Causal Structure in Simplicial Discrete Informational Spacetime: Enforcement of Forward Causality and Constraints on Retrocausal Phenomena

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Abstract:

The Simplicial Discrete Informational Spacetime (SDIS) framework (Karazoupis, 2025) was developed to provide a consistent quantum description of gravity by positing a fundamentally discrete and informational spacetime built from 4-simplices. A core design consideration within SDIS is the implementation of a physically realistic causal structure. This paper elaborates on the mechanisms within SDIS that define causality and the arrow of time. We analyze the role of directed simplex orientation, the forward-evolution dynamics dictated by the system's quantum Hamiltonian and Lindblad master equation, the emergent thermodynamic arrow of time derived from holographic entropy growth and decoherence, and the geometric stability axioms that prevent pathological configurations. The analysis demonstrates that these integral components are specifically constructed to enforce forward causality at both the fundamental Planck scale and the emergent macroscopic level. While acknowledging theoretical discussions of retrocausality in physics, this paper details how the postulates and mathematical structure of SDIS inherently constrain such phenomena, ensuring consistency with observed physical principles and preventing causal paradoxes. The framework's internal logic strongly supports a standard causal structure, precluding stable retrocausality as a feature of its dynamics.

Keywords: Simplicial Discrete Informational Spacetime (SDIS), Retrocausality, Arrow of Time, Quantum Gravity, Simplicial Dynamics, Emergent Time, Quantum Information Theory.

Introduction

The development of the Simplicial Discrete Informational Spacetime (SDIS) framework (Karazoupis, 2025) represents a dedicated effort to construct a predictive and testable theory of quantum gravity by addressing the fundamental nature of spacetime at the Planck scale. Departing from the classical continuum conception of General Relativity (GR), SDIS is founded on the postulate that spacetime is fundamentally discrete and informational, composed of quantum entities – simplicial chronotopes (regular 4-simplices) – whose collective dynamics and interactions generate the emergent fabric of reality. This approach integrates principles from Non-commutative Geometry and Quantum Information Theory, aiming for a unified description of spacetime, gravity, matter, and their quantum interactions (Karazoupis, 2025).

A cornerstone of the SDIS architecture is the implementation of a consistent and physically grounded causal structure. Replacing the smooth manifold with a dynamic quantum network necessitates a precise definition of temporal progression and causal influence directly from the fundamental constituents and their interactions. The very definition of dynamics, the propagation of information and physical fields, and the recovery of classical physics in the appropriate limit hinge upon the robustness of the causal framework established at the Planck scale. Consequently, ensuring a well-behaved causal structure was a primary consideration throughout the development of SDIS.

While the macroscopic world clearly exhibits a thermodynamic arrow of time and adheres to the principle of forward causality (causes preceding effects), the foundational level of physics, particularly within quantum mechanics, presents interpretational challenges and phenomena (e.g., entanglement, measurement) that have occasionally motivated theoretical considerations of non-standard temporal structures, including retrocausality (Price, 1994; Cramer, 1986; Aharonov & Vaidman, 1990). Although such concepts are heavily constrained by the need to avoid logical paradoxes and are generally incompatible with controllable signaling (Shimony, 1984), their theoretical discussion underscores the importance of clarifying the status of causality in any proposed fundamental theory.

This paper aims to provide a detailed exposition of the causal structure inherent within the SDIS framework. We will elucidate the specific mechanisms designed to establish and maintain a consistent arrow of time and forward causal propagation. This includes the foundational role of simplex orientation in defining local causal relations, the nature of the forward time evolution dictated by the framework's quantum Hamiltonian and the associated Lindblad master equation for open system dynamics, the derivation of an emergent thermodynamic arrow of time consistent with cosmological observations, and the crucial function of the geometric stability axioms in precluding the formation of configurations that could support causal pathologies.

By systematically analyzing these integral components of SDIS, this work intends to demonstrate that the framework is not merely compatible with forward causality, but is explicitly constructed to enforce it as a fundamental aspect of its structure and dynamics. We will argue that the internal logic and mathematical formulation of SDIS constrain the possibility of stable retrocausal phenomena, thereby ensuring consistency with established physical principles and providing a sound foundation for describing physical interactions within a discrete quantum spacetime.

Literature Review: Retrocausality in Theoretical Physics

The principle of forward causality, where causes invariably precede their effects, is deeply embedded in our understanding of the physical world and forms a cornerstone of classical physics, including General Relativity. However, the advent of Quantum Mechanics (QM), with its counter-intuitive phenomena like entanglement and the measurement problem, has spurred theoretical investigations into the fundamental nature of time and causality, occasionally leading to considerations of retrocausality – the hypothesis that future events could influence past or present states. While highly constrained and often controversial, understanding these discussions provides essential context for evaluating the causal structure implemented within the SDIS framework.

Philosophically, the primary motivation for exploring retrocausality often stems from a desire to restore locality and determinism to QM, potentially resolving the apparent "spooky action at a distance" associated with entanglement (Einstein, Podolsky, & Rosen, 1935). If influences could propagate backward in time, non-local correlations might be explained via local interactions mediated through the past light cones of the entangled particles (Price, 1994; Costa de Beauregard, 1977). Huw Price, in particular, has argued extensively from a philosophical standpoint for time symmetry in fundamental physics, suggesting that the perceived arrow of time is thermodynamic or cosmological in origin, not intrinsic to the underlying laws, thereby opening the door to retrocausal possibilities (Price, 1996).

Within QM interpretations, the Transactional Interpretation (TIQM), proposed by John Cramer (1986, 1988), explicitly incorporates retrocausality. TIQM describes quantum interactions as a relativistic "handshake" involving retarded (forward-in-time) "offer" waves from the emitter and advanced (backward-in-time) "confirmation" waves from the absorber(s). The completion of this transaction, satisfying boundary conditions at both emitter and absorber, corresponds to the probabilistic collapse of the state vector. While inherently retrocausal in its mechanism, TIQM is carefully formulated to reproduce the statistical predictions of standard QM and, crucially, does not permit controllable signaling to the past or causal paradoxes (Cramer, 1988).

Another relevant area involves time-symmetric formulations of QM, pioneered by Aharonov, Bergmann, and Lebowitz (1964) and further developed through concepts like weak measurements and the Two-State Vector Formalism (TSVF) (Aharonov & Vaidman, 1990; Aharonov & Gruss, 2005). These approaches treat initial (pre-selected) and final (post-selected) boundary conditions more symmetrically than standard QM. The properties of a quantum system between pre- and post-selection can appear to depend on the future post-selection, suggesting a form of backward-in-time influence on the system's state during that interval. While TSVF offers novel perspectives and predictions for specific experimental setups (e.g., weak measurements yielding anomalous values), proponents argue it does not violate standard causality regarding controllable signaling (Aharonov & Vaidman, 2010).

Experimental results, particularly Wheeler's delayed-choice thought experiments (Wheeler, 1978) and their experimental realizations, including the quantum eraser (Kim et al., 2000), are frequently invoked in discussions of retrocausality. In these experiments, a choice made about the measurement setup (e.g., whether to acquire which-path information) after a particle has passed the point of interference seemingly determines whether the particle behaved as a wave or a particle in the past. However, the standard interpretation explains these results through quantum correlations and complementarity without invoking true retrocausality; the interference pattern only emerges upon correlating subsets of data based on the outcome of the later measurement (Englert, Scully, & Walther, 1991; Zeilinger, 2000). Nonetheless, the appearance of future influence on past behaviour fuels the debate and highlights the non-classical nature of quantum causality.

Despite these theoretical explorations, any notion of retrocausality faces severe constraints. The most significant is the prohibition of superluminal or backward-in-time signalling, often formalized through no-signalling theorems derived from QM principles (Ghirardi, Rimini, & Weber, 1980; Shimony, 1984). These theorems demonstrate that while QM allows non-local correlations, these cannot be exploited for controllable faster-than-light or past-directed communication, thus preserving relativistic causality at the operational level and preventing grandfather paradoxes. Any viable physical theory, including interpretations invoking retrocausal elements, must remain consistent with these no-signalling constraints.

This landscape of theoretical possibilities and stringent constraints underscores the critical importance of carefully defining and implementing the causal structure within any fundamental theory like SDIS. While QM opens avenues for non-standard interpretations of temporal relations, the framework must ultimately yield a causal structure consistent with macroscopic observations and free from logical inconsistencies. The SDIS approach prioritizes a robust forward-causal structure emerging from its fundamental discrete dynamics.

Research Questions

The primary objective of this paper is to delineate the causal structure inherent within the Simplicial Discrete Informational Spacetime (SDIS) framework. To achieve this, our analysis is guided by the following specific research questions:

1. Role of Simplex Orientation: How does the defined orientation assigned to each 4-simplex within the SDIS network function mathematically and physically to establish a directed causal ordering between adjacent spacetime events at the fundamental level?
2. Nature of Quantum Dynamics: Do the quantum evolution equations governing the SDIS network – specifically, the unitary evolution generated by the Hermitian Hamiltonian and the dissipative evolution described by the Lindblad master equation – exclusively permit forward time evolution of the system state, or could they accommodate solutions or interpretations allowing for retrocausal influences?
3. Implications of Emergent Time: Given that time in SDIS is proposed as an emergent property arising from the sequence of discrete network state changes, does this emergence mechanism inherently preclude causal influences propagating backward through this sequence from future configurations to past ones?
4. Consistency with Thermodynamic Arrow of Time: How does the framework's derivation of the thermodynamic arrow of time, linked to holographic entropy

growth and quantum decoherence, relate to the microscopic causal structure? Does this emergent arrow provide an additional layer of constraint against fundamental retrocausality?

5. Function of Stability Mechanisms: Do the geometric stability postulates of SDIS, including the critical stress/strain thresholds triggering Pachner moves and the fundamental curvature bound, effectively prevent the formation and persistence of topological configurations within the simplicial network that could potentially support retrocausal loops (e.g., discrete analogues of closed timelike curves)?
6. Conditions for Non-Standard Causality: Under what theoretical conditions, if any – such as hypothetical extreme states, specific topological structures permitted by the dynamics, or alternative interpretations of quantum phases within the network – could phenomena interpretable as retrocausal conceivably arise within SDIS? Would such phenomena be stable features or transient, unstable artefacts?
7. Overall Causal Architecture: Considering the interplay of its foundational postulates, mathematical formalism, dynamical laws, and emergent properties, does the SDIS framework fundamentally enforce a forward-propagating causal structure, thereby rendering stable retrocausality incompatible with its theoretical architecture?

Addressing these questions will allow for a comprehensive characterization of causality within SDIS, clarifying its relationship with standard physical principles and its stance on non-standard temporal phenomena.

Analysis and Results: Causal Structure Enforcement in SDIS

A detailed examination of the mathematical structure and dynamical principles of the Simplicial Discrete Informational Spacetime (SDIS) framework reveals multiple, interwoven mechanisms designed to establish and enforce a consistent forward causal structure. This analysis addresses the research questions by dissecting the relevant mathematical formalisms.

Simplex Orientation and Directed Causal Links

The framework introduces a fundamental orientation parameter for each 4-simplex, s_i, within the simplicial complex S. This orientation is represented by a discrete value, taking values of either +1 or -1. The explicit purpose stated for this assignment is the establishment of a causal structure and ordering within the discrete spacetime fabric. This implies that the links or adjacencies between simplices, defined by the Gluing Condition (sharing a tetrahedral face, $|s_i \cap s_j| = 4$), are imbued with a directionality derived from these orientations. While the specific dynamical rules governing the evolution or assignment of these orientations are part of the ongoing development of the framework's dynamical laws, their defined role is to break time-reversal symmetry at the most fundamental level, providing a directed graph structure upon which causal propagation occurs. This foundational choice inherently opposes the notion of influences propagating backward against the defined causal direction.

Forward Time Evolution from Quantum Dynamics

The evolution of the quantum state of the simplicial network is governed by established quantum mechanical formalisms that inherently describe propagation forward in time.

- Hamiltonian Dynamics: The total quantum Hamiltonian operator, $\hat{H}$, governs the coherent evolution of the network. It is expressed as the sum of geometric, matter, and interaction terms, with the geometric part being: $\hat{H}_{geo} = \Sigma_v (Y/2)\sigma_v^2 - J\Sigma_{(i,j)} \sigma_i^x \sigma_j^x + h\Sigma_i \sigma_i^z$ Here, σ_v represents the vertex stress operator, Y is the spacetime stiffness (Young's modulus), J is the coupling energy (set to the Planck energy, E_P), h is the decoherence parameter, and σ^x, σ^z are Pauli operators acting on the qubit state space H_i of individual simplices. This Hamiltonian is constructed to be Hermitian ($\hat{H} = \hat{H}^\dagger$). Hermitian operators generate unitary time evolution via the Schrödinger equation: $i\hbar \, d|\Psi(t)\rangle/dt = \hat{H}|\Psi(t)\rangle$ The solution is given by the unitary operator $U(t) = \exp(-i\hat{H}t/\hbar)$, such that $|\Psi(t)\rangle = U(t)|\Psi(0)\rangle$. This mathematical structure describes how a state evolves deterministically and unitarily forward in time from a specified initial state $|\Psi(0)\rangle$. Standard Hamiltonian mechanics provides no mechanism for future states to influence this forward evolution.
- Lindblad Dynamics: To incorporate decoherence and interactions with potential environmental degrees of freedom (or tracing out parts of the network), the framework utilizes the Lindblad master equation for the density matrix ρ: $d\rho/dt = -i/\hbar [\hat{H}, \rho] + \Sigma_k \gamma_k (L_k \rho L_k^\dagger - 1/2 \{L_k^\dagger L_k, \rho\})$ Within the framework, the Lindblad operators L_k are associated with decoherence mechanisms, specifically chosen as $L_i = \sigma_i^z$ acting on individual simplices, with γ representing the decoherence rate $\Gamma_{decohere}$. This equation describes a completely positive trace-preserving (CPTP) map, ensuring the physical validity of the density matrix ρ throughout its evolution. Crucially, the Lindblad formalism describes Markovian dynamics – the rate of change $d\rho/dt$ depends only on the present state $\rho(t)$. It dictates an irreversible, dissipative evolution forward in time, modelling the loss of quantum coherence and the emergence of classicality.

Emergent Temporality and Step-by-Step Evolution

Time within SDIS is not postulated as an independent dimension but emerges dynamically from the evolution of the network's structure and quantum state. The progression of time corresponds to a sequence of discrete state changes. These changes can be conceptualized as permutations of the adjacency matrix A_{ij} (where $A_{ij} = 1$ if simplices s_i and s_j share a tetrahedron, 0 otherwise) or, more physically, as the sequence of topological reconfigurations (Pachner moves) triggered by the system's dynamics. The evolution proceeds step-by-step, governed by the application of the evolution operator $U(\Delta t) \approx I - i\hat{H}\Delta t/\hbar$ or the corresponding Lindblad update rule over small discrete time intervals Δt (potentially related to Planck time, $t_P = \sqrt{\hbar G/c^5}$). Since each state $|\Psi(t+\Delta t)\rangle$ or $\rho(t+\Delta t)$ is generated based solely on the state at time t and the dynamical laws ($\hat{H}$, L_k), the emergent temporal sequence is inherently directed forward. There is no mechanism within this step-by-step generation for a future state, which has not yet been computed or dynamically reached, to influence the computation or evolution of past states.

Consistency with the Emergent Thermodynamic Arrow of Time

The framework provides mechanisms that lead to an emergent thermodynamic arrow of time, reinforcing the fundamental forward causality.

- Holographic Entropy Growth: The Holographic Entropy Bound, $S \leq (A / 4l_P^2)\ln(2)$, when applied to the expanding universe (where the relevant boundary area $A(t)$ evolves, e.g., $A(t) \propto e^{2Ht}$ during inflation), provides a basis for entropy increase over cosmological time.
- Geometric Dissipation: The generalization of the second law to spacetime introduces dissipation through terms related to bulk (ζ) and shear (η) viscosity, ensuring non-negative entropy production: $\nabla_\mu s^\mu = \zeta\theta^2 + 2\eta\sigma_{\mu\nu} \sigma^{\mu\nu} \geq 0$ where $\theta = \nabla_\mu u^\mu$ is the expansion scalar and $\sigma_{\mu\nu}$ is the shear tensor.
- Decoherence: The decoherence term $h\Sigma\sigma_z$ in $\hat{H}$ and the Lindblad dissipator $L(\rho)$ explicitly model irreversible processes that increase entropy and drive the system towards classicality.

These processes are inherently time-asymmetric and directed towards the future (increasing entropy, loss of coherence, expansion). The emergence of a consistent thermodynamic arrow from these forward-directed microscopic processes makes fundamental retrocausality highly problematic, as it would likely violate this emergent second law.

Geometric Stability and Prevention of Causal Pathologies

The framework incorporates stability mechanisms designed to prevent the formation of geometries that might permit causal anomalies.

- Curvature/Area Bounds: The fundamental Planck length $l_P = \sqrt{\hbar G/c^3}$ and Planck time t_P define minimal scales. The derived minimal area gap $\Delta A \sim l_P^2$ and the curvature bound $R < l_P^{-2}$ prevent the collapse to zero size and the formation of infinite curvature singularities, respectively.
- Stress and Strain: Geometric distortions are quantified by vertex stress σ_v, calculated from deviations of dihedral angles θ_{actual} from the ideal $\theta_{ideal} = \arccos(1/4) \approx 75.5°$: $\sigma_v = \Sigma_{(e1,e2)\text{ incident at }v} (\theta_{actual}(e1,e2) - \theta_{ideal})^2$

Stress induces strain ε_{ab} via the Planck-scale Hooke's Law: $\varepsilon_{ab} = [(1+\nu)/Y] \sigma_{ab} - [\nu/Y] Tr(\sigma)\delta_{ab}$ where $\nu = 0.25$ is the derived Poisson ratio and $Y = E_P/l_P^3$ is the derived spacetime stiffness.

- Pachner Move Regulation: When strain exceeds the critical threshold, $\varepsilon_{crit} = 1$ (dimensionless), Pachner moves are triggered. These are local topological reconfigurations of the simplicial complex. These moves dynamically alter the network connectivity (adjacency matrix A_{ij}) in a way that reduces local stress concentrations σ_v, thus actively preventing the persistence of highly distorted or pathological geometries that might hypothetically support stable causal loops.

Constraints on Non-Standard Causality

The combined effect of these mechanisms severely constrains non-standard causality:

- The directed causal links (orientation), the exclusively forward nature of the Hamiltonian and Lindblad evolution equations, the step-by-step emergent temporality, the consistent emergent thermodynamic arrow, and the active suppression of pathological geometries via stability bounds and Pachner moves create a robust framework for forward causality.
- Stable retrocausality would require violating one or more of these fundamental components – e.g., allowing orientation to be influenced by future states, modifying the standard quantum evolution equations, or finding stable topological configurations that evade the Pachner move regulation and curvature bounds. No such mechanisms are present in the described framework.
- Unstable, transient effects resembling retrocausality might only be conceivable during the brief moments of topological reconfiguration via Pachner moves in regions of extreme stress, but these are, by definition, unstable states that the system dynamically evolves away from to restore stability and forward causality.

Conclusion of Analysis: The mathematical structure and dynamical principles defined within the SDIS framework consistently enforce forward causality. The theory employs multiple, reinforcing layers – from fundamental simplex properties and standard quantum evolution laws to emergent temporal and thermodynamic arrows and active stability mechanisms – that collectively preclude stable retrocausal phenomena.

Discussion

The analysis presented in the previous section demonstrates that the Simplicial Discrete Informational Spacetime (SDIS) framework, as formulated in Karazoupis (2025), incorporates a robust architecture designed to enforce forward causality. This finding has significant implications for the interpretation of the framework and its position within the broader landscape of quantum gravity research and discussions on the nature of time.

The explicit introduction of simplex orientation as a means to establish causal ordering at the Planck scale is a crucial design choice. Unlike approaches where causality might be purely emergent or potentially violated at the fundamental level, SDIS builds directionality into its very foundation. This aligns the framework with the intuitive and experimentally observed macroscopic arrow of time from the outset, although it raises questions about the deeper origin or dynamical determination of this fundamental orientation itself – a subject for further elaboration beyond the scope of the current text.

The reliance on standard, forward-evolving quantum dynamics (Hermitian Hamiltonian for unitary evolution, Lindblad equation for dissipation) is another key factor. By employing these well-established mathematical tools, SDIS ensures consistency with the predictive success of quantum mechanics in other domains and inherits their inherent temporal asymmetry. This choice contrasts sharply with interpretations like TIQM or TSVF that explicitly introduce retrocausal elements or time symmetry into the quantum formalism itself. SDIS, instead, suggests that the standard forward evolution is sufficient, even at the Planck scale, when applied to its discrete, informational structure.

The emergent nature of time within SDIS offers a compelling perspective. By deriving temporal progression from the sequence of discrete state changes in the underlying quantum network, the framework avoids treating time as an absolute background dimension. This dynamic, step-by-step unfolding naturally supports a presentist view and makes retrocausality difficult to conceptualize, as there is no pre-existing future state to exert influence from. This contrasts significantly with block universe interpretations often associated with classical GR, where the apparent lack of a preferred "now" can make retrocausality seem less problematic conceptually, even if forbidden operationally.

Furthermore, the derivation of a thermodynamic arrow of time from fundamental processes within the framework (holographic entropy growth and decoherence) provides macroscopic validation for the microscopic causal directionality. It suggests that the observed irreversibility of the universe is not an ad hoc addition but a consequence of the interplay between the quantum geometry, information content, and dynamics defined by SDIS. This internal consistency between microscopic laws and macroscopic phenomena strengthens the framework's coherence.

The geometric stability mechanisms, particularly the curvature bound and the stress-triggered Pachner moves, are vital not just for ensuring a well-behaved emergent geometry but also for actively preventing causal pathologies. By dynamically resolving regions of extreme stress or curvature, the framework avoids the persistence of configurations that might, in principle, allow for causal loops or other anomalies. This suggests a self-healing or self-regulating aspect to the quantum spacetime fabric described by SDIS, ensuring its global causal integrity.

While our analysis indicates a strong preclusion of stable retrocausality, the possibility of transient, unstable effects during highly dynamic events (like Pachner cascades near the Planck scale) cannot be entirely ruled out without a more detailed analysis of the dynamics under such extreme conditions. However, such effects, if they exist, would likely be confined to the Planck scale, rapidly suppressed by stability mechanisms, and unlikely to have macroscopic consequences or permit controllable signaling, thus preserving effective macroscopic causality.

In conclusion, the SDIS framework presents a picture where forward causality is not merely assumed but is actively enforced through multiple, consistent layers of its theoretical structure. From the fundamental orientation of spacetime quanta and the laws governing their evolution to the emergent nature of time and the dynamic enforcement of geometric stability, SDIS is constructed to describe a universe evolving predictably, albeit probabilistically at the quantum level, from the present into the future. This inherent directionality aligns SDIS with established physical principles while offering a novel, discrete foundation for understanding spacetime and causality at the Planck scale. The framework thus provides a strong counterpoint to interpretations or theories that might allow for significant retrocausal influences in fundamental physics.

Appendix: Detailed Mathematical Formalisms for Causal Structure in SDIS

This appendix provides expanded mathematical details for the concepts discussed, grounding the analysis of causal structure in the specific equations and definitions presented within the SDIS framework (Karazoupis, 2025).

A.1 Simplicial Structure, Orientation, and Adjacency

- Fundamental Units: Spacetime is composed of N simplicial chronotopes, s_i, mathematically realized as regular 4-simplices. Each s_i has 5 vertices.
- Simplicial Complex: $S = \{s_1, s_2, ..., s_N\}$.
- Adjacency (Gluing Condition): Two simplices, s_i and s_j, are adjacent if they share a common tetrahedral face (3-simplex). Mathematically, $|s_i \cap s_j| = 4$.
- Adjacency Matrix: A square N x N matrix A where:
  $A_{ij} = 1$ if $|s_i \cap s_j| = 4$
  $A_{ij} = 0$ otherwise
- Simplex Orientation: Each simplex s_i is assigned an orientation $O_i \in \{+1, -1\}$. This assignment is explicitly stated to be for the purpose of establishing a causal structure and defining a causal ordering between simplices, potentially related to the local direction of time flow or causal propagation. The specific dynamical rules determining the assignment or evolution of O_i are subject to further elaboration within the framework's dynamical laws but its function is to impose directionality.

A.2 Quantum State Space and Dynamics

- Qubit Space per Simplex: Each simplex s_i is associated with a 2-dimensional Hilbert space H_i (a qubit space), spanned by orthonormal basis states $|0\rangle_i$ and $|1\rangle_i$. A general state is $|\psi_i\rangle = \alpha_i|0\rangle_i + \beta_i|1\rangle_i$, with $|\alpha_i|^2 + |\beta_i|^2 = 1$.
- Total Hilbert Space: The state space for the entire network is the tensor product $H = H_1 \otimes H_2 \otimes \ldots \otimes H_N = \otimes^{(N)}_{(i=1)} H_i$.
- Total Hamiltonian: $\hat{H} = \hat{H}_{geo} + \hat{H}_{matter} + \hat{H}_{int}$. The Hamiltonian is constructed to be Hermitian ($\hat{H} = \hat{H}^\dagger$).
  - Geometric Hamiltonian: $\hat{H}_{geo} = \Sigma_v (Y/2)\sigma_v^2 - J\Sigma_{(i,j)} \sigma_i^x \sigma_j^x + h\Sigma_i \sigma_i^z$ where σ_v is the vertex stress operator (Hermitian), $Y = E_P/l_P^3$ is the spacetime stiffness, $J = E_P$ is the coupling energy, h is the decoherence parameter, and σ^x, σ^z are the standard Hermitian Pauli matrices acting on the respective H_i. The summation $\Sigma_{(i,j)}$ is over adjacent simplices ($A_{ij} = 1$).
  - Matter Hamiltonian (Example: Fermions): $\hat{H}_{fermion} = -t \Sigma_{(v,v')} (\psi_v^\dagger \psi_{v'} + h.c.)$ where $\psi_v^\dagger$, $\psi_{v'}$ are Grassmann-valued Dirac spinor creation/annihilation operators at vertices v, v', satisfying $\{\psi_{v\alpha}, \psi_{v'\beta}^\dagger\} = \delta_{vv'} \delta_{\alpha\beta}$, and $t \approx E_P$ is the hopping parameter. h.c. denotes the Hermitian conjugate.
  - Interaction Hamiltonian (Example: Geometry-Matter): $\hat{H}_{int} = \Sigma_v (\sigma_v \cdot T_v^{matter})$ (Conceptual form, specific operator form depends on T_v^{matter})
- Unitary Evolution: Governed by the Schrödinger equation $i\hbar\, d|\Psi\rangle/dt = \hat{H}|\Psi\rangle$, with the solution $|\Psi(t)\rangle = U(t)|\Psi(0)\rangle$ where $U(t) = \exp(-i\hat{H}t/\hbar)$. As shown before, U(t) is unitary due to $\hat{H}$ being Hermitian, ensuring norm preservation and forward evolution from the initial state $|\Psi(0)\rangle$.

A.3 Lindblad Equation for Open System Dynamics

- Equation: $d\rho/dt = -i/\hbar\, [\hat{H}, \rho] + \Sigma_k \gamma_k (L_k \rho L_k^\dagger - 1/2 \{L_k^\dagger L_k, \rho\})$ where $\{A, B\} = AB + BA$ is the anticommutator.
- SDIS Implementation: The framework primarily associates Lindblad operators with decoherence: $L_i = \sigma_i^z$ (acting on simplex i), and $\gamma_i = \Gamma_{decohere}$ (decoherence rate).
- Properties: The equation preserves trace ($Tr(\rho) = 1$) and positivity ($\rho \geq 0$), ensuring ρ remains a valid density matrix. Its structure dictates evolution based only on the present state ρ(t), enforcing Markovian forward dynamics.
- Derived Transition Rate (Simplex Flip): The rate for a simplex to flip between $|0\rangle$ and $|1\rangle$ due to coupling J and decoherence γ is derived as: $\Gamma_{flip} \approx (J^2/\hbar^2) \cdot \gamma / ((E_P/\hbar)^2 + \gamma^2) \approx (E_P^2/\hbar^2) \cdot \Gamma_{decohere} / ((E_P/\hbar)^2 + \Gamma_{decohere}^2) \approx 10^{-87}\ s^{-1}$ (using Planck scale estimates). This extremely low rate indicates stability but allows for cumulative effects.

A.4 Geometric Stability Mechanisms

- Planck Units: Fundamental length $l_P = \sqrt{\hbar G/c^3}$, time $t_P = l_P/c$, energy $E_P = \hbar/t_P$, area $A_P = l_P^2$, curvature $R_P = l_P^{-2}$.
- Area Quantization: Minimal area gap $\Delta A \sim l_P^2$.
- Curvature Bound: $R < R_P = l_P^{-2}$.
- Ideal Dihedral Angle (Regular 4-Simplex): $\theta_{ideal} = \arccos(1/4) \approx 75.5°$.
- Vertex Stress Operator (Eigenvalue): σ_v quantifies deviation, related to $\Sigma(\theta_{actual} - \theta_{ideal})^2$. Its eigenvalues are bounded: $0 \leq \sigma_v < \sigma_{crit}$.
- Planck-Scale Hooke's Law: Relates stress σ_{ab} and strain ε_{ab} tensors (indices a,b = 1..4):
  $\varepsilon_{ab} = [(1+\nu)/Y]\ \sigma_{ab} - [\nu/Y]\ Tr(\sigma)\delta_{ab}$
  $\sigma_{ab} = Y/(1+\nu)\ [\varepsilon_{ab} + \nu/(1-D\nu)\ Tr(\varepsilon)\delta_{ab}]$ (Inverting for D=4, $\nu=0.25$) where Poisson's ratio $\nu = 0.25$ (derived from simplex rigidity) and Young's Modulus $Y = E_P/l_P^3$ (derived from Planck energy density/holography).
- Critical Thresholds:
  - Strain: $\varepsilon_{crit} = 1$ (dimensionless). Trigger for Pachner moves.
  - Stress: $\sigma_{crit} = Y \cdot \varepsilon_{crit} = Y = E_P/l_P^3$ (Planck stress). Maximum sustainable stress.
- Pachner Moves: Discrete topological transformations (e.g., 4D analogues of 2-3, 3-2 moves) that reconfigure the simplicial lattice locally when $\varepsilon > \varepsilon_{crit}$, acting to reduce σ_v and ε_{ab}, thus restoring stability. The dynamics are driven by minimizing geometric stress/action based on the current configuration.

A.5 Fluctuation-Dissipation Theorem for Spacetime Strain

- Metric Perturbations: $h_{\mu\nu}$ represents quantum fluctuations around the background metric (gravitational waves in the linearized limit).
- Two-Point Correlation Function (Momentum Space):
  $\langle h_{\mu\nu}(k)h_{\alpha\beta}(-k)\rangle = (16\pi G\hbar\, k^{-4} / ((k^2)^2)) \cdot (1/2)[P_{\mu\alpha} P_{\nu\beta} + P_{\mu\beta} P_{\nu\alpha} - P_{\mu\nu} P_{\alpha\beta}] \cdot (\hbar\eta\pi T)$
  Let's use the text's tensor structure:
  $\langle h_{\mu\nu}(k)h_{\alpha\beta}(-k)\rangle = (16\pi G\hbar\, k^{-4} / (...)) \cdot [\eta_{\mu\alpha}\, \eta_{\nu\beta} + \eta_{\mu\beta}\, \eta_{\nu\alpha} - \eta_{\mu\nu}\, \eta_{\alpha\beta}] \cdot (\hbar\eta\pi T)$
  where $\eta_{\mu\nu}$ is the Minkowski metric, η is the shear viscosity coefficient, $T = \hbar H / (2\pi k_B)$ is the de Sitter temperature (with H as Hubble parameter), and (...) represents momentum dependence (e.g., k^2 or k^2+m^2). This relates the spectrum of quantum fluctuations $\langle hh\rangle$ to the dissipation coefficient η.
- Dissipation Relation (Shear Viscosity):

  $\eta = (\hbar / (16\pi G)) \int_0^\infty dt\ \langle\sigma_{\mu\nu}(t)\sigma^{\mu\nu}(0)\rangle$
  This relates the macroscopic dissipation coefficient η to the time integral of the autocorrelation function of the microscopic shear stress fluctuations $\sigma_{\mu\nu}$,

demonstrating that dissipation arises from the time-integrated effect of underlying quantum fluctuations.

These mathematical formulations collectively illustrate how forward causality is embedded and enforced within the SDIS framework through its fundamental definitions, dynamical laws, stability criteria, and emergent thermodynamic properties.

Conclusion

This paper has undertaken a detailed investigation into the causal structure inherent within the Simplicial Discrete Informational Spacetime (SDIS) framework proposed in Karazoupis (2025). Our analysis, grounded in the specific mathematical formalisms and physical postulates of the theory, sought to determine the compatibility of SDIS with standard forward causality versus the potential admission of retrocausal phenomena.

The results of our analysis strongly indicate that the SDIS framework is explicitly constructed to enforce forward causality and preclude stable retrocausal influences. This conclusion is supported by several converging lines of evidence derived directly from the framework's architecture:

1. **Fundamental Directionality:** The assignment of an orientation parameter ($O_i \in \{+1, -1\}$) to each 4-simplex serves the stated purpose of establishing a directed causal ordering at the most fundamental level of the spacetime structure.
2. **Standard Forward Dynamics:** The utilization of a Hermitian Hamiltonian ($\hat{H}$) for coherent evolution and the Lindblad master equation for dissipative dynamics ensures that the quantum state of the simplicial network evolves strictly forward in time, dependent only on the present state.
3. **Emergent Temporality:** The conception of time as an emergent property, arising step-by-step from the sequence of discrete network state changes, inherently supports a forward progression and is incompatible with influences from a non-existent future state.
4. **Consistent Arrow of Time:** The framework provides mechanisms for the emergence of a thermodynamic arrow of time (via holographic entropy growth and decoherence) that aligns with the microscopic directionality, reinforcing the overall causal consistency.
5. **Dynamic Stability Enforcement:** Geometric stability axioms, including curvature bounds ($R < l_P^{-2}$) and stress/strain thresholds ($\varepsilon_{crit} = 1$, $\sigma_{crit} = E_P/l_P^3$) triggering topology-changing Pachner moves, actively prevent the formation and persistence of pathological geometries that might otherwise support causal anomalies.

While hypothetical scenarios involving transient, unstable configurations during extreme dynamical events or non-standard interpretations cannot be definitively excluded without further analysis of the framework under all possible conditions, the core logic and explicitly defined mechanisms of SDIS present formidable barriers to any form of stable or controllable retrocausality. Such phenomena would likely require violating the fundamental postulates or mathematical structures upon which the theory is built.

In conclusion, the Simplicial Discrete Informational Spacetime framework offers a description of quantum gravity where forward causality is a deeply ingrained feature, arising naturally from its discrete, informational, and quantum-dynamical foundations. The theory provides a consistent picture of an evolving universe governed by local, forward-propagating interactions, even at the Planck scale, thereby aligning with macroscopic experience and established physical principles while offering a novel perspective on the quantum origins of spacetime and causality. The constraints against retrocausality identified herein solidify the framework's internal consistency and its potential as a physically realistic model of quantum gravity.

References

Aharonov, Y., Bergmann, P. G. & Lebowitz, J. L. (1964). Time Symmetry in the Quantum Process of Measurement. Physical Review, 134(6B), B1410–B1416. doi:10.1103/PhysRev.134.B1410

Aharonov, Y. & Gruss, E. Y. (2005). Two-time interpretation of quantum mechanics. arXiv preprint quant-ph/0507269. Available at: https://arxiv.org/abs/quant-ph/0507269

Aharonov, Y. & Vaidman, L. (1990). Properties of a quantum system during the time interval between two measurements. Physical Review A, 41(1), 11–20. doi:10.1103/PhysRevA.41.11

Aharonov, Y. & Vaidman, L. (2010). Reply to Mohrhoff's Comment on the Two-State-Vector Formalism. arXiv preprint arXiv:1003.0869 [quant-ph]. Available at: https://arxiv.org/abs/1003.0869

Ashtekar, A. & Lewandowski, J. (2004). Background independent quantum gravity: A status report. Classical and Quantum Gravity, 21(15), R53–R152. doi:10.1088/0264-9381/21/15/R01

Costa de Beauregard, O. (1977). Time Symmetry and Interpretation of Quantum Mechanics. Foundations of Physics, 7(7-8), 539-559. doi:10.1007/BF00708549

Cramer, J. G. (1986). The Transactional Interpretation of Quantum Mechanics. Reviews of Modern Physics, 58(3), 647–687. doi:10.1103/RevModPhys.58.647

Cramer, J. G. (1988). An overview of the transactional interpretation. International Journal of Theoretical Physics, 27(2), 227-236. doi:10.1007/BF00670751

Einstein, A., Podolsky, B. & Rosen, N. (1935). Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?. Physical Review, 47(10), 777–780. doi:10.1103/PhysRev.47.777

Englert, B.-G., Scully, M. O. & Walther, H. (1991). Quantum optical tests of complementarity. Nature, 351, 111–116. doi:10.1038/351111a0

Ghirardi, G. C., Rimini, A. & Weber, T. (1980). A general argument against superluminal transmission of information through the quantum mechanical measurement process. Lettere Al Nuovo Cimento (1971-1985), 27(10), 293–298. doi:10.1007/BF02817189

Karazoupis, M. (2025) Complete Theory of Simplicial Discrete Informational Spacetime: Towards a Predictive and Testable Theory of Quantum Spacetime. doi: 10.20944/preprints202504.0029.v1

Kiefer, C. (2005). Quantum gravity: Approaches and observations. International Journal of Modern Physics D, 14(01), 15-56. doi:10.1142/S021827180500601X

Kim, Y.-H., Yu, R., Kulik, S. P., Shih, Y. & Scully, M. O. (2000). A Delayed Choice Quantum Eraser. Physical Review Letters, 84(1), 1–5. doi:10.1103/PhysRevLett.84.1

Loll, R. (2019). Quantum gravity from causal dynamical triangulations: a review. Classical and Quantum Gravity, 37(1), 013002. doi:10.1088/1361-6382/ab5791

Oriti, D. (Ed.). (2009). Approaches to quantum gravity: Toward a new understanding of space, time and matter. Cambridge University Press. doi:10.1017/CBO9780511575549

Price, H. (1994). A Neglected Route to Realism about Quantum Mechanics. Mind, 103(411), 303-336. doi:10.1093/mind/103.411.303

Price, H. (1996). Time's Arrow & Archimedes' Point: New Directions for the Physics of Time. Oxford University Press.

Rovelli, C. (2004). Quantum Gravity. Cambridge University Press. doi:10.1017/CBO9780511755804

Shimony, A. (1984). Controllable and uncontrollable non-locality. In S. Kamefuchi et al. (Eds.), Foundations of Quantum Mechanics in the Light of New Technology (Proceedings of an International Symposium, Tokyo, Japan, August 29-31, 1983), pp. 225-230. Physical Society of Japan.

Wheeler, J. A. (1978). The 'past' and the 'delayed-choice' double-slit experiment. In A. R. Marlow (Ed.), Mathematical Foundations of Quantum Theory (pp. 9–48). Academic Press.

Zeilinger, A. (1999). Experiment and the foundations of quantum physics. Reviews of Modern Physics, 71(2), S288–S297. doi:10.1103/RevModPhys.71.S288