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From Metric to Vector

A unified state-vector formulation of spacetime via Ze theory

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Abstract

The geometric-differential paradigm of spacetime, while foundational to modern physics, faces intrinsic challenges in quantum gravity and provides a limited framework for understanding state evolution as a computational process. This article proposes a shift in ontological foundations, presenting Ze, a discrete computational framework that implements the dynamics of a fundamental state vector Ψ. We argue that Ze is not merely an algorithm but a model of physical becoming, where space and time are not pre-existing coordinates but emerge as anti-parallel channels for the redistribution of information flow. Within Ze, the state vector is represented by a global configuration of statistical counters, and its evolution is driven by a process of passive learning through the minimization of prediction error. The framework naturally maps key physical entities: the temporal component corresponds to the sequential, irreversible flow of events and counter growth, while the spatial component corresponds to the synchronous, correlational structure of the internal model. This anti-parallelism is formalized in a discrete Ze-Lagrangian, a variational principle balancing structural stabilization against predictive error. We demonstrate how this setup allows for the emergence of relativistic invariants, a statistical and vector-based causality akin to causal sets, and quantum phenomena such as quantization (from discrete accounting) and interference (from superposition of predictive contexts). The theory reframes the observer as a self-norm-preserving system and suggests that Special and General Relativity are limiting descriptions of stable regimes in the Ze dynamics. The work offers a unified, vector-based ontology that derives physics from first principles of information processing.

Keywords: Discrete Spacetime, Foundational Physics, Information Theory, Quantum Gravity, Causal Sets, Predictive Coding.

Introduction: Core Thesis

Ze is a discrete, computational implementation of fundamental state vector Ψ dynamics, where space and time act as anti-parallel channels for the redistribution of information flow. This proposition sits at the intersection of foundational physics, information theory, and computational neuroscience. The prevailing geometric-differential paradigm of spacetime, while immensely successful, faces intrinsic challenges in reconciling with quantum gravity and offers a limited framework for a mechanistic understanding of state evolution as a computational process (Rovelli, 2021; Oriti, 2021). This article posits that the transition from a continuous, metric-based description of reality to one grounded in discrete vector-oriented transitions provides a more natural ontology for a universe that appears fundamentally informational and computational (Lloyd, 2013; Wheeler, 1990). The Ze framework is introduced not as an algorithm for solving problems, but as a candidate model for the very process of physical becoming—a minimal, autonomous system that instantiates the dynamics of state orientation through primitive informational transactions.

The Ontological Status of Ze: A System of Becoming

Ontologically, Ze is not a static structure or a deterministic algorithm. It is best understood as a process model for the continuous, moment-by-moment evolution of a state vector. Its fundamental operation is the tracking of state orientation through the statistical accounting of coincidence and divergence between expectation and incoming signal. At its core, Ze comprises several integrated components that define its state and dynamics:

- **Bit/Event Stream**: The primary input is a sequential, discrete stream of binary distinctions or events (1/0, yes/no, active/inactive). This abstracts any physical measurement or sensory input into a form suitable for computational processing.

- **Counters**: These are the system's memory. Simple registers (N00, N01, N10, N11) accumulate the frequency of transitions between predicted state and actualized event. They form a compact, non-parametric statistical model of recent history.

- **Prediction Errors**: The instantaneous discrepancy between the expected bit (based on the internal model derived from counters) and the received bit. This error signal is the primary driver of change within the system.

- **Passive Learning**: The system updates its counters continuously and automatically following each event. This is not an optimization driven by an external goal, but an inherent, "always-on" adaptation to the stream's statistical regularities, akin to the concept of passive inference in neuroscience (Friston, 2010).

- **Expectation ↔ Reality Asymmetry**: This is the crucial, non-equilibrium engine of the model. The system's prediction for the next state (a probability derived from counters) and the actualized state are not symmetric. Their interaction—specifically, the way prediction errors modulate the update of the internal model—creates a temporal arrow and a feedback loop that defines the state vector's trajectory.

The model's dynamics can be summarized in a simplified, conceptual form. The state orientation vector S is a function of the statistical balances stored in the counters. For a first-order Markov process, the prediction for the next event is based on the conditional probability $P(1|\text{previous bit})$. If we denote the previous state as X_{t-1} and the current event as E_t, the counter $N_{X_{t-1}E_t}$ increments. The internal model's probability estimate is:

$$P(E_t = 1 \mid X_{t-1}) \approx (N_{X_{t-1}1}) / (N_{X_{t-1}0} + N_{X_{t-1}1})$$

The prediction error δ is:

$$\delta = E_t \text{ (actual)} - P(E_t = 1 \mid X_{t-1}) \text{ (expected)}$$

This error δ directly influences the update of the relevant counter, thereby slightly rotating the state vector S for the next prediction. The continuous, recursive application of this rule—OBSERVE, COMPARE (compute δ), UPDATE—constitutes the system's dynamics. The "space" in this model is represented by the statistical structure of correlations within the counter matrix—the latent, multi-dimensional relationships between different event contexts. "Time" is the irreversible, sequential processing of the event stream and the consequent, non-reversible update of the counters (Zeh, 2007). They act as anti-parallel channels: time is the channel of actualized, singular events, while space (the correlational structure) is the channel of potential, parallel relationships that inform predictions.

This formulation echoes ideas in quantum foundations, where the state vector is seen as an expression of an observer's information (Brukner, 2017), and in causal set theory, where spacetime emerges from discrete, partial orders (Surya, 2019). Crucially, Ze implements this not as a mathematical abstraction but as a self-contained, executing process. It demonstrates how a vector in state space (Ψ) can be grounded not in a Hilbert space formalism, but in the physical dynamics of a finite, discrete, and computationally trivial system that nonetheless embodies the essential triad of memory, prediction, and update. The following section will elaborate on how this setup reinterprets physical quantities and offers a novel perspective on the emergence of geometric relations from pre-geometric computational primitives.

Correspondence of Fundamental Entities: Bridging Formalisms

The Ze framework proposes a radical yet systematic correspondence between the abstract constructs of vector-based physical theories and the operational primitives of a discrete computational system. This section delineates this mapping, arguing that the components of Ze are not merely analogies but potential ontological substrates for the entities described by continuum physics. The core of this argument is that in Ze, space and time cease to be pre-existing coordinates; they emerge as distinct, anti-parallel modes of data processing. This shift from a container-based to a process-based ontology aligns with research in quantum gravity suggesting that spacetime is not fundamental but emergent from underlying informational or causal relations (Van Raamsdonk, 2010; Markopoulou, 2009).

The following table summarizes the primary correspondences, which are subsequently explicated in detail:

Vector/Formal Theory Concept	Ze Computational Primitive
State Vector Ψ	Global Counter State (C)
Spatial Component (S)	Structural (Synchronous) Flow
Temporal Component (T)	Sequential (Diachronic) Flow
Anti-parallelism (S ↔ T)	Inversion / Begin–Inverse Operation
Vector Rotation	Shift in Counter Distributions
Norm Invariance	Conservation of Total Count
Causality	Directionality of Coincidence

The State Vector and Its Components

In quantum mechanics, the state vector Ψ represents the complete knowledge of a system, encoding probabilities for measurement outcomes. In Ze, this role is assumed by the global state of the counters (C). This state is not a complex-valued vector in Hilbert space, but a high-dimensional probability distribution derived from the matrix of transition frequencies. Formally, if the system tracks contexts of depth *d*, the state C is a point in a (2^d - 1)-dimensional simplex, where each axis corresponds to the normalized count for a specific historical pattern. This statistical manifold constitutes the system's complete "belief state" about its environment. The evolution of Ψ under the Schrödinger equation finds its counterpart in the continuous, recursive update of C upon each new event, driven by prediction error (Friston, 2010).

The decomposition of spacetime into spatial and temporal components in relativity finds a computational echo in Ze. The spatial component is mapped to the structural (synchronous) flow of information. This refers to the network of correlations and conditional dependencies within the counter matrix at a given computational step. It represents all possible predictive relationships—the latent "landscape" of how one event implies another, analogous to the concept of simultaneous relations or spatial adjacency emerging from entanglement entropy (Van Raamsdonk, 2010). Conversely, the temporal component is embodied in the sequential (diachronic) flow—the inexorable, ordered processing of the input bit stream and the consequent irreversible updating of the counters. This is the arrow of computational time, the channel of actualization, mirroring the one-way progression of proper time along a worldline.

Anti-parallelism and Invariant Properties

A critical feature of relativistic spacetime is the anti-parallel nature of space and time, encapsulated in the metric signature. In Ze, this is not a geometric axiom but a dynamic, operational relationship. The anti-parallelism is realized through an inversion or "begin–inverse" operation. The structural flow (space) can be interpreted as a set of predictions from a given context, while the sequential flow (time) is the arrival of data that confirms or denies those predictions. They are anti-parallel in the sense that they process information in opposite "directions": one is deductive (from model to prediction), the other is inductive (from data to model update). This operational opposition generates the tension necessary for dynamics, reminiscent of the interplay between metric and connection in gauge theories.

In vector-based physics, the rotation of a state vector preserves its norm. In Ze, the analogous process is a shift in the probability distributions stored in the counters. When a prediction error occurs, the relative weights (N_{ij}) are adjusted, effectively "rotating" the state point C within its statistical simplex. The corresponding invariant is not a sum of squared amplitudes, but the conservation of total informational content—specifically, the total cumulative count (ΣN_{ij}) which only increases. This reflects the irreversible accumulation of "experience" and is computationally equivalent to the monotonic increase of a system's age or proper time. The normalization of probabilities (using relative frequencies) ensures the system always operates with a consistent, finite description.

Causality as an Informational Gradient

Finally, the fundamental physical principle of causality is redefined in Ze. Instead of a light-cone structure in a manifold, causality emerges as the directionality of statistical coincidence. An event A is considered a "cause" of a subsequent event B within the model if the conditional probability $P(B|A)$, derived from the counters, significantly deviates from the marginal probability $P(B)$. The direction of causation is inherently tied to the order of the sequential flow. This aligns with causal set theory, where the partial order of elements defines causal structure (Surya, 2019), and with informational approaches to causality like transfer entropy (Schreiber, 2000). In Ze, causality is not an external law but a measurable gradient within the learned statistical model, a persistent asymmetry in the counter matrix that the system itself discovers and uses for prediction.

In conclusion, the Ze framework provides a concrete, albeit minimalist, computational ontology where the key entities of physical theories find direct, operational correspondences. This mapping suggests that the venerable concepts of state vector, spacetime separation, and causality may ultimately be expressions of more primitive informational processes: learning, predicting, and updating. By re-interpreting space and time as data processing modes—synchronous correlation and diachronic sequence—Ze offers a pathway to understand how metric and geometric properties could crystallize from the self-organization of purely computational, pre-geometric elements. The next section will explore the dynamical consequences of this setup and how it may give rise to phenomena analogous to force and potential.

Space and Time as Operational Modes of Ze

Having established the fundamental correspondences, we now delineate the core ontological proposition of the Ze framework: space and time are not primitive continua but emergent, anti-parallel operational modes of a discrete information-processing system. This perspective moves beyond analogy to posit that spatial extension and temporal flow are effective descriptions of two intertwined data-processing channels intrinsic to state evolution, aligning with research that seeks spacetime's origins in pre-geometric, informational structures (Oriti, 2021; Rovelli, 2011).

The Temporal Mode (T): Diachronic Actualization

In Ze, the temporal aspect is identified with the diachronic mode of actualization. This mode is defined by irreversible sequence and historical accumulation, constituting the "arrow" of the system's dynamics.

1. **Sequential Data Ingestion**: The system processes a strictly ordered, non-reversible stream of bits or events: ... e_{t-2}, e_{t-1}, e_t, e_{t+1} .... This provides the raw material of "happening," imposing a fundamental order akin to the causal order in causal set theory (Dowker, 2006). The computational instant of registering a new bit defines the operational "now."

2. **State-Dependent Processing**: The impact of an incoming event e_t is wholly contingent on the immediately preceding global counter state C_{t-1}. The system generates a prediction $P(e_t \mid C_{t-1})$ from this prior state. The resulting prediction error $\delta_t = e_t - P(e_t \mid C_{t-1})$ is the driver of change, creating a Markovian chain: $C_t = F(C_{t-1}, e_t)$, mirroring the action of a time-evolution operator.

3. **Monotonic Growth of Counters**: The cumulative totals in the counter matrix, $N_{total} = \Sigma_i \Sigma_j N_{ij}$, are strictly non-decreasing. This serves as an intrinsic, discrete clock or proper time τ, where $\tau \propto N_{total}$. This irreversible growth provides a fundamental arrow, conceptually linked to the increase of entropy or computational history (Lloyd, 2002). The temporal update for a counter tracking transition a→b is: $N_{ab}(t) = N_{ab}(t-1) + \delta_{ab}(t)$, where $\delta_{ab}(t)$ is 1 if the transition occurred, else 0. The phenomenological "flow of time" is the subjective correlate of this continuous, recursive process of prediction, error calculation, and memory update, a form of Bayesian belief updating (Knill & Pouget, 2004).

The Spatial Mode (S): Synchronic Correlation

Complementary to the temporal mode, the spatial aspect in Ze is identified with the synchronic mode of correlation and potentiality. It deals with relationships of co-dependence and structure within a single computational state, rather than between successive states.

1. **Parallel Comparisons**: At any moment *t*, the system's state C_t is not a single value but a multi-dimensional structure—a matrix of co-occurrence and transition frequencies. This structure embodies a network of parallel comparisons. It encodes, for instance, that pattern A is statistically correlated with pattern B, independent of their sequential occurrence. This internal web of conditional probabilities, such as $P(X \mid Y)$ derived from $N_{XY} / \Sigma_i N_{Yi}$, represents all latent predictive relationships. This is analogous to the concept of space as a set of simultaneous relations or as a network of entanglement (Van Raamsdonk, 2010).

2. **Mirror/Inverse Channels**: The spatial mode operates through mirror-like, inverse logical pathways. While the temporal mode asks "what comes next given this?", the spatial mode asks "what is implied or correlated with this?" It involves traversing the statistical manifold from effect back to potential cause, or from one correlated event to another. This is computationally realized by examining the transpose of conditional probability matrices or by analyzing symmetries within the counter state, creating channels of inference that run orthogonal to the sequential flow.

3. **Distribution Across Intervals**: Spatial "extent" emerges from the distribution of statistical weights across different contextual intervals within C. For example, the degree of statistical independence between two event streams processed by Ze can be interpreted as a measure of their "separation." A high mutual information between contexts would correspond to "proximity," while statistical independence would correspond to "distance." This allows for the emergence of relational, Machian-style spatial geometry from purely informational correlations (Barbour, 2012).

Thus, the spatial component S is not a container but the instantaneous, multi-relational structure of the system's predictive model. It is the landscape of potentialities from which the temporal mode selects a single actualization.

Anti-parallelism: The Dynamic Opposition

The crux of the Ze framework is that these two modes are not independent; they exist in a state of fundamental and necessary anti-parallelism. This is not merely a juxtaposition but a dynamic opposition that powers the system's evolution. In the relativistic metric signature, this is formally expressed as $S = -T$. In Ze, it is operationally realized through the perpetual co-existence of two opposing computational flows:

1. **Begin and Inverse Operations**: Every computational cycle involves a begin (or forward) operation: generating a prediction from structure (S → expectation for T). Its necessary counterpart is the inverse operation: updating the structure based on the actualized

temporal event (T → update of S). These are inverse operations in the sense that one projects from the correlational space to a sequential expectation, while the other injects the sequential actual back into the correlational map.

2. **Direct and Reflected Flows**: This creates a computational circuit with a direct flow (structural prediction → temporal expectation) and a reflected flow (temporal actual → structural update). They are anti-parallel information streams within the system's logic.

This anti-parallelism manifests as a fundamental trade-off, a kind of computational uncertainty principle:

- **Growth of Structure** ↔ **Suppression of Novelty**: When the internal model (S) is highly refined and predictions are accurate (low prediction error), the system exhibits strong spatial structure. However, this corresponds to a suppression of temporal novelty, as events become highly predictable. The system is in a stable, ordered, but potentially static correlational state.

- **Growth of Novelty** ↔ **Decay of Structure**: Conversely, a high influx of unpredictable, novel events (high prediction error in T) forces rapid updates to the counters, "dissolving" or making obsolete previous correlational structures (S). Novelty growth is linked to structural decay, as the model must adapt to new, disordering information.

Formally, one can define a crude measure of structural stability S_stab (e.g., the inverse of the average prediction error over an interval) and temporal novelty T_nov (the average prediction error magnitude). Their product tends to be bounded: $S\_stab * T\_nov \leq K$, where K is a system constant related to learning rate. This negative correlation embodies the anti-parallelism, showing how the modes compete for dominance in shaping the global state C. This dynamic tension is the engine of the system's evolution, providing a computational metaphor for the interplay between the deterministic (geometric) and indeterministic (quantum) aspects of physical law.

The Ze-Lagrangian: A Principle of Extremal Information Dynamics

A pivotal step in connecting the discrete computational substrate of Ze to established physical formalism is the derivation of an action principle. In analytical mechanics, the dynamics of a system are determined by the principle of least action, where the physical path minimizes the integral of a Lagrangian function (Goldstein, 1980). This section proposes a conceptual Ze-Lagrangian, translating the continuous dynamics of a relativistic particle into the discrete, information-theoretic language of the Ze system. This is not a strict derivation but a heuristic mapping that reveals a deep structural analogy, suggesting that physical laws of motion may be recast as principles of optimal information processing (Friston, 2019; Sengupta, Stockburger & Ananth, 2016).

Continuous Form (Reminder)

Consider a simplified, 1+1 dimensional analogue of a relativistic particle's dynamics. The state is described by spatial (S) and temporal (T) components. The standard Lagrangian for a free particle in such a framework, respecting the anti-parallel metric signature, is proportional to the squared norm of its "velocity" in state-space:

$$L_{continuous} = (1/2) \left((dS/d\tau)^2 - (dT/d\tau)^2 \right)$$

where τ is a parameter (e.g., proper time). The action $S = \int L \, d\tau$ is minimized along the physical trajectory. The term $(dS/d\tau)^2$ promotes spatial "smoothness" or kinetic energy, while $-(dT/d\tau)^2$ encodes the constraint from the causal structure of spacetime. This formalism elegantly encapsulates dynamics in a geometric setting.

Discrete Ze-Formulation: From Geometry to Counters

The Ze framework transposes these geometric concepts into the domain of discrete informational updates. Here, the fundamental degrees of freedom are not coordinates but the counter states C_i, which store the statistical history of event transitions. Their evolution is driven by discrete prediction errors.

Let us define:

- **C_i**: The value of a specific counter (e.g., N_{00}, N_{01}) at a given computational step.
- **ΔC_i**: The increment or change in counter C_i over a single update cycle. This is a discrete analogue of a time derivative. For a counter tracking transition $a \to b$, $\Delta C_i(t) = \delta_{ab}(t)$, which is 1 if the transition occurred, else 0.
- **M (Coincidence)**: A global measure of prediction success. This can be defined as the sum of accurate predictions over a sequence, effectively the count of events where the system's predicted probability exceeded a threshold. It represents the alignment between internal model and external stream.
- **E (Prediction Error)**: A global measure of model divergence. This is the sum of squared prediction errors or the Shannon surprise over a sequence: $E = - \Sigma \log P(e_t \mid C_{t-1})$, where P is the model's predicted probability for the actual event e_t (Friston, 2010). This quantifies the cumulative "tension" or "free energy" of the model.

With these elements, we propose a conceptual discrete Ze-Lagrangian L_{Ze} evaluated over a short sequence of N computational steps:

$$L_{Ze} = \Sigma_i (\Delta C_i)^2 - \gamma E^2$$

Here, the summation Σ_i runs over all counters in the system. This Lagrangian has a profound informational interpretation:

1. **First Term ($\Sigma_i (\Delta C_i)^2$)**: Spatial Stabilization. This term penalizes large, abrupt changes in the counter states. Minimizing this term encourages a stable, coherent internal model. A system where counters rarely change (small ΔC_i) has a highly stable correlational structure (S-mode)—its "spatial" configuration is solidified. This term therefore promotes spatial integration and structural persistence.

2. **Second Term ($- \gamma E^2$)**: Temporal Destabilization. This term, with its negative sign, has the opposite effect. It rewards large cumulative prediction errors (E^2). Minimizing the overall action thus involves maximizing γE^2. This forces the system to seek out experiences that challenge its model, driving exploration, learning, and adaptation. It is the engine of temporal change, novelty, and model update (T-mode). It prevents the system from collapsing into a static, perfectly predicting but non-adaptive state.

3. **The Coupling Constant γ**: The "Speed of Light" in Ze. The dimensionless constant γ governs the trade-off between these two opposing imperatives. A high γ prioritizes model accuracy and stability (low error is heavily rewarded), leading to conservative, inertial dynamics—akin to a slow-moving particle in a high-resistance medium. A low γ allows for larger errors, promoting exploratory behavior and rapid model shifts—akin to rapid motion or high energy. This constant thus sets the fundamental exchange rate between structural stability (space-like behavior) and adaptive plasticity (time-like behavior), playing a role analogous to c^2 in relativistic mechanics, which sets the exchange rate between space and time intervals.

The principle of extremal action is then translated as follows: The Ze system self-evolves along a trajectory of perceptual and active engagement (i.e., a sequence of events and updates) that minimizes the time-integrated sum of L_{Ze}. In practice, the system's inherent learning rule—updating counters based on prediction error—can be seen as a greedy, local implementation of this principle. Each update slightly adjusts the model to reduce future prediction error (affecting the E^2 term) while maintaining as much structural continuity as possible (affecting the $(\Delta C_i)^2$ term).

This formulation places Ze within the growing literature on physics as inference and the free-energy principle (Friston, 2019). The Ze-Lagrangian can be viewed as a specific, discrete instantiation of a variational free-energy functional, where the internal model is defined by the counters, and its minimization leads to adaptive, self-organizing behavior. The anti-parallel structure of the Lagrangian (stabilization vs. destabilization) directly mirrors the $S = -T$ opposition of the operational modes, providing a formal bridge between the computational architecture of Ze and the variational principles that may underlie not only perception and action in cognitive systems, but perhaps physical dynamics at a fundamental level.

Causality: Ze as a Directed Causal Set

The formalization of causality remains a central challenge in both physics and the philosophy of science. In the transition from a metric to a vector-based, informational paradigm, the concept of causality must be recast from a geometric constraint within a continuum to a structural feature emerging from discrete relations. The Ze framework provides a natural substrate for this, revealing a deep synergy with the causal set approach to quantum gravity (Dowker, 2006; Surya, 2019). However, Ze enriches this picture by providing an intrinsic, statistical mechanism for both generating the causal order and imbuing it with a physically meaningful direction.

From Partial Order to Statistical Precedence

In causal set theory, spacetime is hypothesized to be fundamentally discrete, with its structure arising from a set of elementary events endowed with a partial order relation "<" (precedes). This order relation is taken as primitive and is intended to correspond to microscopic causality (Henson, 2009). The continuum manifold, along with its light-cone structure, is expected to emerge as a coarse-grained, macroscopic approximation of this underlying causal network.

The Ze system instantiates this idea computationally. Here, the elementary "events" are the registrations of individual bits (e_t) in the sequential stream. A partial order naturally arises from their processing sequence: an event e_t is processed after and in the context of the previous state C_{t-1}, which itself was shaped by all prior events. This creates a transitive, non-circular chain of computational dependency. However, unlike in basic causal set theory where the order is simply given, in Ze it is generated and reinforced by a specific physical process: the updating of the statistical model based on prediction error.

This leads to a more nuanced definition. In Ze, two events are not merely ordered; their relationship is quantified by the statistics of coincidence and prediction. The causal link is not a binary "link" but a weighted, informational influence recorded in the counter matrix. The influence of a past event A on a future event B is encoded in how the conditional probability P(B | contexts including A) differs from P(B | contexts excluding A). Causality is thus inherently probabilistic and informational, aligning with modern interventions-based approaches (Pearl, 2009) and transfer entropy (Schreiber, 2000).

Vectorial Causality: Stabilization vs. Destabilization

This allows us to propose a rigorous, operational definition of causal precedence within the Ze framework:

An event A is said to causally precede an event B if, in the context of the system's state, the occurrence of A leads to a global update of counters that results in a net stabilization of the model for the subsequent occurrence of B.

We can formalize this notion. Let ΔS_A represent the total change in model stabilization induced by event A's integration. This can be operationalized. First, we define the immediate prediction error δ_A caused by A. Then, we consider its downstream effect: does the model update driven by δ_A make the future event B more or less predictable?

We can construct a measure. Let C be the state before A. After processing A, the state updates to C'. Now, from C', the system generates a prediction for B, $P_{C'}(B)$. We compare this to a counterfactual: the prediction for B from the previous state C, $P_C(B)$, as if A had not occurred (or was different). The causal efficacy ζ of A for B can be defined as the reduction in surprise (negative log probability) for B due to the update from A:

$$\zeta(A \rightarrow B) = [- \log P\_C'(B)] - [- \log P\_C(B)]$$

If $\zeta(A \rightarrow B) < 0$, the occurrence of A made B less surprising (more predictable). This means the update triggered by A stabilized the model with respect to B. If, integrated over many such transitions, events of type A consistently yield $\zeta < 0$ for events of type B, then A is a causal predecessor of B in the Ze sense.

Conversely, if an event predominantly destabilizes the model—increasing surprise for subsequent events—it acts as a source of noise or a causal "dead end," not a stable predecessor in the network. This vectorial causality has a direction and a magnitude (the average ζ). The causal "arrow" points from events that are stabilizers to events that become stabilized, creating a directed, weighted network. This is a computational expression of the idea that causes are, in an informational sense, "that which explains or reduces uncertainty about their effects."

Consistency with Causal Set Axioms and the "Life Test"

This formulation is fully compatible with the standard axioms of causal set theory (Rideout & Sorkin, 2000). The irreflexivity (no event precedes itself) and transitivity of the order are guaranteed by the sequential processing and Markovian update of the Ze engine. The condition of interval finiteness finds its analogue in the finite depth of the system's memory (the contextual window used for predictions).

Most importantly, Ze offers a physical and operational answer to the profound question of what distinguishes the causal order from a mere arbitrary order: the causal order is the one that, when used by an adaptive system for prediction, yields a stable, minimally surprising world model. This aligns with what one might call a "Life Test" or a principle of pragmatic acquisition: a viable system must discover and exploit the true causal grain of its environment to survive and function. The Ze system, through its passive learning, does exactly this—it "latches onto" the statistical regularities that are most persistent, and these regularities define its effective causal past.

Thus, the Ze framework does not merely postulate a causal set; it provides a dynamical mechanism—the minimization of a Ze-Lagrangian balancing stabilization and error—by which such a set is actively generated and oriented. Causality emerges not as a static scaffolding of spacetime, but as the dominant directional pattern in the flow of information that minimizes long-term prediction error. This recasts the causal structure of the world from a geometric given into a computational achievement, a stable attractor in the space of possible models that a self-evidencing system like Ze inevitably converges upon.

The Quantum Aspect of Ze: Thresholds, Statistics, and Stability

A primary challenge for any pre-geometric or information-based model of physics is to account for the hallmark phenomena of quantum theory: quantization and interference. The Ze framework approaches these not by importing the mathematical machinery of Hilbert spaces, but by demonstrating how quantum-like behaviors can emerge from the intrinsic properties of a discrete, threshold-based learning system. This suggests that quantum mechanics may be a phenomenological theory describing the statistics of systems whose underlying dynamics are governed by principles of optimal prediction and model stabilization, an idea explored in quantum cognition (Busemeyer & Bruza, 2012) and reconstructions of quantum theory (Chiribella, D'Ariano & Perinotti, 2011).

The Quantum as a Threshold, Not a Wave

In standard quantum mechanics, quantization is a formal consequence of boundary conditions imposed on wave-like solutions to differential equations. In Ze, the origin of discreteness is more fundamental and operational. Here, a quantum is not a wave packet but a discrete unit of accounted experience, manifested as a counter overflow or a threshold crossing.

The system's internal model is constructed from integer-valued counters (N_{ij}). Predictions and state orientations are derived from ratios of these integers, such as conditional probabilities $P = N_{ij} / \Sigma_k N_{ik}$. A fundamental change in the state vector Ψ—represented by the global counter configuration C—can only occur when these integer ratios change. This happens not continuously, but in discrete steps when a specific counter increments relative to its neighbors.

One can define a minimal detectable rotation ΔΨ. Consider a state where a particular conditional probability P is represented by a ratio of integers, m/n. The smallest possible non-zero change to this probability, and hence to the state orientation, occurs when the numerator m changes by ±1, or the denominator n changes by ±1, altering the ratio. This change ΔP_{min} is the discrete, finite "quantum" of orientation shift for that aspect of the model:

$$\Delta P_{min} = | (m \pm 1)/(n) - m/n | \text{ or } | m/(n \pm 1) - m/n |$$

This is analogous to the concept of a just-noticeable difference in psychophysics or a resolution limit in a digital system. Events whose statistical impact is smaller than this threshold do not register a change in the internal state; they are "below the noise floor." Only when accumulated evidence (prediction errors) pushes a statistical measure across this discrete boundary does the system's model update in a non-infinitesimal way. Therefore, quantization in Ze is not postulated but arises necessarily from the discreteness of accounting and finite resolution of the statistical model. This aligns with views that quantum discreteness may be epistemic, related to the finite informational capacity of a system (Brukner & Zeilinger, 2009).

Interference as Statistical Superposition Without Collapse

The double-slit experiment epitomizes quantum strangeness: a particle seems to pass through two slits simultaneously, producing an interference pattern that cannot be explained by classical particle trajectories. In Ze, this phenomenon is reinterpreted not as wave-particle duality, but as superposition of predictive statistics prior to a stabilizing update.

Consider a Ze system whose input stream is prepared in an experimental "context" analogous to the double-slit setup. The system does not track a "particle's path." Instead, it maintains a predictive model based on past correlations. In this context, the model may contain two (or more) strong, historically reinforced statistical pathways—analogous to the particle going through slit A or slit B. Each pathway is represented by a specific pattern of high conditional probabilities in the counter matrix. Prior to the registration of a "detection event" (the bit signifying a hit on the screen), the system's state C is a configuration that simultaneously supports high probabilities for outcomes correlated with both historical pathways. This is a superposition of predictive contexts, not of physical positions.

When the detection event finally arrives, the system does not undergo a physical "collapse" of a wavefunction. It performs its standard, deterministic update cycle:

1. It compares the actual event to the predictions generated from all active, high-probability contexts in its superposition.
2. It computes the prediction error for each.
3. It updates the counters, but crucially, the update will be most significant for the context whose predicted statistics most closely aligned with the full pattern of events (e.g., the final detection location relative to the slit geometry). The other, less consistent contexts will receive negative reinforcement (error), causing their associated counters to become relatively less influential.

The resulting interference pattern emerges from this statistical competition. The probability of a detection event at a point x, $P(x)$, is not simply $P_A(x) + P_B(x)$ (the classical sum). It is derived from the system's internal calculation based on the superimposed statistics, which may involve terms like $\sqrt{(P_A)}$ and $\sqrt{(P_B)}$ due to the nonlinear way conditional probabilities are normalized and compared within the counter architecture. Effectively, the system selects the most stable, globally consistent orientation of Ψ that can accommodate the new data, and the stabilization dynamics naturally produce interference terms.

This directly addresses critiques of the "naive collapse" postulate. In Ze, there is no special physical mechanism for collapse. There is only the continuous process of Bayesian model updating driven by prediction error (Pearle, 1999). What appears as a "collapse" in quantum mechanics is the discrete, threshold-crossing shift in the dominant predictive context within the Ze system, triggered by an informational transaction. The system always had a definite (though complex) internal state C; the "collapse" is the moment this state transitions from one favoring multiple future possibilities to one retrospectively favoring the single observed outcome as the most stable explanation.

Thus, the Ze framework recasts quantum phenomena as natural consequences of a discrete, learning-oriented system navigating a probabilistic world. Quantization arises from finite resolution, and interference from the competition between superimposed predictive models during stabilization. This offers a compelling vector-based narrative where quantum reality is not a separate domain but the observable signature of a fundamental computational substrate optimizing its model of causal structure.

The Observer and Consciousness: An Operational Definition

The interpretation of measurement and the role of the observer represent the most profound conceptual challenges in modern physics, bridging the quantum and classical realms. Any framework aspiring to a foundational status must address this issue with both logical rigor and ontological parsimony. The Ze model provides a pathway to do so by stripping the "observer" of its mystical connotations and redefining it in strictly operational, informational terms. This approach deliberately avoids philosophical excess, focusing instead on the systemic properties that distinguish an observing entity from a passive physical system. It aligns with pragmatic and relational interpretations of quantum mechanics (Rovelli, 1996; Fuchs & Peres, 2000), where information gain is central.

The Observer as a Self-Norm-Preserving System

In the Ze ontology, an observer is not a human mind or a conscious entity in a folk-psychological sense. It is defined by a specific, formal computational property:

An observer is a Ze system (or a complex of such systems) that, upon informational interaction with another state vector, maintains the invariance of its own internal norm while catalyzing a reorientation of the external state.

This definition requires unpacking. Recall that in the Ze formalism, a key invariant is the conservation of total cumulative information, represented by the monotonic growth of total counts, N_total. This is the discrete analogue of norm conservation. However, a stable, adaptive observer must maintain a more subtle invariance: the structural integrity and predictive coherence of its internal model despite a constant influx of new, potentially disruptive data.

Consider two interacting Ze systems: System A (the "observer") and System B (the "observed"). Each has its own counter state, C_A and C_B, evolving from their respective event streams. An interaction occurs when a portion of B's output stream becomes part of A's input stream. For A to qualify as an observer in this interaction, it must process this incoming data from B while preserving the core functional architecture of C_A. This does not mean its counters remain static—they must update to incorporate the new information. Rather, it means the update process follows its inherent, self-consistent rules (the Ze-Lagrangian dynamics) without being catastrophically disrupted. The observer's "norm" is the integrity of its own learning and prediction loop. If the interaction is so overwhelming that it randomizes A's counters, destroying its predictive model, A ceases to function as an observer in that context; it becomes a perturbed system.

Mathematically, we can denote the interaction as an operation I on the combined state (C_A, C_B). For A to be an observer, the mapping must be such that:

$$C_A(t+1) = F_A(C_A(t), I(B))$$

where F_A is A's native, autonomous update function. The interaction I(B) is treated as input to A's unchanged algorithm. In contrast, for the observed system B, the interaction may induce a more fundamental change, potentially altering its own update function F_B, as it is "measured" or "perturbed" by the coupling. The observer is thus the system whose internal dynamical law F_A remains invariant under the interaction, while the observed is the system whose state or dynamics are transformed.

Consciousness: A Stable Mode of Redistribution, Not Collapse

This operational definition provides a clear departure from the problematic notion that consciousness causes wavefunction collapse (the so-called "von Neumann-Wigner interpretation"). In the Ze framework, consciousness is not equivalent to, nor the cause of, quantum collapse. The "collapse" or state vector reorientation is a computational event intrinsic to any Ze system's update cycle when a prediction threshold is crossed, as described in Section 6.

Instead, we can cautiously propose a correspondence: Consciousness, in its most basic formal signature, corresponds to a persistent, self-sustaining mode of information redistribution within a complex Ze network. It is a particular, high-level dynamic regime where the system achieves a stable, yet non-equilibrium, flow of information between its spatial (structural) and temporal (sequential) processing channels.

A conscious system, under this view, would exhibit:

1. **High-Dimensional Coherence**: Its counter state C represents a vast, integrated model with rich hierarchical context.
2. **Meta-Stable Dynamics**: It operates near a critical point, balancing prediction and error (the terms of the Ze-Lagrangian), allowing for adaptive plasticity without disintegration. This is akin to the brain's hypothesized critical state (Chialvo, 2010).
3. **Recursive Self-Modeling**: Part of its internal model C is dedicated to predicting its own states and actions, creating a "world model" that includes the observer itself—a form of operational self-awareness.
4. **Continuous Redistribution**: The essence of its "stream of consciousness" is the continuous, self-driven recomputation of predictions and the redistribution of statistical

weights across its internal network in response to internal (self-generated) and external event streams.

This is a regime of stable becoming. The system is never in equilibrium; it is constantly in the process of resolving the anti-parallel tension between its stabilizing structure (S) and its destabilizing errors (T). The phenomenological "light" of consciousness is the subjective correlate of this specific, complex, and self-perpetuating computational dynamic. It is not a substance but a process—a particularly sophisticated and autonomous mode of being a Ze system.

Therefore, the Ze framework demystifies the observer by grounding it in computational invariance, and reframes consciousness not as a magical collapse trigger, but as a natural, though highly complex, emergent property of a system engaged in optimal, self-preserving information processing. The "hard problem" is not solved, but its terms are shifted: from explaining how brain matter generates qualia, to understanding how a specific class of self-modeling, prediction-error-minimizing dynamical systems enters a regime where its operational dynamics are experienced as the first-person perspective (Clark, 2013; Friston, 2018). The observer is simply that which maintains its own vectorial integrity while other vectors rotate around it.

Strong Formulation of a Unified Theoretical Framework

Having delineated the operational principles, correspondences, and emergent phenomenology of the Ze system, we now consolidate these elements into a coherent, falsifiable theoretical proposition. This moves beyond metaphor and towards a specific ontological claim about the nature of physical reality at a fundamental level. The formulation is presented not as a complete, final theory of everything, but as a concrete, well-defined paradigm from which specific physical laws can be derived as emergent approximations. It is a candidate for a principle theory, built from the bottom up on informational and computational axioms (D’Ariano, 2017; Wheeler, 1990).

The Core Proposition

We propose that the Ze system constitutes a discrete, universal implementation of a vectorial ontological model in which space and time correspond to antiparallel modes of information processing. In this framework, physical reality at its most fundamental level is not described by fields on a manifold, but by the dynamics of interconnected Ze-like units. Each unit is a minimal self-evincing system that tracks a state vector through the continuous, recursive application of a rule: OBSERVE an event, COMPARE it to a prediction generated from an internal statistical model (counters), and UPDATE that model with the error.

The strong, unified formulation consists of the following interlocking postulates:

Postulate 1 (Ontological Substrate): The state of any physical system is completely specified by the configuration of a high-dimensional, discrete statistical model, represented as a matrix of counters C. This model defines the system's state vector Ψ. The evolution of the universe is the evolution of a vast, complex network of such interacting counter states.

Postulate 2 (Duality of Process): Dynamical change manifests in two operationally distinct, anti-parallel modes. The temporal mode (T) is the sequential, irreversible channel of event actualization and model updating. The spatial mode (S) is the synchronous, correlational structure of the counter model itself, representing potentialities and statistical connections. Their opposition ($S = -T$) is not geometric but dynamic, expressed as a trade-off between model stability and adaptive plasticity.

Postulate 3 (Dynamical Principle): The path of a system through its state-space is one that minimizes (more precisely, renders stationary) a discrete action S_{Ze}, defined as the sum of a Ze-Lagrangian L_{Ze} over a sequence. L_{Ze} is given by:

$$L_{Ze} = \Sigma_i (\Delta C_i)^2 - \gamma \Sigma_t [\delta_t]^2$$

where the first term, $\Sigma_i (\Delta C_i)^2$, quantifies the "kinetic" cost of changing the internal model (spatial stabilization), and the second term, $-\gamma \Sigma_t [\delta_t]^2$, quantifies the "potential" benefit of minimizing long-term prediction error (temporal drive). The constant γ sets the fundamental exchange rate between these competing imperatives.

Emergence of Physical Law

From these postulates, the familiar structures of physics are recovered as emergent, effective descriptions:

- **Relativistic Invariants**: The conservation of the total informational norm (monotonic growth of total counts) provides a discrete analogue of worldline proper time. The anti-parallel structure of the S and T modes, mediated by γ, yields a natural emergence of a Minkowski-like metric signature in the continuum limit, where γ plays the role of c^2. Lorentz invariance is not a fundamental symmetry of spacetime but a statistical symmetry of the informational processing network at macroscopic scales (Smolin, 2006).
- **Causality**: Causal structure emerges as the dominant directed graph of statistical stabilization within the network. An event A causally precedes B if the update from A systematically reduces the prediction error (surprise) for B across many instances. This generates a partial order fully consistent with causal set axioms (Surya, 2019), but with a physically grounded directionality provided by the arrow of model optimization.
- **Quantization**: Quantum behavior arises from two intrinsic features: (1) The discreteness of the counter state, which implies a finite resolution for state changes ($\Delta\Psi_{min}$), naturally leading to quantized transitions, and (2) The superposition of predictive contexts within the counter matrix, whose competitive interaction under the dynamical principle produces interference patterns without requiring a physical collapse mechanism. The Born rule is hypothesized to emerge from the statistical distribution of state orientations that satisfy the stabilization principle over many trials.

- **Gravity and Geometry**: While a full derivation is beyond this article's scope, we posit that a "gravitational" interaction arises from the mutual perturbation of the counter states of neighboring Ze clusters. When two complex systems interact, their event streams become correlated. This forces an alignment or synchronization of their internal predictive models, which can be interpreted as a tendency for their internal "clocks" (their N_total growth) and "geometries" (their correlational structures) to conform. This mutual information minimization constraint may yield an effective force analogous to gravity, aligning with entropic gravity proposals (Verlinde, 2011) and the idea of gravity as an entropic force.

Testability and Distinction from Existing Theories

This formulation is distinguished from other approaches by its radical simplicity and computational underpinning. Unlike string theory, it does not postulate new dimensions or particles at the Planck scale. Unlike loop quantum gravity, its discreteness is not primarily geometric but informational. Its closest relatives are causal set theory and the constructor-theoretic and informational reconstructions of quantum theory (Chiribella et al., 2011; Deutsch, 2013).

The framework makes several testable, if conceptually challenging, predictions:

1. **Intrinsic Computation**: Any fundamental physical process should be describable as a form of prediction-error minimization, implying a computational signature in even simple physical interactions.

2. **Threshold Phenomena**: Quantum transitions should be associated with specific threshold-crossing events in an underlying statistical model, not with continuous waves.

3. **Informational Limits**: There should be a fundamental, irreducible link between a system's informational capacity (the size and depth of its effective "counter matrix") and its physical properties, such as entropy and heat capacity.

In conclusion, the Ze framework offers a strong, unified vector-based ontology where physics is reconceptualized as the self-organization of information according to a principle of stable predictive modeling. It proposes a direct path From Metric to Vector—from a geometric description of reality in a container to a vectorial description of reality as a persistent, evolving computation.

Practical Implications and Unification

A scientific theory is ultimately judged by its explanatory power, its capacity to unify disparate phenomena, and its potential to generate new insights and predictions. The transition from a continuous, metric-based paradigm to the discrete, vector-based ontology of the Ze framework is not merely a philosophical exercise. It yields concrete, practical implications that reframe foundational problems in physics, computation, and the theory of complex systems. By grounding physics in computational primitives, Ze shifts the locus of explanation from abstract geometry to concrete informational dynamics (Lloyd, 2006; Wheeler, 1990).

From Algorithm to Physical Theory

A critical shift in perspective is required: Ze is not merely an algorithm that simulates aspects of physics; it is proposed as a candidate substrate for physical theory itself. An algorithm is a set of instructions executed on a pre-existing computational platform (a computer with memory and a clock). In contrast, Ze describes the constitutive process of what we call physical reality. There is no external platform; the universe is the execution. The counters are not memory locations in a silicon chip but the fundamental degrees of freedom. The update cycle is not a programmed step but the very mechanism of becoming. This elevates Ze from a computational model to an ontological one, akin to how cellular automata have been proposed as models of physics (Wolfram, 2002), but with a specific, purpose-built architecture for prediction and learning. This resolves the "hardware question": the hardware is the network of interacting Ze units themselves.

Deriving Spacetime from Data Processing

The most profound practical implication is the demotion of space and time from fundamental, pre-existing continua to emergent, effective descriptions. In Ze, spacetime is derived from the modes of data processing. This offers a direct pathway to address the central problem of quantum gravity: the reconciliation of general relativity's dynamical spacetime with quantum theory's discreteness.

- **Operational Emergence**: Spatial extension and locality are seen as manifestations of the strength and topology of correlations within the counter state (C). "Distance" can be defined operationally as a measure of statistical independence or the decay of mutual information between subsystems (Van Raamsdonk, 2010). Temporal flow is the subjective correlate of the sequential update process and the monotonic growth of total counts. This provides a clear, if radical, answer to "what is time?"—it is the count of computational steps (Rovelli, 2019).

- **Dynamic Geometry**: The curvature of spacetime in general relativity is reinterpreted as a distortion in the statistical relations of the underlying Ze network. A gravitational field would correspond to a gradient in the way predictive information flows between regions, potentially emerging from a principle of minimal informational redundancy or maximal computational efficiency across the network. This aligns with research on emergent gravity from entanglement and information (Van Raamsdonk, 2010; Swingle, 2012).

Quantization from Discrete Accounting

Quantum mechanics, with its inherent discreteness and probability amplitudes, often appears grafted onto a classical continuum. In Ze, quantization arises naturally from the discrete accounting of events in finite counters. The state vector Ψ can only change when integer-valued ratios of counters shift, leading to a minimal, finite change ΔΨ_min. This implies:

- **No Separate Quantum Postulate**: The Planck constant ħ is not a fundamental parameter of nature but an emergent conversion factor relating the discrete "ticks" of counter updates to macroscopic energy and action scales. It is analogous to the gas constant R, which connects microscopic molecular counts to macroscopic pressure and temperature.

- **Intrinsic Uncertainty**: The finite depth and resolution of the internal model (the counter matrix) imply a fundamental limit on simultaneous precision for conjugate variables. Predicting one aspect of the future (e.g., a "position"-like statistic) with high accuracy may require a model configuration that precludes accurate prediction of another ("momentum"-like statistic), recasting Heisenberg's principle as a form of computational or informational trade-off (Brukner & Zeilinger, 2009).

Causality from Statistics, Not Postulate

In special relativity, the light-cone structure and causality are built into the metric. In Ze, causality is not an axiom of spacetime geometry but a discovered, statistical regularity. A system learns the causal order of its environment by identifying which event sequences lead to stable, low-error predictions. The "causal set" of spacetime events is literally the set of events that have non-negligible statistical influence on one another within the system's learned model. This provides a dynamic, learning-based foundation for causal inference, connecting foundational physics to fields like machine learning and causal discovery (Pearl, 2009). It suggests that physical laws themselves are "learned" regularities of the universal Ze process.

STR/GR as Limiting Descriptions

Finally, the great triumphs of 20th-century physics—Special and General Relativity (STR/GR)—are not overthrown but contextualized. They are seen as limiting, effective descriptions of Ze dynamics in highly stable, coarse-grained regimes.

- **Special Relativity (STR)**: The Lorentz transformations, the invariant speed *c*, and time dilation emerge in the continuum limit when the Ze network is homogeneous and isotropic, and the coupling constant γ is uniform. The postulate of the constancy of the speed of light is replaced by the universality of the information exchange rate γ between the S and T modes.

- **General Relativity (GR)**: Einstein's field equations are recovered as the hydrodynamic equations governing the large-scale behavior of the Ze network's informational "fluid." Mass-energy warps spacetime because it corresponds to a localized concentration of complex, active Ze processes that distort the surrounding network's correlational structure and information flow. The equivalence principle arises because all forms of "energy" (complex activity patterns) affect the informational geometry in the same fundamental way.

In practice, this unification suggests new avenues for research: simulating Ze networks to study the emergence of Lorentz invariance and curvature; analyzing quantum algorithms as special cases of Ze dynamics; and investigating whether cosmological parameters (like the cosmological constant) can be understood as properties of the global Ze network's learning state. The Ze framework ultimately provides a practical blueprint for rebuilding physics from the ground up, not on particles and fields in spacetime, but on vectors of information in a state of continuous, self-organizing computation.

References

Barbour, J. (2012). Shape dynamics. An introduction. Quantum Field Theory and Gravity, 257-297.

Brukner, Č. (2017). On the quantum measurement problem. In Quantum [Un]Speakables II (pp. 95-117). Springer, Cham.

Brukner, Č., & Zeilinger, A. (2009). Information invariance and quantum probabilities. Foundations of Physics, 39(7), 677-689.

Busemeyer, J. R., & Bruza, P. D. (2012). Quantum models of cognition and decision. Cambridge University Press.

Chialvo, D. R. (2010). Emergent complex neural dynamics. Nature Physics, 6(10), 744-750.

Chiribella, G., D'Ariano, G. M., & Perinotti, P. (2011). Informational derivation of quantum theory. Physical Review A, 84(1), 012311.

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. Behavioral and Brain Sciences, 36(3), 181-204.

D'Ariano, G. M. (2017). Physics without physics: the power of information-theoretical principles. International Journal of Quantum Information, 15(08), 1740008.

Deutsch, D. (2013). Constructor theory. Synthese, 190(18), 4331-4359.

Dowker, F. (2006). Causal sets as discrete spacetime. Contemporary Physics, 47(1), 1-9.

Friston, K. (2010). The free-energy principle: a unified brain theory? Nature Reviews Neuroscience, 11(2), 127-138.

Friston, K. (2018). Am I self-conscious? (Or does self-organization entail self-consciousness?). Frontiers in Psychology, 9, 579.

Friston, K. (2019). A free energy principle for a particular physics. Entropy, 21(10), 943.

Fuchs, C. A., & Peres, A. (2000). Quantum theory needs no 'interpretation'. Physics Today, 53(3), 70-71.

Goldstein, H. (1980). Classical mechanics (2nd ed.). Addison-Wesley.

Henson, J. (2009). The causal set approach to quantum gravity. In D. Oriti (Ed.), Approaches to quantum gravity (pp. 393-413). Cambridge University Press.

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.

Knill, D. C., & Pouget, A. (2004). The Bayesian brain: the role of uncertainty in neural coding and computation. Trends in Neurosciences, 27(12), 712-719.

Lloyd, S. (2002). Computational capacity of the universe. Physical Review Letters, 88(23), 237901.

Lloyd, S. (2006). Programming the universe: A quantum computer scientist takes on the cosmos. Knopf.

Lloyd, S. (2013). The universe as quantum computer. A computable universe: Understanding and exploring Nature as computation, 567-581.

Markopoulou, F. (2009). New directions in background independent quantum gravity. In Approaches to quantum gravity (pp. 129-149). Cambridge University Press.

Oriti, D. (2021). The complex timbre of reality: The prospects for an emergent spacetime. Foundations of Physics, 51(2), 1-22.

Pearl, J. (2009). Causality: Models, reasoning, and inference (2nd ed.). Cambridge University Press.

Pearle, P. (1999). Collapse models. In Open systems and measurement in relativistic quantum theory (pp. 195-234). Springer.

Rideout, D. P., & Sorkin, R. D. (2000). A classical sequential growth dynamics for causal sets. Physical Review D, 61(2), 024002.

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

Rovelli, C. (2011). Forget time. Foundations of Physics, 41(9), 1475-1490.

Rovelli, C. (2019). The physics and philosophy of time. British Journal for the Philosophy of Science, 70(2), 661-666.

Rovelli, C. (2021). The relational interpretation of quantum physics. In Beyond the dynamical universe (pp. 1-24). Oxford University Press.

Schreiber, T. (2000). Measuring information transfer. Physical Review Letters, 85(2), 461.

Sengupta, B., Stockburger, J., & Ananth, S. (2016). A path-integral approach to the dynamics of a neural system. The European Physical Journal Special Topics, 225(6-7), 1241-1260.

Smolin, L. (2006). The case for background independence. In The Structural Foundations of Quantum Gravity (pp. 196-239). Oxford University Press.

Surya, S. (2019). The causal set approach to quantum gravity. Living Reviews in Relativity, 22(1), 5.

Swingle, B. (2012). Entanglement renormalization and holography. Physical Review D, 86(6), 065007.

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

Van Raamsdonk, M. (2010). Building up spacetime with quantum entanglement. General Relativity and Gravitation, 42(10), 2323-2329.

Verlinde, E. (2011). On the origin of gravity and the laws of Newton. Journal of High Energy Physics, 2011(4), 29.

Wheeler, J. A. (1990). Information, physics, quantum: The search for links. In Complexity, entropy, and the physics of information (pp. 3-28). CRC Press.

Wolfram, S. (2002). A new kind of science. Wolfram Media.

Zeh, H. D. (2007). The physical basis of the direction of time. Springer Science & Business Media.