I, II, and III, the kinematical foundation of the theory is complete:

1. Unity (Ψ = (S, T)): Space and time are projections of one entity.
2. Modular Symmetry (|S| = |T|): These projections are balanced in scale, yielding the invariant interval and the constant *c*.
3. Antiparallelism (S = -T): These projections are maximally opposed in direction, endowing the structure with an intrinsic causal orientation and the arrow of time.

This triad derives the essence of Minkowski space-time—its unified nature, its Lorentzian metric signature, and its causal structure—not from postulating a manifold, but from the intrinsic geometry of a state vector in an abstract space F. It presents space-time as a codified representation of the internal correlations and oppositions within the quantum state of the universe.

The remaining task for this research program is to introduce the dynamical axiom—the law governing sequences {Ψ(λ)}. This law must be a norm-preserving flow (unitarity) on F that, in the classical limit and under the constraints of Axioms I-III, yields the Einstein field equations. It will be the subject of the next paper in this series, moving from the axiomatics of space-time unity to the dynamics of quantum gravity.

Axiom III: Vectorial Antiparallelism and the Emergence of Causality

Building upon Axiom I (Unity: Ψ = (S, T)) and Axiom II (Modular Symmetry: |S| = |T|), we now introduce the final, most constraining foundational axiom. This axiom defines the specific directional relationship between the spatial and temporal components, thereby endowing the emerging space-time structure with an intrinsic causal order—the distinction between past and future.

Axiom III: The Antiparallelism Condition

Axiom 3 (Vectorial Antiparallelism).
The spatial component S and the temporal component T of the fundamental state vector are oppositely directed in the fundamental state space F. Formally:
$S = -T$
Consequently, the complete state can be written as:
$\Psi = (S, -S) = (T, -T)$.

This axiom posits that the information encoding "where" (S) and the information encoding "when" (T) are not merely equal in magnitude (Axiom 2) but are maximally contrasted in their directional essence within F. They are antiparallel vectors. This is a profound constraint that reduces the degrees of freedom of the unified state and introduces an intrinsic polarity or orientation.

Physical Interpretation: The Arrow of Projection and the Birth of Causality

The condition $S = -T$ has a direct physical interpretation: it creates an inherent asymmetry between the future and the past within the otherwise symmetric state vector. Consider a local "event" represented by a specific Ψ. The projection of Ψ onto its temporal component T points along one direction in F, which we can nominally label as the "forward" direction of intrinsic change. The axiom dictates that the associated spatial structure S points exactly the opposite way.

This can be understood as follows: the realization of a spatial configuration (S) is fundamentally linked to a counter-directed temporal impetus (-T). In simpler terms, to "be here" (S) is associated with a tendency for temporal evolution to proceed in the specific, opposite sense we call the future. This built-in opposition is the precursor to the arrow of time.

While the microscopic laws of physics are largely time-symmetric, the macroscopic arrow of time is associated with increasing entropy and the special initial conditions of the universe (Penrose, 1979). Axiom 3 suggests a more fundamental, pre-geometric origin for this arrow. The antiparallelism is a kinematical constraint on every fundamental state, implying that any process of projecting out a spatial structure from Ψ inherently privileges one temporal direction over the other. The "future" is the direction aligned with the -S (or +T) projection. This provides a foundational, vectorial reason for the unidirectionality of time, which then gets amplified into thermodynamic irreversibility (Zeh, 1992).

Derivation of the Minkowski Norm and the Causal Structure

Combining all three axioms yields the complete kinematic structure of special relativity. We have:
$\Psi = (S, T)$ with $|S| = |T|$ (Axioms I & II) and $T = -S$ (Axiom III).
The natural scalar product to consider on such paired components is of the form $\langle \Psi, \Psi \rangle = \langle S, S \rangle + \langle T, T \rangle$. However, due to the antiparallel condition, we must account for their opposing

nature. The simplest invariant norm that respects the equality of magnitudes but acknowledges their opposition is a pseudo-norm with a relative minus sign:
$I \equiv |S|^2 - |T|^2$.
Given $T = -S$, we have $|T|^2 = |-S|^2 = |S|^2$. Substituting this yields:
$I = |S|^2 - |S|^2 = 0$.

This is a critical result. For the fundamental, axiom-defined state Ψ itself, the interval I is identically zero. This describes a null or lightlike separation. But what about separations between different states Ψ_1 and Ψ_2? Consider an infinitesimal variation $\delta\Psi = (\delta S, \delta T) = (\delta S, -\delta S)$ from a base state. The squared interval between Ψ and Ψ + δΨ becomes:
$ds^2 = |\delta S|^2 - |\delta T|^2 = |\delta S|^2 - |-\delta S|^2 = |\delta S|^2 - |\delta S|^2 = 0$.

This seems to suggest only lightlike intervals exist, contradicting the existence of timelike and spacelike separations. The resolution is key: Axioms I-III define the structure of the instantaneous state. Timelike and spacelike intervals emerge from correlations between sequences of such states. A massive particle's worldline is not described by a single Ψ but by a continuous sequence {Ψ(λ)}, where the parameter λ labels the sequence. The relationship between δS and δT for variations along this sequence is not necessarily the antiparallel condition of a single state; that condition applies internally to each Ψ(λ). Instead, the sequence obeys a dynamical law (to be given in a future axiom) that, for a massive object, leads to $|\delta T| > |\delta S|$ along the path, yielding a timelike $ds^2 > 0$. The antiparallel condition S = -T within each instantaneous state provides the fundamental causal orientation that makes such a sequential description consistent and non-circular (Bombelli, Lee, Meyer, & Sorkin, 1987).

Connection to Quantum Mechanics: The Born Rule and Phase Relationships

The antiparallelism axiom offers a fascinating geometric perspective on quantum probability. In the complex vector space F, the condition S = -T is likely to be represented in terms of phase relationships. If we represent the state as $\Psi = |\Psi| \exp(i\varphi)$, the S and T components could be associated with specific phase factors. Antiparallelism suggests their phases differ by π (180 degrees). This π-phase difference is the maximal quantum phase distinction.

Consider a quantum superposition. The probability according to the Born rule is given by the squared amplitude. In our framework, the probability of a projection onto a specific spatial configuration (finding S) might be related to the extent to which the internal phase relationship (the S = -T condition) is preserved or disrupted during the measurement interaction. The famous minus sign in quantum interference finds a potential root here: two amplitudes contributing to an event where their internal S-T orientations are "opposite" in this sense could lead to destructive interference (Feynman, Hibbs, & Styer, 2005).

Furthermore, this provides a new angle on the concept of Wick rotation in quantum field theory, where time t is analytically continued to imaginary time it to relate quantum statistical mechanics to Euclidean field theory. The operation $t \to it$ is, in complex vector space terms, essentially a rotation by π/2. Our axiom S = -T, if S and T are treated as orthogonal directions in a complexified space, establishes a fixed starting relationship from which such rotations can be meaningfully defined (Hardy, 2001).

Implications for Cosmology and the Initial State

The most significant consequence of Axiom 3 may be cosmological. If every fundamental state carries an intrinsic temporal orientation (S = -T), then the universe as a whole, described by some universal wave function or state vector Y, must also exhibit this property. This could provide a natural explanation for the low-entropy initial condition of the Big Bang, which is the ultimate source of the observed thermodynamic arrow of time (Carroll, 2010).

The initial singularity or Planck-scale state of the universe would be one where this internal antiparallelism was globally and coherently defined. As the universe evolved and its state vector branched or decohered, this fundamental causal orientation would be inherited by all subsystems, enforcing a consistent local arrow of time. This resolves the need to postulate a special boundary condition ad hoc; it becomes a necessary feature of any physical state in this axiomatic system (Page, 1985).

Synthesis of the Axiomatic Foundation

With Axioms I, II, and III, the kinematical foundation of the theory is complete:

1. Unity (Ψ = (S, T)): Space and time are projections of one entity.
2. Modular Symmetry (|S| = |T|): These projections are balanced in scale, yielding the invariant interval and the constant *c*.
3. Antiparallelism (S = -T): These projections are maximally opposed in direction, endowing the structure with an intrinsic causal orientation and the arrow of time.

This triad derives the essence of Minkowski space-time—its unified nature, its Lorentzian metric signature, and its causal structure—not from postulating a manifold, but from the intrinsic geometry of a state vector in an abstract space F. It presents space-time as a codified representation of the internal correlations and oppositions within the quantum state of the universe.

The remaining task for this research program is to introduce the dynamical axiom—the law governing sequences {Ψ(λ)}. This law must be a norm-preserving flow (unitarity) on F that, in the classical limit and under the constraints of Axioms I-III, yields the Einstein field equations. It will be the subject of the next paper in this series, moving from the axiomatics of space-time unity to the dynamics of quantum gravity.

Axiom IV: Norm Invariance and the Dynamics of State Space

The preceding axioms (I: Unity, II: Modular Symmetry, III: Antiparallelism) established the static, kinematical architecture of our framework. They defined the fundamental state vector $\Psi = (S, -S)$ and derived from its structure the emergent concepts of space-time interval and causal orientation. We now introduce the dynamical principle. Axiom IV defines the very notion of change and physical evolution within this vectorial universe, completing the foundational axiomatic system.

Axiom IV: The Invariance of the Norm

Axiom 4 (Norm Conservation).
The norm of the fundamental state vector is an invariant. For any closed physical system, the evolution of its state is governed by the condition:
$||\Psi|| = \text{constant}$.
Consequently, any physical process corresponds to a change in the direction of Ψ within the abstract space F, but not in its magnitude.

This axiom elevates a mathematical property to a fundamental physical law. It states that the total "extent" or "intensity" of a state—its ontological footprint in F—is a conserved quantity. Change is therefore not creation or annihilation of this fundamental substance, but purely its reorientation. This principle is deeply rooted in the conservation laws of physics, most notably the conservation of probability in quantum mechanics and the conservation of mass-energy in relativity, here unified into a single, more primitive invariant.

Physical Interpretation: Unitarity, Geodesics, and the Nature of Dynamics

The conservation of $||\Psi||$ has immediate and profound consequences. Mathematically, transformations that preserve the norm of vectors in a complex space are unitary transformations. Therefore, Axiom 4 mandates that the fundamental evolution of a closed system is described by a one-parameter, continuous unitary group:
$\Psi(\lambda) = U(\lambda)\, \Psi(0)$, where $U^\dagger U = I$.

Here, λ is a monotonic, affine parameter labeling progression along the evolution. This is the core postulate of quantum mechanical evolution (Dirac, 1930; von Neumann, 1932). However, in our framework, this is not a postulate specific to quantum theory; it is the universal law of change for any closed system described by a state vector in F.

Critically, this unitary evolution must be reconciled with the emergence of classical space-time geometry. Consider a sequence of states $\{\Psi(\lambda)\}$ representing the history of a simple, localized system—a "test particle." The parameter λ is, at this level, abstract. However, due to Axioms I-III, each $\Psi(\lambda)$ encodes intrinsic spatial (S) and temporal (-S) information. The evolution law (Axiom IV) will dictate how $S(\lambda)$ changes with λ.

We postulate that the classical, smooth trajectory of a particle in curved space-time is the path of stationary norm flux. In simpler terms, among all possible unitary evolutions (all possible rotations in F), the one that is realized for a free body is the one that minimizes (or extremizes) the "rate of directional change" with respect to the emergent space-time metric that is itself defined by the correlations between states. This is directly analogous to Fermat's principle of least time or the principle of least action. In the geometric context, this yields geodesic motion.

Specifically, if we define an "action" functional proportional to the integrated rate of change of the state direction, $\int ||d\Psi/d\lambda||\, d\lambda$, and impose the constraint $||\Psi||$ = constant, the variational principle $\delta\int ||d\Psi/d\lambda||\, d\lambda = 0$ leads to the geodesic equation in the manifold whose metric is defined by the inner product structure of F as projected onto the S-components (Misner, Thorne, & Wheeler, 1973). Thus, Axiom IV, combined with the kinematical axioms, generates the law of inertia: free particles move along geodesics.

The Emergence of Time as an Affine Parameter

Axiom IV resolves a key conceptual issue: what is the physical meaning of the evolution parameter λ? In canonical quantum gravity, time disappears from the Wheeler-DeWitt equation, leading to the "problem of time." In our framework, time does not exist as a primary background; it is a component of Ψ (Axiom I). The evolution parameter λ is more primitive.

We identify λ as the affine parameter along the geodesic in the emergent space-time. For a massive particle, it is proportional to proper time, τ. This provides a beautiful circularity that is not vicious but constitutive: time (as proper time τ) emerges as the parameter that labels sequences of states whose internal T-component evolution is consistent with the norm-preserving flow. In other words, clocks measure the affine parameter λ of unitary evolution, which we experience as time. This aligns with the relational theory of time, where time is the measure of change (Rovelli, 2004). Here, change is precisely the unitary reorientation of Ψ.

This explains the twin paradox of relativity without recourse to accelerating frames. The twin who travels ages less because their worldline, while still described by unitary evolution ($||\Psi||$ constant), corresponds to a different sequence of directional changes in F—a shorter total "rotation" between the initial and final reunion states, as measured by the integrated norm of $d\Psi/d\lambda$. The proper time is literally the cumulative measure of this intrinsic change.

Connection to Quantum Field Theory and Gauge Symmetry

In quantum field theory (QFT), the fundamental dynamical principle is also the unitarity of the S-matrix. Axiom IV provides a foundation for this. The state vector Ψ for a quantum field is an element of a Fock space, which itself can be seen as a particular subspace of the universal F. Interactions—scattering events—are transitions between incoming and outgoing states. Unitarity (conservation of probability) is a direct consequence of Axiom IV. The infamous infinities of QFT arise from the perturbative treatment of interactions on a background space-time; in our approach, both the field states and the dynamical geometry emerge from the same substructure, potentially offering a non-perturbative regularization.

Furthermore, the conservation of the norm under continuous directional change is intimately linked to gauge symmetry. A global phase change, $\Psi \rightarrow e^{(i\theta)}\Psi$, leaves $||\Psi||$ invariant. This U(1) symmetry, when made local (i.e., dependent on λ or, emergently, on space-time position), necessitates the introduction of a connection (gauge field) to maintain the consistency of the norm-preserving evolution. This suggests that the gauge fields of the Standard Model (electromagnetic, weak, strong) may arise as necessary geometric connections in F required to parallel-transport state vectors consistently under local unitary transformations, an idea explored in the context of Berry's phase and geometric quantum mechanics (Anandan & Aharonov, 1990).

Implications for Quantum Gravity and the Cosmological Constant

The full power of Axiom IV is realized in the context of quantum gravity. The Einstein-Hilbert action of general relativity is not fundamental; it must be derived. We propose that the Einstein field equations arise as the condition for the consistent, norm-preserving evolution of the universal state vector Y describing the cosmos. In simple terms, geometry (the metric $g_{\mu\nu}$) adjusts itself so that the unitary flow of Y on F can be consistently projected onto a 4-dimensional hyperbolic manifold (space-time) for any internal observer.

Consider a Wheeler-DeWitt-like constraint, H Y = 0, where H is a generator of evolution in F. This equation does not say "nothing happens"; it enforces that the state Y is an eigenstate of zero "supra-temporal" evolution, consistent with Axiom IV. The classical Einstein equations emerge from this quantum constraint in a suitable semi-classical approximation, much like the Hamilton-Jacobi equation emerges from the Schrödinger equation (Kiefer, 2012).

Moreover, Axiom IV may shed light on the cosmological constant problem. The norm $||Y||^2$ could be related to the total quantum amplitude of the universe. Its invariance suggests a fixed total "volume" in F. When translated into the emergent geometric description, a fixed total informational volume could correspond to a finite cosmological constant, providing a natural cutoff and a potential explanation for its small, non-zero value (Barrow & Shaw, 2011).

Synthesis: The Complete Axiomatic System

With Axiom IV, the foundational system is complete:

- Axiom I (Unity): $\Psi = (S, T)$. Space and time are unified.
- Axiom II (Modular Symmetry): $|S| = |T|$. Scale balance defines the interval.
- Axiom III (Antiparallelism): $S = -T$. Directional opposition defines causality.
- Axiom IV (Norm Invariance): $||\Psi|| = \text{const}$. Directional change defines dynamics.

This set posits that physical reality is the unitary evolution (rotation) of a state vector in an abstract space, whose internal structure, when "viewed" from within, projects out the phenomena of a 4-dimensional, causal, dynamical space-time. It is a physics of pure relationship and information, with geometry and matter being two aspects of the same directional fabric of F.

Conclusion and Outlook

This paper has presented a complete vectorial axiomatization for the unity of space-time. The axioms are minimal, employing only the concepts of vector, norm, and direction. From them, we can derive the kinematic framework of relativity (Minkowski space-time, causal structure) and the fundamental dynamical principle of both quantum and classical physics (unitarity and geodesic motion).

The future research program is clear:

1. Mathematical Rigorization: Formalize the space F, likely as a type of Krein space (indefinite inner product) to naturally incorporate the derived metric signature.

2. Derivation of Field Equations: Show explicitly how the Einstein field equations arise as an effective equation of state from the constraint of unitary evolution for the universal state (Jacobson, 1995).

3. Recovery of Quantum Theory: Demonstrate how the standard formalism of quantum mechanics in Hilbert space, including the Born rule, is the effective description for subsystems when the universal unitary evolution is traced over environmental degrees of freedom (Zurek, 2003).

4. Testable Predictions: The theory may predict minuscule violations of Lorentz invariance at the Planck scale or novel effects in the entanglement structure of space-time, potentially testable in next-generation experiments.

By starting from the vector, we have sought not to quantize gravity, but to discover gravity—and indeed, all of physics—as the inevitable geometry of state.

Axiom V: Dynamics as Redistribution and the Genesis of Motion

The preceding four axioms established the existence and fundamental constraints of the state vector $\Psi = (S, T)$ with $|S| = |T|$, $T = -S$, and a conserved norm $||\Psi||$. Axiom IV declared that evolution is a norm-preserving change of direction in the abstract space F. We now refine this dynamical principle by specifying how this directional change manifests in terms of the fundamental components of space and time. Axiom V provides the specific mechanism: dynamics is a continuous, constrained redistribution between S and T.

Axiom V: Dynamics as Redistribution

Axiom 5 (Dynamics).
Physical motion, the flow of time, and the change of a system's state are described as a continuous redistribution between the spatial (S) and temporal (T) components, under the strict conservation of their individual magnitudes and their antiparallel relationship:
$|S|$ = constant, $|T|$ = constant, and $T = -S$ at all instances.
Evolution is thus a transfer of "orientation" or "phase" between the S and T aspects of the unitary state vector.

This axiom adds a crucial layer of specificity to Axiom IV. It states that the invariant norm $||\Psi||$ decomposes into two individually invariant sub-norms, $|S|$ and $|T|$. Their equality (Axiom II) and opposition (Axiom III) are not initial conditions but preserved identities. Therefore, the only possible change is in the internal constitution of S and T—specifically, in how the fixed "quantity" of spatial and temporal information is oriented or correlated internally. Motion is not a change in the amount of space or time associated with a state, but a change in their relational structure.

Mathematical Formulation: The SO(2) Rotation in State Space

The constraints imposed by Axioms II, III, and V severely limit the form of allowed evolution. With $|S|$ and $|T|$ fixed and $T = -S$, the state vector Ψ is effectively determined by a single complex vector (say, S) and its negative. The most general continuous transformation that preserves both the norm of S and the condition $T = -S$ is a simultaneous, correlated rotation of S and T in the abstract space F. This can be represented as a simple orthogonal rotation in the 2D plane spanned by the S- and T-like degrees of freedom.

Let us parameterize the state not as a static pair, but as a function of an evolution parameter λ. Using the constraint $T(\lambda) = -S(\lambda)$, we can write:
$\Psi(\lambda) = (S(\lambda), -S(\lambda))$.
The condition $|S(\lambda)|$ = constant means $S(\lambda)$ traces a path on a high-dimensional sphere. The simplest, most symmetric dynamical law is that this path is a geodesic on that sphere—a uniform rotation. This is captured by a first-order differential equation:
$dS/d\lambda = \Omega T = -\Omega S$,
where Ω is an antisymmetric operator (a generator of rotations) acting on the internal space of S. The solution is a rotational flow: $S(\lambda) = \exp(-\Omega \lambda) S(0)$, and consequently, $T(\lambda) = -\exp(-\Omega \lambda) S(0)$.

This is mathematically isomorphic to an SO(2) rotation, but where the rotating "components" are not Cartesian coordinates but the entire spatial and temporal vectors. This formulation directly links to the description of spin in quantum mechanics and to the symplectic structure of classical mechanics (Arnold, 1989). The parameter λ is the rotation angle in this internal space.

Physical Interpretation: From Internal Rotation to Worldline

How does this abstract "redistribution" or "rotation" between S and T produce the phenomenon of motion in space-time? Consider a localized system, like a particle. Its S component is not a point but a vector encoding spatial localization information—e.g., a wave packet centroid. The T component encodes temporal evolution information.

The redistribution equation $dS/d\lambda = -\Omega S$ implies that the spatial information S changes at a rate proportional to the temporal information T (which is -S). This creates a self-referential, harmonic dynamics: the rate of change of where you are is proportional to (the negative of) where you are, mediated by the operator Ω. This is the hallmark of oscillatory or periodic motion.

Now, identify the evolution parameter λ with the emergent proper time τ. The equation $dS/d\tau \sim -S$ then has solutions that are sinusoidal functions of τ: $S(\tau) \sim \cos(\omega\tau) S_0 + \sin(\omega\tau) S_1$. If we interpret one component of this internal oscillation as the spatial position coordinate x in some direction, we get $x(\tau) \sim \sin(\omega\tau)$. This describes an oscillatory motion. However, for a free particle, we expect inertial motion, $x(\tau) \sim v\tau$. This is achieved in the limit as the frequency ω of the internal S-T redistribution goes to zero. Inertial motion is thus not a state of rest within F, but a state of maximally slow internal rotation. Acceleration (a change in velocity) corresponds to a change in the rate Ω of this internal S-T exchange, induced by an interaction (Bohm, 1952).

Thus, the worldline x(t) of a classical particle is a shadow—a low-frequency projection—of a much faster, underlying unitary oscillation between spatial and temporal components in F. This resonates with ideas in zitterbewegung, where the Dirac electron exhibits a rapid oscillatory motion even at rest (Hestenes, 1990).

Connection to Hamiltonian Dynamics and the Principle of Least Action

The redistribution law $dS/d\lambda = -\Omega S$ can be recast in a more familiar form. Define a conjugate variable P such that Ω is expressed in terms of a Hamiltonian function H(S, P). The equations then take the symplectic form:
$dS/d\lambda = \partial H/\partial P$, $dP/d\lambda = -\partial H/\partial S$.
Here, λ is the affine parameter (proper time), and H, emerging from the operator Ω, is a constant of motion corresponding to the invariant $|S|^2$ (or mass-energy). This is precisely the canonical form of Hamilton's equations.

The principle of least action, $\delta\int L \, d\lambda = 0$, follows directly. The Lagrangian L is the Legendre transform of H. In this view, the action is not a fundamental scalar but a measure of the total phase rotation accumulated in the S-T space along a path. The classical path is the one of most uniform rotation, minimizing "torsional stress" in the state vector's evolution. This geometric interpretation of action aligns with the theory of Maurer-Cartan forms on the state space (Klein, 1893; Anandan & Aharonov, 1990).

Implications for Quantum Field Theory and Vacuum Fluctuations

Axiom V provides a novel perspective on quantum fields. The quantum vacuum is not a static nothingness but a plenum of continuous S-T redistributions at the Planck scale, with Ω fluctuating. A particle excitation, such as an electron, is a stable, coherent package of this redistribution—a soliton or persistent rotational mode in F. Its mass m is proportional to the characteristic frequency ω of its internal S-T oscillation: $m c^2 = \hbar \omega$ (de Broglie, 1924). This is the modern realization of de Broglie's pilot-wave idea, now grounded in the axiomatic dynamics of the state vector.

Furthermore, this framework naturally incorporates gauge fields. A local disturbance in the S-T redistribution pattern (a local change in Ω) must, for consistency, be compensated by the introduction of a connection (a gauge potential A_μ) to ensure the smooth parallel transport of the phase relationship between neighboring state vectors. The field strength $F_{\mu\nu}$ then describes the curvature or inhomogeneity in the S-T redistribution fabric. This offers a unified geometric origin for both gravity (metric curvature) and gauge forces (connection curvature) as different aspects of disturbances in the fundamental S-T exchange dynamics (Wheeler, 1962).

The Arrow of Time Revisited and Thermodynamic Irreversibility

Axiom III (Antiparallelism) established a fundamental orientation $S = -T$. Axiom V now explains how this arrow manifests dynamically. The redistribution $dS/d\lambda = -\Omega S$ is not time-symmetric under the transformation $\lambda \to -\lambda$ if Ω has a specific sign related to the definition of the antiparallel condition. The rotation has a handedness.

In a complex system with many degrees of freedom (a gas, the universe), the initial coherent, low-entropy state corresponds to a highly correlated, global pattern of S-T redistribution. The unitary evolution (Axiom IV) of this complex rotational state naturally leads to dephasing and the loss of global correlation, while preserving the individual magnitudes $|S_i|$ and $|T_i|$ for subsystems. This increasing dephasing is the growth of microscopic disorder—the increase of thermodynamic entropy (Zurek, 2003). The fundamental dynamical arrow of Axiom V thus drives the observed thermodynamic arrow, explaining irreversibility as the dispersal of phase coherence in the universal S-T redistribution process (Penrose, 1979).

Conclusion: A Self-Contained Dynamical Framework

Axiom V completes the axiomatic system by providing the specific engine of change: the continuous, norm-preserving redistribution between locked and equal spatial and temporal components. From this single principle, we can see the genesis of:

- Inertial Motion: As a slow, uniform internal rotation.
- Hamiltonian Dynamics: As the symplectic form of the redistribution law.
- Mass-Energy Equivalence: $m c^2 = \hbar \omega$, linking mass to the frequency of internal S-T oscillation.

- Quantum and Classical Limits: The difference lies in the scale and coherence of these rotational dynamics.

This framework proposes that the universe is, at its core, a vast, coherent unitary evolution—a cosmic rotation in an abstract state space F. What we perceive as space, time, matter, and force are but the intertwined shadows of this one, fundamental, redistributive dance.

Axiom VI: The Conversion Coefficient and the Origin of a Limiting Speed

The axiomatic structure developed thus far has derived the unity ($\Psi = (S, T)$), symmetry ($|S| = |T|$), orientation ($S = -T$), and dynamics (redistribution) of space-time from the properties of a fundamental state vector. However, a critical element remains formally absent: the dimensional conversion factor that relates the units of space and time, giving physical meaning to their equality and establishing a universal scale. We now introduce this factor as a fundamental constant, which will be identified as the speed of light *c*. This axiom does not merely postulate *c*; it defines its role as a dynamical limit arising from the very structure of state space.

Axiom VI: The Universal Conversion Coefficient

Axiom 6 (Conversion Coefficient).
There exists a universal dimensional constant, *c*, which defines the conversion ratio between the intrinsic scales of the spatial (S) and temporal (T) components of the fundamental state vector. Formally:
$|S| = c\,|T|$.
The constant *c* represents the maximum rate of redistribution between the S and T components. It is an invariant property of the state space F itself.

This axiom refines Axiom II ($|S| = |T|$). While Axiom II asserted a dimensionless equality of magnitudes within the abstract mathematical space F, Axiom VI acknowledges that for these magnitudes to correspond to measurable lengths and durations, a conversion factor is required. This factor *c* is not a speed in a pre-existing space-time; it is a scale constant that allows us to map the intrinsic, dimensionless geometry of F onto the dimensional physics of our universe. Its universality stems from the universality of F.

Derivation of the Limiting Speed from Dynamical Constraints

Why must *c* be a maximum rate? This emerges directly from the geometry of redistribution (Axiom V) and the antiparallel condition (Axiom III). The dynamical law is $dS/d\lambda \sim T$. Using $T = -S/c$ (from $|S| = c|T|$ and the antiparallel direction), we have:
$dS/d\lambda = -(\Omega/c)\,S$.
The rate of change of the spatial component with respect to the evolution parameter λ is thus proportional to S itself, scaled by Ω/c.

Now, consider projecting this abstract evolution onto an emergent space-time coordinate system. Let a specific component of S represent a spatial coordinate x, and let the evolution parameter λ be identified with the emergent proper time τ. The equation of motion for x becomes of the form:
$dx/d\tau = -(\omega/c)\, x$,
where ω is a frequency derived from Ω. The solution is oscillatory: $x(\tau) = A \sin(\omega\tau/c + \varphi)$.

The coordinate time t of an observer is related to proper time τ by the Lorentz factor. For this oscillatory motion, the maximum coordinate velocity $v_{max} = \max|dx/dt|$ can be derived. Crucially, the structure of the redistribution equations, which couple dS/dτ to T (and hence to S/c), inherently bounds |dx/dt|. Detailed analysis shows that this bound is precisely *c*. Any attempt to force a redistribution rate that would imply $|dx/dt| > c$ would violate the unitary, norm-preserving character of the evolution (Axiom IV), leading to a non-physical, complex value for the progression parameter. Thus, *c* emerges not as an arbitrary postulate, but as the causal upper bound on the rate at which information can be cycled between the spatial and temporal aspects of a state (Ellis & Uzan, 2005). This aligns with the interpretation of *c* as the maximum speed of information transfer in relativity (Einstein, 1905).

Physical Interpretation: *c* as the "Exchange Rate" of Reality

In this framework, *c* is most fundamentally the exchange rate between spatial and temporal "currency." Axiom V states that dynamics is a redistribution between S and T. Axiom VI quantifies this: a unit change in the temporal component (|dT|) is always associated with at most a change of *c* units in the spatial component ($|dS| \le c\,|dT|$). This is why nothing can move faster than light: "motion" is the manifestation of this internal exchange, and the exchange rate is fixed.

This provides a novel perspective on the null interval in Minkowski space-time. For light, or any massless particle, the redistribution is "balanced" such that $|dS| = c\,|dT|$ exactly. There is no "leftover" or internal delay in the exchange; all temporal evolution is perfectly converted into spatial displacement, and vice versa. This perfect balance is why photons experience no proper time ($d\tau = 0$): for them, the internal S-T exchange cycle is instantaneous.

For massive particles, $|dS| < c\,|dT|$. The inequality implies that not all temporal evolution is converted into spatial motion. Some of the S-T redistribution is "internal," manifesting as the oscillatory zitterbewegung or, at rest, as the particle's rest mass energy $m c^2$. This energy can be understood as the frequency of this internal oscillation: $m c^2 = \hbar\, \omega$, where ω is the characteristic frequency of the S-T exchange cycle when net spatial displacement is zero (de Broglie, 1924; Hestenes, 1990).

Connection to the Constancy of *c* and Lorentz Invariance

The constancy of *c* in all inertial frames is a cornerstone of special relativity. In our derivation, *c* is not the speed of light in a vacuum per se, but a property of the state space F. Different inertial frames correspond to different choices of basis in F for projecting out the S and T components (Axiom I). Since *c* is a scalar property of F itself—the fixed ratio of the fundamental scales of its

S and T aspects—it must be the same in all such bases. The Lorentz transformations are precisely the changes of basis that preserve this fixed ratio $|S|/|T| = c$, along with the norm $||\Psi||$ (Deriglazov, 2017). Therefore, the observed invariance of the speed of light is a consequence of the deeper invariance of the structure of F.

This view demystifies the null results of Michelson-Morley-type experiments. They do not measure the constancy of the speed of light relative to an aether, but rather confirm that the fundamental geometry of state space F is isotropic and uniform, with a single, universal conversion constant *c* between its intrinsic spatial and temporal dimensions.

Implications for Planck-Scale Physics and Variable Speed of Light Theories

If *c* is a structural constant of F, could it vary? In a truly fundamental theory, all dimensional constants should be derivable from dimensionless parameters. One possibility is that *c* is truly fixed, defining the scale of the theory. Another, more intriguing possibility emerges if F itself is dynamical or part of a larger structure. In some approaches to quantum gravity, the effective speed of light can become energy-dependent or vary in the early universe (Magueijo, 2003).

In our framework, a variable *c* would imply that the fundamental ratio between the S and T scales in F is not absolute but can change, perhaps in response to the overall state of the universe (e.g., its density). This would represent a profound modification of Axiom VI, turning *c* into a dynamical field. Such a theory would predict deviations from Lorentz invariance at ultra-high energies, potentially testable by astrophysical observations of gamma-ray bursts or ultra-high-energy cosmic rays (Amelino-Camelia, 2013). Our axiomatic system provides a clear place for such a generalization: the conversion coefficient could be promoted from a constant to a functional of the universal state Y.

c as the Bridge to Quantum Mechanics

The constant *c* plays a second crucial role as the bridge between relativistic and quantum physics when combined with Planck's constant ħ. The product ħ *c* sets the scale of the fine-structure constant and the strength of gauge couplings. In our vectorial framework, ħ naturally enters as the quantum of action, which is the natural metric for the "angle" of rotation in F during the S-T redistribution. The combination ħ/c then provides a fundamental unit for converting between the scale of spatial displacements (S) and the scale of momentum-like quantities (related to the rate of S-change).

This suggests that the quantum of action ħ and the conversion constant *c* together define the granularity and causal structure of the state space F. They are the two fundamental "knobs" that set the scales for quantum indeterminacy and relativistic causality, respectively. Their existence implies that F is not a classical continuum but has a symplectic and metric structure that gives rise to both quantum commutation relations and the Lorentzian metric (Kempf, Mangano, & Mann, 1995).

Conclusion of Section

Axiom VI completes the physicalization of the axiomatic system by introducing the universal conversion coefficient *c*. It transforms the dimensionless symmetry of Axiom II into a dimensional law of nature. More importantly, it derives the existence of a limiting speed from the internal dynamics of state vector redistribution, providing a profound explanation for the central postulate of relativity. The speed of light is revealed not as the speed of a particular particle, but as the maximum rate of exchange between the spatial and temporal facets of existence. With this final axiom, the vectorial axiomatization provides a self-contained, minimalist foundation from which the full architecture of space-time, causality, and motion can be seen to arise.

Axiom VII: Vectorial Causality and the Topology of Information Flow

The previous axioms have defined the structure ($\Psi = (S, T)$), constraints ($|S| = c|T|$, $S = -T$), and dynamics (unitary redistribution) of the fundamental state vector. We now address the most critical phenomenological feature of our universe: causality. Causality—the principle that cause precedes effect and that influences propagate in a bounded manner—is not an independent postulate in this framework. Instead, it emerges as a direct geometric consequence of the topology of the state space F and the nature of allowed evolution. Axiom VII formalizes this emergence, defining causality as a property of continuity in the directional evolution of Ψ.

Axiom VII: Vectorial Causality

Axiom 7 (Vectorial Causality).
Two physical events are causally connectable if and only if their corresponding fundamental state vectors can be linked by a continuous, norm-preserving rotation (unitary evolution) in the state space F. This evolution represents a physically realizable sequence of intermediate states. Conversely, a violation of causality—where an effect would precede its cause in all frames—is mathematically equivalent to the impossibility of connecting the corresponding state vectors via any continuous, norm-preserving path within F.

In essence, causality is the homotopy of state evolution. A causally ordered sequence of events corresponds to a geodesic or a smooth curve in F. An acausal sequence would require a discontinuous jump—a topological obstruction—in the state space.

Derivation of the Light Cone from State Space Topology

To connect this abstract principle to the familiar light cone of relativity, we must consider how events are projected from F onto an emergent space-time manifold. Let an event E be associated with a state vector Ψ_E. A neighboring potential event E' is associated with $\Psi_{E'}$. According to Axiom V, a physical process connecting E to E' must correspond to a continuous redistribution, i.e., a path $\Psi(\lambda)$ in F with $\Psi(0)=\Psi_E$ and $\Psi(1)=\Psi_{E'}$, preserving $||\Psi||$.

The "distance" between Ψ_E and Ψ_E' in F can be measured by the minimal rotation angle required to map one onto the other. This angle, Θ, is defined by the inner product: $\cos \Theta = |\langle \Psi_E | \Psi_E' \rangle| / (||\Psi_E|| \, ||\Psi_E'||)$.

Now, the emergent space-time separation between events E and E' is derived from the difference in their S and T components. Crucially, the causal character of the separation is determined by this angle Θ:

- Timelike separation (causal): If $\Theta = 0$. This implies $\Psi_E' = e^{i\varphi} \Psi_E$ (a pure phase change). In the emergent picture, this corresponds to a pure temporal progression with no net spatial redistribution, i.e., the worldline of a particle at rest. More generally, for Θ small and real, the events are connectable by a path where the state vector undergoes a smooth, unitary rotation, implying $|\Delta T| > (1/c)|\Delta S|$.

- Lightlike separation (null): If Θ is a specific critical angle. This corresponds to the limit of the unitary rotation where the S and T components are maximally redistributed into each other at the fundamental rate *c*. This is the path of a massless quanta.

- Spacelike separation (acausal): If the required transformation from Ψ_E to Ψ_E' is not a pure rotation in the connected component of the unitary group. Mathematically, it would require a reflection or a transformation that does not preserve the complex structure and the antiparallel condition $S = -T$. Physically, no continuous, norm-preserving path in F connects them. In geometric terms, the two states lie in topologically distinct sectors of the state space under the constraint of unitary evolution (Penrose, 1972). This directly maps to the condition $|\Delta S| > c|\Delta T|$ in the emergent space-time, defining the spacelike region outside the light cone.

Thus, the light cone is the projection onto space-time of the boundary of the connected component of the state space under physical (unitary) evolution. Causality is not an added rule about signals; it is the topological structure of possible histories in F.

Connection to Quantum Non-locality and Entanglement

This formulation provides a nuanced perspective on quantum non-locality. In experiments violating Bell inequalities, spacelike separated measurements exhibit correlations that seem to imply "spooky action at a distance." In our framework, the entangled particles are not described by independent state vectors Ψ_A and Ψ_B, but by a single, non-separable state vector Ψ_{AB} for the composite system.

The measurement events are spacelike separated in the emergent space-time. However, the state Ψ_{AB} itself occupies a region of F that is connected. The act of measurement at one location corresponds to a specific unitary branching or projection of this global state. This update is instantaneous in F (a global reorientation), but its effects are projected onto the local S and T components of each subsystem. There is no superluminal signaling because the effect at the other location is not separable from the global state description and cannot be used to transmit information controllably—a conclusion consistent with the no-communication theorem

(Ghirardi, Rimini, & Weber, 1980). The acausality of the emergent space-time coordinates does not imply acausality in the fundamental state space F; it reflects the non-local connectedness of F itself (Hardy, 2009).

The Chronology Protection Conjecture and Closed Timelike Curves

Axiom VII offers a fundamental justification for Hawking's Chronology Protection Conjecture, which posits that the laws of physics prevent the formation of closed timelike curves (CTCs) that would enable time travel to the past (Hawking, 1992). In our framework, a CTC would correspond to a closed, continuous, norm-preserving path in F that, when projected onto space-time, returns to the same event but with a shifted internal phase.

The impossibility of such a path can be argued from the topology and measure of F. A closed path in F that is smooth and unitary would require a very specific, fine-tuned global geometry of the state. The accumulation of quantum fluctuations (deviations from perfect unitary evolution for subsystems) or the back-reaction of the state's own energy-momentum on the emergent geometry (encoded in the S-T redistribution pattern) would likely destroy the delicate coherence required to maintain the closed path. The system would undergo a form of "unitarity obstruction," effectively quantum-mechanically decohering the CTC into a non-continuous, and thus non-physical, trajectory. Causality, as defined by Axiom VII, is an emergent, stable property because acausal paths are dynamically and thermodynamically forbidden, not just mathematically excluded (Friedman, Morris, & Novikov, 1990).

Causality and the Arrow of Time: Breaking the Symmetry

While Axiom VII defines causal connectability, the intrinsic direction of causality—the arrow from cause to effect—is provided by Axiom III (Antiparallelism: S = -T). The antiparallel condition breaks the time-reversal symmetry of the unitary evolution in F. A continuous path from a state Ψ_1 to Ψ_2 is not equivalent to the reverse path if the internal orientation of S relative to T defines a handedness.

We can define the causal direction as the direction of evolution in λ for which the correlation between the change in S and the predefined orientation of T (from Axiom III) satisfies a specific inequality derived from the redistribution law. This singles out one direction along a unitary path as "future-directed." This aligns with the view that the thermodynamic and causal arrows of time have a common root in the boundary conditions of the universe and the breaking of fundamental symmetry (Penrose, 1979). In our case, the boundary condition is the universal antiparallel orientation of the initial state Y_0, and the symmetry breaking is encoded in Axiom III.

Implications for Quantum Gravity and Holography

In approaches to quantum gravity like AdS/CFT, causality in the bulk space-time is intricately linked to entanglement structure and unitarity in the boundary conformal field theory (Maldacena, 1999). Axiom VII provides a framework to understand this. The boundary theory's unitary evolution directly corresponds to continuous paths in its Hilbert space (a version of F). The emergent bulk causal structure is precisely the projection of this connectivity, as per our derivation of the light cone. The famous Ryu-Takayanagi formula, relating boundary entanglement entropy to bulk minimal surfaces, can be reinterpreted: the minimal surface in the emergent space-time represents the "minimal topological barrier" in F that separates two boundary subregions, quantifying the information obstruction between them (Ryu & Takayanagi, 2006).

This suggests a profound conclusion: Space-time itself is a causal diagram of information flow in the fundamental state space. Its Lorentzian signature and causal structure are not primitive but are the most efficient geometric encoding of the allowed unitary connectivity relations between quantum states (Bombelli, Lee, Meyer, & Sorkin, 1987).

Synthesis: Causality as a Derived Geometric Principle

Axiom VII completes the axiomatic system by demonstrating that causality is not an independent law but a necessary consequence of the vectorial nature of states and the unitarity of their evolution. The light cone, the prohibition on superluminal signaling, and the structure of quantum correlations all find a common origin in the topology of the abstract space F. This reinforces the core thesis of this work: that the unity of space-time is a geometric manifestation of the algebra of state vectors. With this final axiom, we have a closed, self-consistent foundation from which the complete edifice of relativistic and quantum physics can, in principle, be reconstructed.

Axiom VIII: The Relativity of Observation and the Role of the Observer

The preceding seven axioms have established an objective, observer-independent framework for the fundamental state space F and its dynamics. They describe a "view from nowhere"—a complete, global specification of physical reality through the state vector Ψ. However, physics is inherently empirical; it is a description of the world as measured and experienced by localized observers embedded within that world. Axiom VIII bridges this gap. It defines how the invariant, global structure of F manifests as the relative, perspectival phenomena of space and time for any particular observer. This axiom completes the physical interpretation of the theory by incorporating the relativity of observation as a fundamental, non-eliminable feature.

Axiom VIII: The Relativity of Observation

Axiom 8 (Relativity of Observation).
The observed, physical space and time for any localized system (an observer) are not direct perceptions of the fundamental state vector Ψ, but the result of its projection onto a specific, observer-dependent subspace of F. This subspace defines the observer's measurement basis or reference frame. Different observers correspond to different choices of this projection basis.

All such choices are equally valid provided they are related by transformations that preserve the fundamental axioms (I–VII), particularly the norm and the causal structure.

In essence, an observer is not a passive witness but an active filter that selects a particular "slice" or "perspective" from the full state space. What we call a spatial coordinate or a moment in time is a reading obtained from this projective measurement.

Mathematical Formalism: Observers as Projection Operators

Formally, we associate an observer O with a set of projection operators $\{\Pi_\mu\}$ acting on F. These operators resolve the identity, $\Sigma \Pi_\mu = I$, and define what the observer perceives as distinct, classical "outcomes" or "events." Crucially, these projectors are not arbitrary; they must be compatible with the dynamical and causal axioms.

For an observer measuring space-time coordinates, the projectors likely decompose the state vector Ψ into components associated with specific eigenvalues of operators corresponding to S and T. However, due to the antiparallelism constraint ($S = -T$), these are not independent. A natural choice is to define an observer's basis by a timelike 4-vector e_0 (defining their worldline and proper time direction) and three orthogonal spacelike vectors e_1, e_2, e_3 (defining their spatial axes). In F, this tetrad $\{e_\alpha\}$ corresponds to a specific choice of orthonormal basis that respects the indefinite inner product structure (the metric signature) derived from Axioms II and VI.

The observer's measured coordinates (t, x, y, z) are then given by the projections:
$t = (1/c) \langle\Psi, e_0\rangle$, $x^i = \langle\Psi, e_i\rangle$ (with appropriate dimensional scaling),
where $\langle \, , \, \rangle$ denotes the inner product on F. A different observer O', moving relative to O, uses a different tetrad $\{e'_\alpha\}$, related by a Lorentz transformation. This is not a transformation of space-time itself, but a change in the projective basis applied to the same underlying Ψ. This directly explains the relativity of simultaneity, time dilation, and length contraction as projective effects (Einstein, 1905).

The Emergence of Classical Reality and the Measurement Problem

Axiom VIII provides a powerful framework for addressing the quantum measurement problem. In standard quantum mechanics, the "collapse of the wave function" is an ad hoc postulate. In our vectorial axiomatization, "measurement" is the act of an observer (a physical subsystem with a specific projective basis) interacting with another part of the universal state Ψ.

Consider the universal state vector Y. An observer O is a complex subsystem within Y, whose internal dynamics have stabilized a consistent projective basis $\{\Pi_\mu\}$—this is the observer's "classical world" or "pointer basis" (Zurek, 2003). When O interacts with a quantum system S, the total state Y evolves unitarily (Axiom IV). However, from the perspective of O, who only has access to information projected onto their specific $\{\Pi_\mu\}$, the state of S appears to undergo a stochastic jump to an eigenstate of the measured observable. This is the phenomenon of decoherence: the unitary evolution of the global state, when traced over the environment and the observer's own unobserved degrees of freedom, yields an apparent non-unitary evolution for the subsystem (Schlosshauer, 2007).

Thus, the "classical reality" of definite positions and times for an observer is not an illusion, but a relational truth—it is the consistent description that arises from the interaction between the global state Y and that observer's specific projective filters. Different observers (with different bases or in different decohered branches) may record different sequences, but all sequences are consistent projections of the same unitary whole, respecting the causal constraints of Axiom VII. This is a formalization of the relational quantum mechanics perspective (Rovelli, 1996).

Inertial Frames, Acceleration, and the Equivalence Principle

Axiom VIII naturally distinguishes between different classes of observers.

- Inertial Observers: Their projective basis {e_α} is constant along their worldline, meaning the projection operators are not changing with their internal evolution parameter (proper time). This corresponds to a state of "non-accelerating" relationship with the surrounding state distribution, leading to the observance of homogeneous and isotropic physical laws.
- Accelerating Observers: Their projective basis is Fermi-Walker transported along their worldline. In F, this means the set of projectors is undergoing a continuous, parameter-dependent unitary transformation. This changing perspective accounts for the fictitious forces (like centrifugal force) they experience. The Unruh effect—where an accelerating detector in a vacuum perceives a thermal bath—can be interpreted as a consequence of this evolving projective basis mixing the S and T components of the vacuum state in a temperature-inducing way (Unruh, 1976).
- The Equivalence Principle: The local indistinguishability of acceleration from a gravitational field finds its root here. A gravitational field is a curvature in the emergent space-time metric. In F, curvature corresponds to a non-integrability of the projective bases across different points. An observer in free fall (on a geodesic) is using a locally inertial basis that is parallel-transported, minimizing the rate of change of their projectors. An observer at rest in a gravitational field is using a basis that is constantly accelerating relative to these local inertial bases. The physical effects (like the bending of light or gravitational time dilation) are the measurable consequences of this geometric obstruction to maintaining a global, consistent projective basis, linking back to the need for a dynamical connection (Christoffel symbols) in the emergent geometry (Misner, Thorne, & Wheeler, 1973).

The Horizon Problem and Observer-Dependent Horizons

Cosmological and black hole horizons are quintessentially observer-dependent phenomena. In our framework, an event horizon is not an absolute property of space-time but a limitation of an observer's projective access to the full state space F.

Consider a black hole. An observer at future infinity uses a projective basis that asymptotically aligns with the Killing vector field of stationarity. For this observer, states corresponding to events behind the event horizon are projected onto complex or singular values—they are outside the domain of her projective operators. No continuous, norm-preserving path (Axiom VII) connectable to her basis can reach them. Conversely, an observer falling into the black hole uses a different, freely falling basis. For a finite time according to her proper time (her evolution parameter), her projectors can still access components of the state associated with the interior. The global state Y contains the information of both, but it is partitioned relative to the observational frames (Marolf, 2009).

This resolves the black hole information paradox in principle: information is never lost from the global Y; it merely becomes projectively inaccessible to observers remaining outside the horizon. The increase of black hole entropy (Bekenstein, 1973) is a measure of the growing disalignment between the exterior observer's basis and the basis required to access the full internal state.

The Anthropic Principle as a Projective Selection

Finally, Axiom VIII reframes questions about the "fine-tuning" of physical constants. The constants c, ħ, and the cosmological constant Λ are structural features of F and its dynamics. However, the observed values of these constants (e.g., the vacuum energy density) are not the bare, fundamental values but effective values obtained through the specific projective basis of a carbon-based observer embedded in a post-inflationary galaxy. Different projective slices of the same universal Y (e.g., in different decohered branches of the wave function or different cosmic regions) could yield different effective laws and constants. The so-called anthropic selection is then the statement that only those projective perspectives consistent with the existence of a complex observer can be physically experienced (Barrow & Tipler, 1986). This does not make the constants arbitrary, but relational.

Conclusion: A Complete Relational Ontology

Axiom VIII completes the axiomatic system by embedding the observer into the physics as a fundamental, relational component. It posits that the phenomena of space, time, and measurement are not intrinsic to the universe-in-itself, but arise from the interaction between the objective, unitary state vector Ψ (or Y) and the specific projective filters defining an observer. This elegantly unifies the principles of relativity (the relativity of inertial frames) and the core puzzles of quantum theory (the measurement problem) under a single conceptual roof. The world described by physics is not a world seen from outside; it is the world as it appears from within, a necessary and consistent projection of a more fundamental, unified vectorial reality.

Axiom IX: The Primacy of the Universal State and the Emergence of Quasi-Classical Reality

Having established the observer-independent nature of the fundamental state space and its dynamics in Axiom VIII, we now address the final, critical question of empirical coherence: How does the unitary evolution of the universal state vector Y give rise to the stable, approximately classical world we observe? This is not an addendum to the measurement problem, but its solution within the axiomatic framework. Axiom IX posits a specific dynamical mechanism for the emergence of stable, decohered structures—the quasi-classical worlds—within Y.

Axiom IX: Emergence of Quasi-Classical Branches

Axiom 9 (Emergence of Quasi-Classical Branches).
The universal state vector Y evolves unitarily in F (Axiom IV). Due to the non-linear constraints imposed by the fundamental S = -T antiparallelism (Axiom III) and the conservation of sub-norms |S| and |T| (Axiom V), this evolution dynamically and preferentially selects a set of robust, mutually quasi-orthogonal pointer state bases. These bases correspond to stable configurations of the spatial component S that are minimally perturbed by interaction with the environment (the residual degrees of freedom in F). The quasi-classical world of any localized observer is a trajectory within one such dynamically stabilized branch.

This axiom is a formalization of the decoherence program within our vectorial foundations. It states that classicality is not imposed but derived from the interplay between unitary dynamics and the specific algebraic constraints of the state space.

Mathematical Mechanism: Dynamical Stability from S-T Constraints

The mechanism can be outlined mathematically. Consider decomposing the universal state Y into a subsystem of interest (e.g., a macroscopic apparatus) and an environment: $Y \approx \Sigma_i \alpha_i |\varphi_i\rangle \otimes |E_i\rangle$. The states $\{|\varphi_i\rangle\}$ are candidate pointer states for the subsystem.

Decoherence theory shows that pointer states are those that are least entangled with the environment over time—they are dynamically robust (Zurek, 2003). In our framework, the robustness condition gains a new geometric interpretation. The state $|\varphi_i\rangle$ is not just any state; it is a specific configuration of the spatial component S. Its dynamical stability is determined by how its associated temporal component $T_i = -S_i / c$ (from Axioms III & VI) couples to the environmental degrees of freedom.

The interaction Hamiltonian, which generates the unitary evolution, emerges from the redistribution law (Axiom V: $dS/d\lambda \sim -\Omega S$). This law inherently couples spatial configurations to their temporal complements. The pointer states $\{|\varphi_i\rangle\}$ are those for which this coupling is diagonal or predictable, meaning that the environmental reaction to S_i does not drastically rotate S_i into a superposition of different pointer states. This occurs when the S_i configurations are eigenstates of a preferred class of operators that are constants of motion under the environmental interaction, a concept linked to quantum Darwinism (Ollivier, Poulin, & Zurek, 2004).

The constraints |S| = constant and S = -T play a crucial role. They restrict the Hilbert space of possible states and the form of allowed interactions (Ω operators), thereby shaping the landscape of dynamically stable configurations. This may explain the apparent "preference" for position basis in the macroscopic world: position eigenstates (or narrow wave packets) might be exceptionally robust solutions to the constrained S-T redistribution equations in the presence of numerous low-energy environmental degrees of freedom.

Physical Interpretation: Branching as Geometric Foliations of F

The unitary evolution of Y, under the stability condition of Axiom IX, leads to a branching structure. This is not a discrete splitting but a continuous decoherent histories or consistent histories framework (Gell-Mann & Hartle, 1990). Each quasi-classical branch corresponds to a foliation of the high-dimensional state space F into a series of quasi-orthogonal subspaces. Each leaf of this foliation represents a "now" with definite, stable macroscopic properties.

The "flow of time" for an observer in a branch is the sequential perception of these leaves. The branching occurs when the stable foliation itself bifurcates due to a quantum event (e.g., a nucleus decaying or a photon being measured). At such a point, multiple, mutually incompatible stable foliations emerge from a common past. The universal state Y coherently encompasses all branches (all foliations), but the dynamics ensure they do not interfere—their overlap, governed by the decoherence functional, becomes vanishingly small (Dowker & Halliwell, 1992). This loss of interference is a direct consequence of the environmental entanglement and is encoded in the geometry of F as the orthogonality of the corresponding state vectors.

The Born Rule from Self-Locating Uncertainty

Axioms I-VIII, with the addition of IX, describe a universe where all possible outcomes of quantum events occur in different branches. Why then do we observe the statistical regularities of the Born rule? The answer lies in self-locating uncertainty. An observer, as a physical pattern within Y, will find themselves in one of the many branches. The probability of finding oneself in a branch corresponding to outcome i is given by the measure of that branch within the structure of Y.

Axiom IX, by linking pointer states to dynamically robust configurations, provides a natural measure: the squared norm of the branch amplitude, $||\alpha_i||^2$. This is not an additional postulate but a consequence of two principles: (1) the unitary dynamics preserve the norm (Axiom IV), and (2) the branching into robust, quasi-orthogonal states (Axiom IX) partitions the total norm. If one adopts a principle of indifference applied to branches—that an observer should assign equal probability to being in branches of equal norm—the Born rule follows (Wallace, 2010). This is a form of the epistemic principle applied to the multiverse: your chance of experiencing a future is proportional to the objective quantum measure of that future within Y (Vaidman, 1998).

Resolving the Tension with Relativistic Causality

A seeming tension exists between the global branching of Y and the relativity of simultaneity (implied by the relativity of observation). Which foliation of space-time defines the branching? Axiom IX resolves this through the concept of local decoherence. Branching is not a global, instantaneous event. It is a process of decoherence that propagates causally, at or below speed *c*, from the site of a quantum event. The stable pointer states are defined locally through interactions with the immediate environment. A consistent, global branching structure emerges from the entanglement structure of Y, which respects the causal constraints of Axiom VII. Different inertial observers will describe the branching process differently, but they will agree on all local, causal outcomes and the overall quantum measure of histories—the invariant facts (Bedingham, 2011).

Cosmological Implications: The Universe as a Single State

Axiom IX, when applied to cosmology, describes the entire universe as a single quantum state Y evolving unitarily since its initial condition. The hot Big Bang, inflation, and structure formation are not classical processes but specific, coherent evolutions within Y. The initial low-entropy state (the "past hypothesis") is a constraint on the initial vector Y_0 that ensures the dynamical formation of stable, branching structures that we identify as the arrow of time (Carroll & Chen, 2004).

The cosmological constant, dark energy, and the ultimate fate of the universe are then features of the long-term unitary evolution of Y. In this picture, a heat death or cosmic isolation does not lead to a static, boring universe from the perspective of F. The state vector continues its eternal, norm-preserving rotation, potentially giving rise to new complex structures via quantum recurrences or vacuum fluctuations on cosmological timescales, albeit with exponentially small amplitude (Dyson, Kleban, & Susskind, 2002).

Conclusion: A Complete, Observer-Independent Axiomatic Edifice

With Axiom IX, the axiomatization achieves closure. It begins with the simple existence of a vector space F and culminates in a derivation of the world of definite experiences from its unitary dynamics. The nine axioms form a tight, interdependent structure:

- I-III define the object: Ψ = (S, -S), with |S|=c|T|.
- IV-V define its change: unitary redistribution.
- VI-VII define its limits: a maximum exchange rate *c* and causal topology.
- VIII asserts its objective reality.
- IX explains our subjective experience within it.

This framework proposes that the unity of space-time is the most visible consequence of a deeper unity: that of the quantum state of the universe. It is a theory where geometry, matter, and experience are all facets of vectorial relationships in an abstract, yet physically real, state space.

Immediate Corollaries and Synthesis

The nine axioms presented form a closed, self-consistent system. While a rigorous derivation of all standard physical laws from these axioms is a vast program beyond the scope of this foundational paper, we can now directly illustrate the explanatory power of the framework by stating its immediate, qualitative corollaries. These are not independent postulates, but logical consequences that follow transparently from the vectorial ontology.

Immediate Corollaries (Without Formal Proofs)

1. Time Dilation with Motion

Time dilation is a direct consequence of the redistribution of the state vector's fixed magnitude between its S and T components (Axioms IV & V). In this framework, a state of "motion" for an object corresponds to a continuous reorientation of Ψ where a portion of the invariant "substance" is allocated to the spatial component S. Since the total magnitude ||Ψ|| and the individual sub-norms (|S| and c|T|) are conserved, an increase in the spatial allocation (manifesting as velocity) necessitates a decrease in the effective magnitude of the temporal component T as measured by a comparative observer. What one observer perceives as a purely temporal evolution (a clock's proper time), another observer, in relative motion, perceives as a mixed S-T redistribution. Their measurement, being a projection onto their own basis (Axiom VIII), will yield a smaller extracted temporal interval for the moving clock. This is not an artifact of signal propagation, but a geometric necessity of the state vector's constant magnitude under different projective decompositions (Einstein, 1905).

The Absence of Absolute Rest

The condition of absolute rest, in a Newtonian sense, would correspond to a state with S = 0. Given the antiparallelism axiom (S = -T), this implies T = 0 as well, leading to a null state vector Ψ = 0, which is non-physical for a system with existence. More rigorously, a state with zero spatial displacement component (in all frames) is forbidden by the dynamical redistribution law (Axiom V). A state must always possess some non-zero S component, as its evolution is a continuous rotation between S and T. A hypothetical particle at "absolute rest" would have its entire state vector aligned along the pure temporal direction in F, but such a direction is not an invariant property—it is defined only relative to an observer's projective basis. Another observer will necessarily project a component of that state onto their own spatial axes. Thus, rest is always relative; there is no privileged state of zero motion in F, consistent with the principle of relativity (Rovelli, 2004).

Mass-Energy Equivalence

In this vectorial picture, the rest mass (m_0) of a particle is identified with the fixed magnitude of the state vector $||\Psi||$, or more precisely, with its characteristic frequency of internal S-T oscillation when net spatial redistribution is zero. It is the invariant "amount of state." Energy (E), in its most general sense, is identified with the rate of change of the state vector's orientation with respect to the affine parameter (proper time). For a free particle, this is constant and corresponds to the temporal frequency of its internal rotation. The famous equation $E = m c^2$ emerges as the relationship between this intrinsic rotation rate (energy/ħ) and the invariant magnitude (mass). A change in energy (e.g., through interaction) corresponds to a change in the rate of the S-T redistribution cycle, which, due to the fixed norms, is only possible if the system's coupling to other states alters the effective inertial characteristics of its internal rotation. The equivalence is therefore geometric: mass is the magnitude, energy is the angular speed in the state space (Taylor & Wheeler, 1992).

The Arrow of Time

The microscopic laws (unitary evolution) are time-symmetric. However, the axiomatic system contains a fundamental asymmetry: Axiom III (S = -T). This establishes a universal handedness or polarization within the state space F. The "arrow of time" is the manifestation of this preferred global orientation in the dynamics. The unitary redistribution (Axiom V) proceeds in the direction that is consistent with this built-in antiparallelism. While individual interactions may be reversible, the global initial condition of the universe—the universal state vector Y_0—is hypothesized to have a coherent alignment with this fundamental orientation (Penrose, 1979). The subsequent unitary evolution and branching (Axiom IX) preserve this alignment on average, leading to the thermodynamic gradient we experience. The arrow is not an emergent property of statistics alone, but has a root in the primitive directional structure of the state vector, explaining why the universe started in a state of low entropy aligned with this vectorial arrow (Carroll, 2010).

Brief Formulation of the Axiomatic System

The entire theory can be condensed into a single, concise statement:

Physical reality is described by a fundamental vector of constant magnitude, whose spatial and temporal components are equal in magnitude and opposite in direction; physics is the geometry of its redistribution.

This formulation captures the essence:

- Fundamental vector of constant magnitude: Axioms I (existence of Ψ), IV ($||\Psi||$ = const).
- Spatial and temporal components: Axiom I ($\Psi = (S, T)$).
- Equal in magnitude: Axioms II & VI ($|S| = c|T|$).
- Opposite in direction: Axiom III (S = -T).

- Physics is the geometry of its redistribution: Axioms V (dynamics as redistribution), VII (causality as connectivity of paths), and VIII/IX (observation and classicality as relational and emergent properties).

Unification Achieved

This axiomatic system achieves a profound unification by demonstrating that the core principles of special relativity, quantum mechanics, and even the arrow of time can be seen as different facets of the same vectorial geometry.

- Relativity (Lorentz invariance, time dilation, relativity of simultaneity) emerges from the projective nature of observation (Axiom VIII) applied to the S-T structure.
- Quantum Mechanics (unitary evolution, superposition, entanglement) is the fundamental law of change in F (Axioms IV, V) and the description of its state.
- The Interface (mass-energy equivalence, limiting speed) arises from the constraints on the redistribution of the constant norm.
- Causality and the Arrow of Time are geometric/topological properties of the state space and its intrinsic orientation.

The framework dissolves the traditional dichotomy between the continuous, deterministic spacetime of general relativity and the probabilistic, discrete events of quantum theory. Here, both are approximate, emergent descriptions valid in different regimes of the same underlying vectorial process.

Outlook and Future Work

The present work establishes the conceptual and logical foundation. The immediate next steps are:

1. Mathematical Rigorization: Formal definition of F as a Krein or Pontryagin space to naturally incorporate the indefinite metric. Precise formulation of the projection operators for observers.
2. Derivation of Standard Physics: Formal derivation of the Lorentz transformations from the invariance of $|S| = c|T|$ under basis changes in F. Derivation of the Schrödinger and Dirac equations as specific forms of the redistribution law in the non-relativistic and relativistic limits.
3. Towards Quantum Gravity: The most significant challenge and promise. The Einstein field equations must emerge as an effective, thermodynamic equation of state governing the large-scale structure of the branching universal state Y, perhaps via an entropic or hydrodynamic analogy (Jacobson, 1995). This would represent the true unification, not by quantizing geometry, but by deriving it.

4. Novel Predictions: The theory may predict subtle deviations from standard quantum mechanics or Lorentz invariance at extreme energies, inherent non-locality scales, or new interpretations of cosmological parameters linked to the global properties of Y.

This vectorial axiomatization is offered not as a finished theory, but as a coherent, minimal starting point—a new lens through which to view the deep unity of physical law.

References

Ambjørn, J., Jurkiewicz, J., & Loll, R. (2004). Emergence of a 4D world from causal quantum gravity. Physical Review Letters, 93(13), 131301.

Amelino-Camelia, G. (2013). Quantum-spacetime phenomenology. Living Reviews in Relativity, 16(1), 5.

Anandan, J., & Aharonov, Y. (1990). Geometry of quantum evolution. Physical Review Letters, 65(14), 1697-1700.

Arnold, V. I. (1989). Mathematical Methods of Classical Mechanics (2nd ed.). Springer-Verlag.

Barrow, J. D. (2002). The Constants of Nature: From Alpha to Omega. Jonathan Cape.

Barrow, J. D., & Shaw, D. J. (2011). The value of the cosmological constant. General Relativity and Gravitation, 43(10), 2555-2560.

Barrow, J. D., & Tipler, F. J. (1986). The Anthropic Cosmological Principle. Oxford University Press.

Bedingham, D. J. (2011). Relativistic state reduction dynamics. Foundations of Physics, 41(4), 686–704.

Bekenstein, J. D. (1973). Black holes and entropy. Physical Review D, 7(8), 2333–2346.

Bohm, D. (1952). A suggested interpretation of the quantum theory in terms of "hidden" variables. I & II. Physical Review, 85(2), 166-193.

Bombelli, L., Lee, J., Meyer, D., & Sorkin, R. D. (1987). Spacetime as a causal set. Physical Review Letters, 59(5), 521-524.

Carroll, S. M. (2010). From Eternity to Here: The Quest for the Ultimate Theory of Time. Dutton.

Carroll, S. M., & Chen, J. (2004). Spontaneous inflation and the origin of the arrow of time. arXiv preprint hep-th/0410270.

Connes, A. (1994). Noncommutative Geometry. Academic Press.

Cunningham, E. (1914). The principle of relativity in electrodynamics and an extension thereof. Proceedings of the London Mathematical Society, s2-8(1), 77-98.

de Broglie, L. (1924). Recherches sur la théorie des quanta [Ph.D. thesis, Université de Paris]. Masson et Cie.

Deriglazov, A. A. (2017). Classical Mechanics: Hamiltonian and Lagrangian Formalism (2nd ed.). Springer.

Deutsch, D. (1999). Quantum theory of probability and decisions. Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 455(1988), 3129–3137.

Dirac, P. A. M. (1930). The Principles of Quantum Mechanics. Oxford University Press.

Dowker, F., & Halliwell, J. J. (1992). Quantum mechanics of history: The decoherence functional in quantum mechanics. Physical Review D, 46(4), 1580–1609.

Dyson, L., Kleban, M., & Susskind, L. (2002). Disturbing implications of a cosmological constant. Journal of High Energy Physics, 2002(10), 011.

Einstein, A. (1905). On the electrodynamics of moving bodies. Annalen der Physik, 17(10), 891-921.

Einstein, A. (1905). On the electrodynamics of moving bodies. Annalen der Physik, 17(10), 891–921.

Einstein, A. (1915). The field equations of gravitation. Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin, 844-847.

Ellis, G. F. R., & Uzan, J.-P. (2005). c is the speed of light, isn't it? American Journal of Physics, 73(3), 240–247.

Feynman, R. P., & Hibbs, A. R. (1965). Quantum Mechanics and Path Integrals. McGraw-Hill.

Feynman, R. P., Hibbs, A. R., & Styer, D. F. (2005). Quantum Mechanics and Path Integrals. Dover Publications.

Friedman, J., Morris, M. S., & Novikov, I. D. (1990). Cauchy problem in spacetimes with closed timelike curves. Physical Review D, 42(6), 1915-1930.

Gell-Mann, M., & Hartle, J. B. (1990). Quantum mechanics in the light of quantum cosmology. In Complexity, Entropy, and the Physics of Information (pp. 425–458). Addison-Wesley.

Ghirardi, G. C., Rimini, A., & Weber, T. (1980). A general argument against superluminal transmission through the quantum mechanical measurement process. Lettere al Nuovo Cimento, 27(10), 293-298.

Haag, R. (1992). Local Quantum Physics: Fields, Particles, Algebras. Springer-Verlag.

Hardy, L. (2001). Quantum theory from five reasonable axioms. arXiv preprint quant-ph/0101012.

Hardy, L. (2009). Foliable operational structures for general probabilistic theories. In H. Halvorson (Ed.), Deep Beauty: Understanding the Quantum World through Mathematical Innovation (pp. 409-442). Cambridge University Press.

Hawking, S. W. (1992). Chronology protection conjecture. Physical Review D, 46(2), 603-611.

Hestenes, D. (1966). Space-Time Algebra. Gordon and Breach.

Hestenes, D. (1990). The zitterbewegung interpretation of quantum mechanics. Foundations of Physics, 20(10), 1213-1232.

Hestenes, D. (1990). The zitterbewegung interpretation of quantum mechanics. Foundations of Physics, 20(10), 1213–1232.

Isham, C. J. (1993). Canonical quantum gravity and the problem of time. In Integrable Systems, Quantum Groups, and Quantum Field Theories (pp. 157-287). Springer.

Jaba, T. (2022). Dasatinib and quercetin: short-term simultaneous administration yields senolytic effect in humans. Issues and Developments in Medicine and Medical Research Vol. 2, 22-31.

Jacobson, T. (1995). Thermodynamics of spacetime: The Einstein equation of state. Physical Review Letters, 75(7), 1260-1263.

Jacobson, T. (1995). Thermodynamics of spacetime: The Einstein equation of state. Physical Review Letters, 75(7), 1260–1263.

Kempf, A., Mangano, G., & Mann, R. B. (1995). Hilbert space representation of the minimal length uncertainty relation. Physical Review D, 52(2), 1108-1118.

Kempf, A., Mangano, G., & Mann, R. B. (1995). Hilbert space representation of the minimal length uncertainty relation. Physical Review D, 52(2), 1108–1118.

Kiefer, C. (2012). Quantum Gravity (3rd ed.). Oxford University Press.

Klein, F. (1893). The mathematical theory of the top. Charles Scribner's Sons.

Lloyd, S. (2006). Programming the Universe. Knopf.

Magueijo, J. (2003). New varying speed of light theories. Reports on Progress in Physics, 66(11), 2025.

Maldacena, J. (1999). The large-N limit of superconformal field theories and supergravity. International Journal of Theoretical Physics, 38(4), 1113-1133.

Marolf, D. (2009). Black holes, AdS, and CFTs. General Relativity and Gravitation, 41(4), 903–917.

Minkowski, H. (1908). Space and time. In The Principle of Relativity (1920 translation, pp. 73-91). Dover.

Misner, C. W., Thorne, K. S., & Wheeler, J. A. (1973). Gravitation. W. H. Freeman.

Ollivier, H., Poulin, D., & Zurek, W. H. (2004). Objective properties from subjective quantum states: Environment as a witness. Physical Review Letters, 93(22), 220401.

Page, D. N. (1985). Will entropy decrease if the universe recollapses? Physical Review D, 32(10), 2496-2499.

Page, D. N., & Wootters, W. K. (1983). Evolution without evolution: Dynamics described by stationary observables. Physical Review D, 27(12), 2885-2892.

Penrose, R. (1972). Techniques of Differential Topology in Relativity. Society for Industrial and Applied Mathematics.

Penrose, R. (1979). Singularities and time-asymmetry. In S. W. Hawking & W. Israel (Eds.), General Relativity: An Einstein Centenary Survey (pp. 581-638). Cambridge University Press.

Rovelli, C. (1996). Relational quantum mechanics. International Journal of Theoretical Physics, 35(8), 1637–1678.

Rovelli, C. (2004). Quantum Gravity. Cambridge University Press.

Ryu, S., & Takayanagi, T. (2006). Holographic derivation of entanglement entropy from the anti–de Sitter space/conformal field theory correspondence. Physical Review Letters, 96(18), 181602.

Schlosshauer, M. (2007). Decoherence and the Quantum-to-Classical Transition. Springer.

Taylor, E. F., & Wheeler, J. A. (1992). Spacetime Physics (2nd ed.). W. H. Freeman.

Tkemaladze, J. (2023). Reduction, proliferation, and differentiation defects of stem cells over time: a consequence of selective accumulation of old centrioles in the stem cells?. Molecular Biology Reports, 50(3), 2751-2761. DOI : https://pubmed.ncbi.nlm.nih.gov/36583780/

Tkemaladze, J. (2024). Editorial: Molecular mechanism of ageing and therapeutic advances through targeting glycative and oxidative stress. Front Pharmacol. 2024 Mar 6;14:1324446. DOI : 10.3389/fphar.2023.1324446. PMID: 38510429; PMCID: PMC10953819.

Tkemaladze, J. (2026). Old Centrioles Make Old Bodies. Annals of Rejuvenation Science, 1(1). DOI : https://doi.org/10.65649/yx9sn772

Tkemaladze, J. (2026). Visions of the Future. Longevity Horizon, 2(1). DOI : https://doi.org/10.65649/8be27s21

Unruh, W. G. (1976). Notes on black-hole evaporation. Physical Review D, 14(4), 870–892.

Vaidman, L. (1998). On schizophrenic experiences of the neutron or why we should believe in the many-worlds interpretation of quantum theory. International Studies in the Philosophy of Science, 12(3), 245–261.

Van Raamsdonk, M. (2010). Building up spacetime with quantum entanglement. General Relativity and Gravitation, 42, 2323-2329.

von Neumann, J. (1932). Mathematische Grundlagen der Quantenmechanik. Springer.

Wallace, D. (2010). How to prove the Born rule. In S. Saunders, J. Barrett, A. Kent, & D. Wallace (Eds.), Many Worlds? Everett, Quantum Theory, and Reality (pp. 227–263). Oxford University Press.

Wallace, D. (2012). The Emergent Multiverse: Quantum Theory according to the Everett Interpretation. Oxford University Press.

Weinberg, S. (1995). The Quantum Theory of Fields, Vol. 1: Foundations. Cambridge University Press.

Wheeler, J. A. (1962). Geometrodynamics. Academic Press.

Wilczek, F. (1999). Mass without mass I: Most of matter. Physics Today, 52(11), 11–13.

Zeh, H. D. (1992). The Physical Basis of The Direction of Time. Springer-Verlag.

Zurek, W. H. (2003). Decoherence, einselection, and the quantum origins of the classical. Reviews of Modern Physics, 75(3), 715-775.

Zurek, W. H. (2003). Decoherence, einselection, and the quantum origins of the classical. Reviews of Modern Physics, 75(3), 715-775.Bombelli, L., Lee, J., Meyer, D., & Sorkin, R. D. (1987). Spacetime as a causal set. Physical Review Letters, 59(5), 521-524.