Immortalitas in Hac Vita

Longevity Platform

https://www.longevity.ge

Longevity Horizon
ISSN:3088-4063

2026

Vol.2 No.4:10

Emergence of the Minkowski Metric from Ze Dynamics

A Numerical Demonstration

Jaba Tkemaladze [^] [1]
Affiliation: [1] Kutaisi International University, Georgia
Citation: Tkemaladze, J. (2026). Emergence of the Minkowski Metric from Ze Dynamics. Longevity Horizon, 2(4).
DOI : https://doi.org/10.65649/hqm2c554

Abstract

This paper presents a novel derivation of the Minkowski metric from first principles within the framework of Ze dynamics. I demonstrate that the fundamental structure of spacetime, characterized by the Lorentzian interval $ds^2 = -c^2dt^2 + dx^2$, emerges not as an a priori geometric postulate but as a statistical invariant of a discrete, information-theoretic substrate. The primitive elements are counters updated by a stream of events, governed by a statistically conserved quadratic sum. A critical functional bifurcation separates the dynamics into a temporal channel, defined by sequential, order-dependent prediction error, and a spatial channel, defined by parallel, order-invariant structural differences. The inherent antagonism between these channels—where spatial stabilization is paid for by temporal destabilization—forces their contributions to combine with opposite signs in the conserved quantity, thereby deriving the minus sign of the metric signature. The constant *c* emerges as a conversion factor between the natural scales of the two counting processes. The resulting interval, computed via a concrete numerical algorithm, recovers the kinematics of Special Relativity in the continuum limit, with the light cone arising as a numerical stability boundary for coherent signal propagation within the network. This work reframes Minkowski spacetime as an effective geometry, positing that space and time are emergent operational modes of information processing rather than fundamental dimensions.

Keywords: Emergent Spacetime, Minkowski Metric, Ze Dynamics, Information-Theoretic Foundations, Special Relativity, Causal Structure, ZDV.

Introduction: The Objective and Conceptual Foundation

The fundamental geometry of spacetime in special relativity, encapsulated in the Minkowski metric with its distinctive negative sign, is traditionally introduced as a postulate. This foundational axiom, which separates timelike from spacelike intervals, underlies the entirety of relativistic kinematics and dynamics. While empirically robust, its origin within a deeper theoretical framework remains a subject of profound inquiry. The primary objective of this work is to demonstrate that the signature and structure of the Minkowski metric, specifically the expression $ds^2 = -c^2dt^2 + dx^2$, can emerge not from an a priori geometric postulate, but from the intrinsic counting statistics and state-space dynamics of a system governed by what we term "Ze dynamics." In this formalism, dt and dx are not fundamental, continuous coordinates but rather effective, coarse-grained variables derived from underlying discrete state transitions. Crucially, the negative sign, the defining feature of the Lorentzian metric signature, is shown to arise naturally from the combinatorial structure of counting paths in a dual-state network, representing a fundamental asymmetry between activation and propagation phases.

This approach aligns with a broader research direction seeking to derive relativistic phenomena from pre-geometric, information-theoretic, or quantum-gravitational principles (Bombelli, Lee, Meyer, & Sorkin, 1987; Rovelli, 1991). The Ze dynamics framework posits that an observed "event" is the macroscopic manifestation of a completed cycle within a network of binary states. Each cycle consists of two fundamental, irreducible phases: a temporal activation phase, which is a prerequisite step that does not translate to a change in an external configuration label, and a spatial propagation phase, which updates an external positional register. This dichotomy is reminiscent of the distinction between internal "clock" degrees of freedom and external spatial coordinates in models of emergent spacetime (Fong et al., 2016; Vedral, 2010).

The central hypothesis is that the counting of possible histories leading to an observed macro-state—a pair (t, x) interpreted as time and position—follows a statistical distribution that, in the continuum limit, is governed by an action-like quantity. This quantity takes the form of a squared interval. The sign of the contributions from the activation and propagation phases to this statistical weight is determined by their respective roles in the state-counting combinatorics. The activation phase, being internally constrained and obligatory, contributes with a sign opposite to that of the proliferating, branching possibilities of the propagation phase. This is a direct consequence of the inherent non-commutativity in the sequence of operations within Ze dynamics, an algebraic structure analogous to that observed in certain quantum walks and pregeometric models (Kauffman, 2015; Singh, 2017). The emergence of the constant cc* is then a scaling factor relating the natural units of counting in the temporal activation lattice to those in the spatial propagation lattice, setting a universal conversion rate akin to a "signal speed" within the network.

The derivation proceeds as follows: We first define the discrete microstates and transition rules of the Ze dynamics model. We then enumerate the number of distinct micro-histories N(T, X) that yield a given macro-coordinate (T, X), where T and X are discrete counts of activation and propagation steps, respectively. Using Stirling-type approximations for large counts, we show that the logarithm of this number, which corresponds to an entropy $S = \log N$, takes the asymptotic form $S(T, X) \approx A - (1/2)K(\alpha T^2 - \beta X^2)$, where A, K, α, and β are positive constants determined by the network's connectivity. The statistical weight exp(S) for a history thus becomes proportional to $\exp(-K\ I\ )$, where the quantity $I = (\alpha\Delta t^2 - \beta\Delta x^2)$ appears in the exponent, with Δt and Δx being the continuum limits of T and X.

The functional form of I is immediately recognizable. By identifying the most probable history as the one minimizing I (maximizing S), we obtain a variational principle. Defining $c = \mathrm{sqrt}(\beta/\alpha)$ and choosing units where the scaling factor K is absorbed into the definition of the interval, the fundamental object governing the statistics of paths becomes $I = \Delta t^2 - (1/c^2)\Delta x^2$. This is precisely the Lorentzian squared interval, up to a sign convention. The negative signature is therefore not postulated; it is a direct output of the subtraction inherent in the asymptotic form of the counting entropy, which itself originates from the different combinatorial roles of the two phase types in the Ze dynamics.

This result provides a novel perspective on the nature of spacetime intervals. It suggests that the Minkowski metric is primarily a statistical descriptor, encoding the relative likelihood of different coarse-grained histories in an underlying discrete dynamics. The causal structure (timelike, null, spacelike separation) emerges from the dominance of certain statistical ensembles of micro-histories over others. The proposed mechanism offers a concrete, albeit simplified, model that contributes to the discourse on the informational origins of spacetime structure (Fong et al., 2016; Rovelli, 1991). The following sections will detail the formal structure of Ze dynamics, the precise combinatorial derivation, the analysis of the continuum limit, and a discussion of the implications and potential connections to quantum foundations and quantum gravity phenomenology.

The Fundamental Ze Quantity: A Counting Invariant

The Ze dynamics framework is predicated on a minimalist ontological assumption: an observable world is the emergent, coarse-grained picture of a discrete, stochastic process of state transitions. The fundamental elements are not points in a continuum but discrete events and the counting registers they update. Before any notion of geometry or metric can arise, one must define the intrinsic, pre-geometric quantities that characterize the state of the system. In this section, we introduce the core invariant of Ze dynamics, a conserved sum of squares analogous to the squared norm in quantum state evolution or the conservation of energy in physical systems. This invariant serves as the bedrock from which the properties of emergent spacetime will be shown to crystallize.

Let us define the primitive constituents. We consider a discrete, ordered sequence of input events, denoted as e_k, where the index *k* labels the sequential order of occurrence. These events are not yet "spacetime events" but abstract triggers or stimuli for the internal dynamics of the system. Associated with the system is a set of N internal counters, C_i, where *i = 1, 2, ..., N*. These counters are non-negative integers that represent the accumulated "activity" or "response" along N independent, abstract channels. Each input event e_k induces an increment (or, in a generalized model, a possible decrement) in one or more of these counters. We denote the change in counter *i* due to event e_k as $\Delta C_i(k)$. The update rule is simply $C_i(k) = C_i(k-1) + \Delta C_i(k)$.

The central postulate of Ze dynamics is the existence of a global, conserved (or statistically conserved) quantity constructed from these counters. We define the Ze invariant I as the sum of the squares of all counter values:

(1) $I = \Sigma_{i=1}^{N} (C_i)^2$.

This quadratic form is reminiscent of the squared Euclidean norm of a vector $C = (C_1, C_2, ..., C_N)$. The dynamical rule is constrained such that, despite the individual counters C_i fluctuating in response to the stochastic input stream, the total value of I is maintained invariant on average, or within a bounded range, over the course of the dynamical evolution. This is not a strict, step-by-step conservation law but a statistical one, maintained through a specific regulatory mechanism involving filtering and resets.

The conservation mechanism operates as follows. The input events e_k are filtered; only those whose associated increments $\Delta C_i(k)$ would not drive I beyond a certain soft upper bound are allowed to update the counters fully. An event that would cause a violation of this bound triggers a different protocol: a coordinated reset. During a reset, a subset of counters is decremented in a correlated manner designed precisely to restore the value of I to a baseline level, akin to a dissipation or relaxation process. This create-and-dissipate cycle is crucial. It ensures that the system operates in a non-equilibrium steady state where I hovers around a mean value, exhibiting small fluctuations, much like the energy in a driven-dissipative system maintained at a fixed point (Tél, 2015). This statistical conservation is analogous to the preserved norm of a state vector under unitary evolution in quantum mechanics, where the overall probability is conserved despite the flow of amplitude between different bases (Nielsen & Chuang, 2010).

The significance of a sum of squares as the fundamental invariant cannot be overstated. Firstly, it is a positive-definite quantity, providing a natural measure of the total "scale" or "intensity" of the system's state. Secondly, and more importantly for our geometric emergence program, it is quadratic. In the continuum limit, where discrete counts C_i are interpreted as components along some axes, the preservation of a quadratic form is the hallmark of a metric. The invariant I can be written as $I = C^T \cdot G \cdot *C$, where G is the identity matrix in this pre-geometric space. This simple Euclidean metric in the high-dimensional counter space is the seed from which the low-dimensional Lorentzian metric of spacetime will sprout.

This structure finds parallels in several pre-geometric approaches to spacetime. For instance, the causal set program postulates a discrete set of events with a partial order, and the continuum geometry is to be recovered from the counting of causal relations (Bombelli, Lee, Meyer, & Sorkin, 1987). Here, the counters C_i can be interpreted as a coarser measure, aggregating such relational data. Similarly, in some quantum informational approaches, the emergence of a metric is linked to the conservation of informational purity or the constraints on correlation growth (Fong et al., 2016). The Ze invariant I plays precisely such a constraining role, limiting the total "activity" and enforcing correlations between counter updates during resets.

The next step is to introduce the critical bipartition of the N counters into two distinct classes. Let us designate one special counter, C_0, which possesses a unique property: its increments are prerequisite for any subsequent update in the other *N-1* counters, which we denote as C_j (where $j = 1, 2, ..., N-1$). The counter C_0 will be the progenitor of the temporal dimension, while the ensemble of C_j counters will give rise to spatial degrees of freedom. This functional asymmetry in the dynamics—the requirement of "activation" via C_0 before "propagation" in the C_j—is the origin of the fundamental distinction between time and space in the emerging picture. The invariant I now reads:

(2) $I = (C_0)^2 + \Sigma_{j=1}^{N-1} (C_j)^2$.

The statistical conservation of I implies that an increase in the sum of squares from the spatial sector, $\Sigma (C_j)^2$, must, on average, be compensated by a dynamics that ultimately leads to a corresponding adjustment in $(C_0)^2$, or vice-versa. It is from the statistical interplay between these two sectors, governed by the conservation of this simple quadratic form, that the relative minus sign in the Minkowski interval will be born. The following section will detail this bipartite dynamics and the combinatorial counting of histories that leads to the Lorentzian signature.

Bifurcation into Temporal and Spatial Channels

The homogeneous, high-dimensional counter space defined by the invariant $I = \Sigma (C_i)^2$ contains no intrinsic geometric distinction. All counters are formally equivalent. The emergence of a causal structure with a privileged temporal dimension requires a symmetry-breaking mechanism within the dynamics. This section delineates this crucial step: the bifurcation of the global Ze dynamics into two operationally distinct modes. These modes are defined not by labeling counters a priori as "time" or "space," but by the functional role their increments play in processing the event stream. We identify a sequential-temporal channel, sensitive to order and prediction, and a parallel-spatial channel, sensitive to correlation and configuration.

The Temporal Component T: Sequential Variability and Prediction Error

The first mode characterizes change that is fundamentally dependent on the sequential order of events. In Ze dynamics, not all event-induced increments are equal. A significant class of updates is tied to the system's internal model of event sequences. The system maintains an implicit prediction of likely subsequent events based on prior sequences (Friston, 2010). When an input event e_k deviates from this prediction, it generates a prediction error signal.

We define the temporal component increment, ΔT, at step k as a measure constructed from these sequential deviations. Specifically, we consider a subset of counters—let us call them sequential counters S_i—whose updates are governed by the following rule: their increment $\Delta S_i(k)$ is proportional to the mismatch between the actual event e_k and the event predicted based on the sequence ($e_{k-1}, e_{k-2}, \ldots$). In the simplest linearized form, this error can be represented as a weighted sum of differences. The squared temporal increment for a macro-step (an aggregate over many micro-events) is then defined as the sum of squares of these sequential counter changes:

(1) $\Delta T^2 = \Sigma_{i \in \text{Sequential}} (\Delta S_i)^2$.

This quantity, ΔT^2, measures the total squared sequential variability or surprise (in a formal information-theoretic sense) incurred over that interval (Friston, 2010). It is a metric of pure change, of the inexorable flow that distinguishes one ordered sequence from another. Crucially, it is a magnitude that accumulates only because events happen in a specific order; a permuted sequence with the same set of events would yield a different ΔT^2. This sensitivity to order, to the directedness of the process, is the fundamental signature of temporality. The temporal coordinate T itself is the cumulative sum (the integral) of these ΔT increments, rooted in a chosen origin. It is important to note that T is not a pre-existing background parameter but an emergent, internal measure of accumulated sequential discord.

The Spatial Component S: Parallel Structural Difference

In contrast to the sequential mode, the second mode characterizes change that is invariant to the order of events and instead depends on the correlational structure between concurrent or complementary channels. This involves a different subset of counters, which we term parallel counters P_j. These counters are updated not primarily by prediction errors on the event stream, but by the co-activation patterns across channels. For instance, certain events may simultaneously increment one subset of P_j counters while decrementing another, mirroring or inverting patterns.

The spatial component is derived from comparing structural distributions. Consider a "snapshot" of the parallel counter state vector $P = (P_1, P_2, \ldots, P_M)$ at a given point in the process. A change in the spatial configuration is measured not by the order-dependent surprise, but by the difference between two such snapshots, treated as geometric objects in the M-dimensional parallel space. We define the squared spatial interval ΔS^2 between two states P and P' as the squared Euclidean distance between their normalized or baseline-corrected configurations:

(2) $\Delta S^2 = \Sigma_{j=1}^{M} (\Delta P_j)^2$, where $\Delta P_j = (P'_j - P_j) / \kappa$.

Here, κ is a normalization constant related to the mean activity level, ensuring that ΔS^2 measures a relative, structural difference rather than an absolute change in overall scale (which is already governed by the global invariant I). The increments ΔP_j are computed from the net change over an interval, irrespective of the detailed sequence of updates within that interval. This quantity is inherently permutation-invariant with respect to the micro-ordering of events that led to the net change $\{\Delta P_j\}$; only the final distribution matters. This property—order invariance—is the hallmark of a spatial degree of freedom. It captures the idea of a "state of affairs" or a "configuration" that can be arrived at via multiple equivalent histories, much like the position of an object is independent of the precise sequence of infinitesimal movements that brought it there (Rovelli, 1991).

The operational distinction is now clear. The temporal channel T monitors the directed process of information update (the "how" in sequence), while the spatial channel S monitors the resulting configuration (the "what" in state). They engage different aspects of the underlying counter network. Crucially, both are expressed within the same mathematical language of sums of squares of counter increments, reflecting their common origin in the quadratic invariant I. This shared language is what will allow them to be combined into a single interval.

Interplay and the Path to a Unified Interval

The dynamics of Ze enforce a tight coupling between these two modes through the statistical conservation of the global invariant I (Eq. 1, Section 2). Recall that $I = \Sigma (C_i)^2$ includes contributions from both sequential (S_i) and parallel (P_j) counters: $I = \Sigma (S_i)^2 + \Sigma (P_j)^2$.

A significant update in the spatial configuration (a large $\Sigma (\Delta P_j)^2$) necessarily alters the $\Sigma (P_j)^2$ term. To maintain statistical conservation of I, this alteration must be compensated by an opposite change in the $\Sigma (S_i)^2$ term over the relevant statistical ensemble. This compensatory mechanism is implemented through the reset protocol mentioned in Section 2. A large spatial reconfiguration that threatens to increase I triggers a reset that strategically adjusts the sequential counters, often by dissipating accumulated prediction error (surprise) in a coordinated fashion. This introduces a fundamental statistical anticorrelation: histories with large accumulated spatial changes ΔS^2 tend to be associated with histories that have concomitantly large (but opposite in sign) adjustments in the squared temporal measure ΔT^2.

It is this statistical anticorrelation, enforced by the conservation law, that plants the seed for the minus sign in the metric. The invariant I can be reinterpreted in terms of changes. For two system states separated by a coarse-grained interval, the conservation implies that the sum $\Sigma (S_i)^2 + \Sigma (P_j)^2$ is roughly constant. Therefore, the variation $\Delta[\Sigma (S_i)^2]$ between these states is approximately the negative of the variation $\Delta[\Sigma (P_j)^2]$. Identifying $\Delta[\Sigma (S_i)^2]$ with $(\Delta T)^2$ and $\Delta[\Sigma (P_j)^2]$ with $(\Delta S)^2$ up to scaling factors, we arrive at a conserved quantity of the form $(\Delta T)^2 - (\Delta S)^2 = \text{constant}$. This heuristic argument will be made rigorous in the next section through a combinatorial analysis of micro-histories, which will yield the precise asymptotic form of the path weight, $\exp(-\alpha\Delta T^2 + \beta\Delta S^2)$, revealing the Lorentzian signature directly from the counting statistics.

Antiparallel Contributions and the Origin of the Minus Sign

The bifurcation into temporal (T) and spatial (S) channels establishes two distinct modalities of change. However, the profound feature of relativistic spacetime—the Lorentzian signature—arises not merely from their distinction, but from the specific, oppositional relationship between them. In this section, we demonstrate how the core operational axioms of Ze dynamics naturally enforce a statistical anticorrelation between the squared increments of these channels. This anticorrelation manifests mathematically as a difference in their contributions to a conserved quantity, thereby introducing the critical minus sign that differentiates a spacetime interval from a mere Euclidean distance.

The Stabilization-Destabilization Axiom

The dynamical engine of Ze is driven by a principle of efficient state management, reminiscent of thermodynamic or information-theoretic optimization principles (Friston, 2010; Tishby, Pereira, & Bialek, 1999). We posit the following foundational axiom derived from the system's function: Growth in structural stabilization (spatial configuration) is necessarily accompanied by a reduction in prediction error (temporal surprise), and vice-versa.

Operationally, this axiom emerges from the interplay between the parallel (P) and sequential (S) counter networks. A "spatially" stabilized configuration corresponds to a state of the parallel counters P that is highly resilient to perturbations, meaning it requires minimal subsequent updates to its pattern to accommodate incoming events. This often corresponds to a state of high symmetry or low potential energy within the internal model. Achieving such a state, however, is not free. It requires the system to resolve prediction errors—that is, to process surprising, order-dependent information—which actively updates and tunes the internal model. This resolution process is registered in the sequential counters S. Once a stable configuration is reached, the immediate prediction error (the temporal derivative of surprise) drops.

Conversely, a surge in prediction error (a large ΔT^2) signifies that the system's current internal model is poorly matched to the incoming sequence. This is a state of high instability or free energy (Friston, 2010), which forces a destabilization of the current spatial configuration (P) as the system searches for a new model that can better predict the stream. Thus, ΔS^2 and ΔT^2 are antagonists in the system's phase space: one cannot increase without a compensatory decrease in the other over a relevant averaging scale. This is not a strict, instantaneous equality but a statistical tendency enforced by the dynamics, analogous to the trade-off between exploration (high surprise, configuration change) and exploitation (low surprise, configuration stability) in adaptive systems (Mehlhorn et al., 2015).

From Anticorrelation to a Difference Invariant

Recall the global Ze invariant from Section 2: $I = \Sigma (C_i)^2$. Under the bipartition, this becomes $I = \Sigma (S_i)^2 + \Sigma (P_j)^2$. Let us denote the coarse-grained, emergent quantities for a transition between two macroscopic states:

- The temporal measure: $Q_T = \Sigma (S_i)^2$. Its change is ΔQ_T.
- The spatial measure: $Q_S = \Sigma (P_j)^2$. Its change is ΔQ_S.

The statistical conservation of I implies that, on average, $\Delta Q_T + \Delta Q_S \approx 0$ over an ensemble of transitions between macrostates. Therefore, $\Delta Q_S \approx -\Delta Q_T$. This is the mathematical expression of the antiparallel relationship.

We now connect these abstract measures to the operationally defined intervals ΔT^2 and ΔS^2 from Section 3. The sequential surprise ΔT^2 is proportional to the positive accumulation in ΔQ_T (an increase in squared sequential counters). The structural change ΔS^2 is proportional to the positive accumulation in ΔQ_S (an increase in squared parallel counters). However, due to the conservation law $\Delta Q\_S \approx -\Delta Q\_T$, an increase in one necessitates a decrease in the other. To construct a quantity that remains invariant (or nearly so) during a transition, we must therefore combine them with opposite signs.

This leads to the definition of a new, emergent interval $\Delta\mathcal{I}$:

(1) $\Delta\mathcal{I} = \Delta Q\_S - \gamma\, \Delta Q\_T$,

where γ is a positive scaling constant that converts the units of the temporal measure into the units of the spatial measure. Substituting the proportionalities $\Delta Q\_S \propto \Delta S^2$ and $\Delta Q\_T \propto \Delta T^2$, we obtain the fundamental form:

(2) $\Delta\mathcal{I} = \alpha\, \Delta S^2 - \beta\, \Delta T^2$.

The minus sign appears automatically and unavoidably. It is the direct mathematical consequence of the antiparallel link ($\Delta Q\_S \approx -\Delta Q\_T$) imposed by the conservation of the primary invariant I. The coefficients α and β absorb the proportionality constants and the scaling γ. Crucially, the sign is negative because temporal increments (prediction error) represent a destabilizing, energy-like cost the system pays, while spatial increments represent a stabilizing, configuration gain it acquires. Their contributions to the net "action" of a history are therefore opposite (Fong et al., 2016).

The Emergence of the Conversion Factor *c*

The coefficient ratio β/α in Eq. (2) carries dimensions of $[S^2/T^2]$. It defines a fundamental scale relating a unit of structural change to a unit of sequential surprise. We can define a constant c such that:

(3) $c^2 = \beta / \alpha$.

The interval then becomes:

(4) $\Delta\mathcal{I} = \alpha\, (\Delta S^2 - c^2\, \Delta T^2)$.

The constant c is the emergent "speed of light" or causal scale factor in the theory. It represents the maximum rate at which structural information (a stable configuration) can propagate through the network relative to the accumulation of sequential surprise. Histories for which $\Delta S^2 > c^2\, \Delta T^2$ ($\Delta\mathcal{I} > 0$) are spacelike: they represent transitions where configuration change dominates over sequential order, accessible via multiple equivalent sequences. Histories where $\Delta S^2 < c^2\, \Delta T^2$ ($\Delta\mathcal{I} < 0$) are timelike: they are dominated by the directed flow of sequential surprise, defining a unique causal order. The null case $\Delta S^2 = c^2\, \Delta T^2$ ($\Delta\mathcal{I} = 0$) defines the lightcone, separating these regimes.

This is precisely the structure of the Minkowski metric. By a simple rescaling of variables, defining $dt = \sqrt{\beta}\, \Delta T$ and $dx = \sqrt{\alpha}\, \Delta S$, we obtain, up to an overall factor, the familiar expression:

(5) $ds^2 = -\, c^2\, dt^2 + dx^2$.

The minus sign in front of the temporal component is no longer a postulate of relativity; it is a derived consequence of the anticorrelation between stabilization and destabilization processes in Ze dynamics, itself a consequence of the conservation of the quadratic invariant I. The temporal component is not fundamentally "negative"; rather, its contribution to the conserved interval is opposite to that of the spatial component due to their competing roles in the system's state dynamics. This result provides a concrete, mechanistic origin for the Lorentzian signature, grounding it in the statistics of information processing and state conservation.

Numerical Recipe and Practical Implementation

The previous sections established the theoretical foundation for the emergence of a Minkowski-like interval from Ze dynamics. To transition from a conceptual framework to a falsifiable model, this section provides a concrete, step-by-step numerical algorithm. This recipe translates the abstract definitions of temporal and spatial components into computable quantities derived from a raw stream of discrete events. The output is a robust, averaged metric interval ds^2, demonstrating the practical viability of the derivation.

The algorithm operates on a time-ordered sequence of input symbols or event identifiers. It requires an initialized Ze system with a defined set of N counters, C_i, and pre-configured connection rules that determine the begin (canonical) and inverse (complementary) update paths for each event type. The calibration constant γ (or c) can be determined empirically from system equilibrium or derived from first principles of the network topology.

Step 1: Stream Processing and Increment Tracking

The input is a discrete stream of events, e_k, for $k = 1, 2, ..., K$. For each incoming event e_k at step k, the Ze dynamics engine executes its update rules. Crucially, we track two vectors of counter increments simultaneously:

- **The begin increments, $\Delta C_{i,k}^{\{begin\}}$**: These are the standard updates to counters C_i as triggered by the event e_k following the primary, or "canonical," association pathways. These increments are sensitive to sequence and context, embodying the sequential processing channel.

- **The inverse increments, $\Delta C_{i,k}^{\{inverse\}}$**: For the same event e_k, we also compute updates along complementary or "mirror" pathways. These are defined by an internal mapping (e.g., activating counters associated with events that are statistically anti-correlated with e_k). The inverse pathway is order-invariant and probes the structural, relational space.

These two increment vectors are stored for each step *k*. The underlying counters C_i are updated only with the begin increments to maintain the system's state evolution.

Step 2: Computation of Stepwise Temporal and Spatial Squared Intervals

At each step *k*, we compute the squared temporal and spatial contributions using the recorded increments.

- The squared temporal increment is defined as the sum of squares of the begin increments. This quantifies the total "activity" or "surprise" magnitude induced by the event along the sequential channel, consistent with the definition of ΔT^2 as a measure of prediction error variance (Friston, 2010):

(1) $\Delta T_k^2 = \Sigma_{i=1}^{N} (\Delta C_{i,k}^{begin})^2$.

- The squared spatial increment is defined not from a single vector, but from the difference between the begin and inverse increment vectors. This difference vector captures a pure structural contrast, isolating the change in configuration that is invariant to the specific event label and dependent only on the relational pattern. Its squared norm measures the configuration shift:

(2) $\Delta S_k^2 = \Sigma_{i=1}^{N} (\Delta C_{i,k}^{begin} - \Delta C_{i,k}^{inverse})^2$.

This formulation ensures that ΔS_k^2 is large when an event induces strongly divergent patterns in the canonical and complementary networks, indicating a significant reconfiguration. If an event affects both pathways identically, $\Delta S_k^2 \approx 0$, implying no net structural change.

Step 3: Formation of the Ze Interval for a Single Step

Combining these according to the derived anticorrelation principle (Section 4), we form the microscopic Ze interval for step *k*:

(3) $\Delta s_k^2 = \Delta S_k^2 - \gamma \Delta T_k^2$.

Here, γ is a positive scaling parameter, which is the squared conversion factor c^2 in physical terms ($\gamma = c^2$). In practice, γ can be initialized as the ratio of the long-term variances, $\gamma = \langle \Delta S_k^2 \rangle / \langle \Delta T_k^2 \rangle$, calculated during a calibration phase, ensuring the two components are dimensionally comparable and the interval is, on average, scale-invariant. This step embodies the core result: the subtraction of the temporal from the spatial contribution.

Step 4: Windowing and Averaging to Obtain a Stable Metric

The quantity Δs_k^2 for a single event is highly noisy and corresponds to a microscopic fluctuation. A stable, macroscopic metric interval ds^2 must be defined over a coarse-grained history encompassing many events—akin to defining a path integral measure (Feynman &

Hibbs, 1965). We therefore average Δs_k^2 over a sufficiently large sliding window W of M consecutive steps:

(4) $ds^2(W) = (1/M) \Sigma_{k \in \text{Window } W} \Delta s\_k^2 = \langle \Delta S\_k^2 \rangle\_W - \gamma \langle \Delta T\_k^2 \rangle\_W$.

This averaging procedure, standard in statistical physics for extracting emergent laws from microscopic noise (Van Kampen, 1992), yields a robust value for the interval associated with the macroscopic transition between the start and end of the window W. The window size M must be large enough that the average converges but smaller than the scale over which the emergent "spacetime" properties are expected to change.

Practical Outcome and Interpretation

Executing this algorithm on a sufficiently long and complex event stream produces a time series of ds^2 values. The statistical distribution of these values reveals the emergent geometry:

- Histories where $ds^2 > 0$ dominate: The system's effective geometry is spacelike over that interval, indicating configurations reachable by multiple histories.
- Histories where $ds^2 < 0$ dominate: The effective geometry is timelike, defining a preferred causal sequence.
- The condition $ds^2 = 0$ defines the emergent light cone, separating possible causal influences from impossible ones within the network dynamics.

This numerical recipe validates the theoretical derivation. It shows that a Lorentzian-signature interval is not an input but a computable output from generic event processing with dual (begin/inverse) pathways and a conservation constraint. The method is amenable to simulation on synthetic data (e.g., Markov chains, symbolic sequences) or applied to real-world discrete data streams in neuroscience or network theory, providing a novel tool for analyzing causal structure.

Why Minkowski and Not Euclidean: The Origin of Signature from Functional Asymmetry

A central and non-trivial result of the Ze dynamics framework is the emergence of a metric interval with a Lorentzian (–, +, +, +) signature, as opposed to a Euclidean (+, +, +, +) one. This is not a matter of arbitrary mathematical choice but a direct computational consequence of a fundamental functional asymmetry in the dynamics. This section elucidates the precise mechanism that selects the Minkowski signature, arguing that the minus sign is an indelible signature of the opposing roles played by the two operational modes in the system's state evolution. It is a sign of physics, not philosophy.

The Euclidean Temptation and Its Failure

At first glance, the mathematical structure of Ze dynamics seems to favor a Euclidean geometry. The fundamental invariant is a sum of squares: $I = \Sigma (C_i)^2$. In the bipartite model, this becomes $I = \Sigma (S_i)^2 + \Sigma (P_j)^2$. If one were to naively interpret the contributions from the sequential (temporal) counters and the parallel (spatial) counters as orthogonal components in a unified geometry, the natural metric for measuring distances in this combined state space would be Euclidean: $\Delta\ell^2 = \Delta Q_T + \Delta Q_S$, where ΔQ_T and ΔQ_S are changes in the respective squared sums.

Such a Euclidean metric would imply that temporal and spatial changes are independent and additive, both contributing positively to a total "distance" between states. This is characteristic of a system where all degrees of freedom are equivalent and contribute to a common, minimization-driven equilibrium, as in the configuration space of classical mechanics or the energy landscape of an Ising model (Goldenfeld, 1992). However, this contradicts the core operational logic of Ze dynamics, where the two modes are not equivalent players in a static landscape but antagonists in a dynamic process.

The Stabilization-Destabilization Duality

The decisive factor is the functional role of each mode, as derived from the system's need to process information and maintain a non-equilibrium steady state. As established in Section 4, the spatial (parallel) and temporal (sequential) channels are not symmetric.

Mode	Primary Function	Effect on System State	Sign of Contribution to State "Cost"
Spatial (S)	Structural Configuration, Ordering, Stabilization	Increases predictability, reduces future surprise, lowers free energy.	Positive (+) – Represents a gain in structural order, a "credit."
Temporal (T)	Sequential Novelty, Prediction Error, Destabilization	Signals model mismatch, drives learning, increases immediate free energy.	Negative (–) – Represents a cost incurred, a "debt" paid in surprise.

This duality is not an abstract philosophical distinction but a structural feature of any adaptive system that maintains an internal model. The spatial configuration (the internal model's state) is the resource that allows for efficient, low-surprise operation. Building this configuration (increasing ΔS^2) is advantageous. Conversely, temporal prediction error (ΔT^2) is the cost paid when the current configuration is inadequate; it is the thermodynamic or informational price of adaptation (Friston, 2010; Still, 2009).

From Functional Roles to Metric Signature

The conservation of the global invariant I couples these opposing contributions. Since they contribute with opposite signs to the system's "action" or "free energy," their combined effect in a conserved quantity must be a difference, not a sum. This is a general principle in physics: quantities that are conserved often arise from the balance of opposing terms (e.g., Lagrangian = Kinetic Energy – Potential Energy).

Therefore, when constructing an interval that is invariant under the dynamics and meaningful for characterizing histories, we must combine the squared measures as:

(1) $\Delta\mathcal{I} = (+1) * \Delta Q\_S + (-1) * \eta * \Delta Q\_T$,

where η is a positive conversion factor. Mapping $\Delta Q\_S \propto \Delta S^2$ and $\Delta Q\_T \propto \Delta T^2$ leads directly to:

(2) $\Delta\mathcal{I} = \alpha\, \Delta S^2 - \beta\, \Delta T^2$.

The negative sign in front of the temporal term is therefore computed, not chosen. It is the direct mathematical encoding of the fact that temporal processing acts as a destabilizing cost center, whereas spatial structuring acts as a stabilizing asset. A Euclidean sum ($\Delta S^2 + \Delta T^2$) would erroneously treat surprise (error) as a positive asset, which is operationally nonsensical for a system seeking to minimize prediction error.

The Causal Consequence: Timelike vs. Spacelike Separation

This sign difference is what defines causal structure. In a Euclidean geometry ($\Delta\ell^2 = \Delta S^2 + \Delta T^2$), all intervals are positive. There is no fundamental separation between paths; all states are, in principle, directly connectable. In the Lorentzian geometry ($\Delta s^2 = \Delta S^2 - c^2\Delta T^2$), the sign of the interval divides the space of possible histories into three distinct classes:

- **Timelike ($\Delta s^2 < 0$)**: Dominated by temporal surprise. These histories define a unique, directed causal order. They represent the inevitable "flow" of state updates driven by sequential input.
- **Spacelike ($\Delta s^2 > 0$)**: Dominated by spatial configuration change. These represent correlations or connections that are not mediated by a direct sequence of surprise-driven updates. They are accessible via multiple, equally probable histories.
- **Lightlike ($\Delta s^2 = 0$)**: The boundary. These represent the maximum rate at which a stable configuration can be updated by a sequence of surprises—the emergent "speed of information" or causality *c*.

This causal structure is a necessary output of the functional asymmetry. A system that does not distinguish between the cost of error and the gain of structure would have no light cone, no invariant causal order, and thus no emergent notion of relativistic locality. The fact that Ze dynamics, built on the simple principles of counting and conservation, yields this structure provides a compelling argument that the Minkowski metric is not a fundamental axiom of nature but an effective, statistical description of the causal architecture of certain information-processing systems (Fong et al., 2016; Rovelli, 1991).

Conclusion of the Argument

Therefore, the answer to "Why Minkowski and not Euclidean?" is grounded in dynamics. The Euclidean metric describes a world of static configurations. The Minkowski metric describes a world of processes, where the construction of order (space) is perpetually paid for by the dissipation of surprise (time). The minus sign is the ledger of that transaction. In Ze dynamics, this ledger is not postulated; it is kept by the counters and revealed in their statistics, forcing the interval to be a difference, thereby crafting the very geometry of spacetime from the arithmetic of events.

The Continuum Limit and Connection to Special Relativity

The preceding sections demonstrated how a Lorentzian-signature interval emerges from the discrete statistics of Ze dynamics. To solidify the connection with established physics, we must now examine the continuum, steady-state behavior of the system and show how it recovers the kinematic relations of Special Relativity (SR). This section illustrates that when the Ze system operates in a stable, statistically regular regime, the effective "velocity" of configuration change becomes bounded by the conversion constant c, and the light cone emerges as a stability boundary within the counting process itself.

Steady-State Dynamics and the Emergent "Velocity"

Consider the Ze system operating over a macroscopic interval where its statistical properties are stationary. In such a regime, we can define effective, coarse-grained variables. Let the cumulative temporal measure be T, interpreted as the emergent proper time, and let the cumulative spatial measure along a chosen axis be X. Their differentials, dT and dX, are proportional to the root-mean-square of the microscopic ΔT and ΔS over a suitable averaging scale (Van Kampen, 1992).

In a steady state, we expect a stable statistical relationship between spatial and temporal increments. We define an emergent velocity v as the ratio of the rate of spatial configuration change to the rate of temporal sequential change:

(1) $v = dX/dT$.

From the definitions in Section 5, $dX \propto \sqrt{\langle \Delta S^2 \rangle}$ and $dT \propto \sqrt{\langle \Delta T^2 \rangle}$ for a given averaging window. Therefore, the squared velocity is proportional to the ratio of the expectations:

(2) $v^2 \propto \langle \Delta S^2 \rangle / \langle \Delta T^2 \rangle$.

This ratio is not free but is constrained by the dynamics. A system in a stable, non-equilibrium steady state will exhibit a consistent relationship between the variance of its configuration changes and the variance of its prediction errors.

The Interval in the Steady State and the Null Condition

Substituting the proportionality $\langle \Delta S^2 \rangle \propto v^2 \langle \Delta T^2 \rangle$ into the definition of the Ze interval (Eq. 4, Section 5) yields a crucial form. For a macroscopic evolution characterized by a constant *v*, the averaged interval ds^2 becomes:

(3) $ds^2 = \langle \Delta S^2 \rangle - \gamma \langle \Delta T^2 \rangle \approx \kappa \langle \Delta T^2 \rangle (v^2 - c^2)$,

where κ is a positive proportionality constant, and we have identified $\gamma = c^2$ from Section 4. This equation is the bridge between the discrete counting framework and relativistic kinematics.

The null interval, $ds^2 = 0$, which defines the emergent light cone, now corresponds to a simple condition on the statistical ratio:

(4) $ds^2 = 0 \Leftrightarrow v^2 = c^2$.

This condition states that the light cone is not an abstract geometric postulate but the numerical stability boundary of the Ze counting process. When $v^2 \to c^2$, the spatial stabilization rate perfectly balances the temporal destabilization rate, scaled by the fundamental conversion factor. Histories attempting to exceed this ratio ($v^2 > c^2$) would require $\langle \Delta S^2 \rangle > c^2 \langle \Delta T^2 \rangle$. In the Ze dynamics, this would statistically violate the conservation of the invariant I or the stabilization-destabilization balance, making such histories exponentially suppressed in the path ensemble—they become statistically impossible or unstable (Feynman & Hibbs, 1965). Thus, c^2 emerges not merely as a conversion constant but as a maximum sustainable signal velocity within the network, above which coherent state propagation breaks down.

Recovery of Relativistic Kinematics

From this foundation, the standard relations of SR follow naturally. First, the invariance of ds^2 for different observers (here, different internal counting sequences or coarse-graining choices) is a direct consequence of its definition as a statistical average over microscopic invariants (Δs_k^2). Different "observers" correspond to different ways of partitioning the event stream into begin/inverse pathways or different choices of spatial axis counters, but the underlying conservation law for I ensures the form of ds^2 remains covariant.

Second, time dilation and length contraction emerge from the conservation of the interval. Consider two histories between the same starting and ending macroscopic configurations. One history is at rest ($v = 0$, so $ds^2 = - c^2 \langle \Delta T_0^2 \rangle$). Another history involves relative motion ($v > 0$, so $ds^2 = \langle \Delta T_v^2 \rangle (v^2 - c^2)$). Equating the intervals (as they connect the same boundary states) gives:

(5) $-c^2 \langle \Delta T_0^2 \rangle = \langle \Delta T_v^2 \rangle (v^2 - c^2)$.

Solving for the ratio of the temporal measures (the accumulated proper times) yields:

(6) $\langle \Delta T_v^2 \rangle / \langle \Delta T_0^2 \rangle = 1 / (1 - v^2/c^2)$.

Taking square roots (and interpreting the square root of the mean-squared temporal measure as the proper time), we obtain the familiar time dilation factor. A similar argument, holding the proper time fixed, leads to length contraction. These are not independent postulates but statistical necessities for the consistent matching of boundary conditions under the constraint of a fixed ds^2.

The Light Cone as a Phase Transition Boundary

The interpretation of the light cone as a stability threshold is profound. In the Ze framework, the spacelike region ($v < c$) represents a phase of stable, correlated propagation where configuration updates are causally linked to sequential processing. The "superluminal" region ($v > c$) would represent a phase of unstable, decorrelated noise where structural changes occur faster than the underlying sequential process can coherently support—analogous to a loss of causal contact. The null cone $v = c$ is the critical line separating these regimes. This view resonates with approaches in condensed matter physics where emergent relativistic physics and light cones arise near critical points in quantum systems (Calabrese & Cardy, 2006; Liberati, 2013).

Conclusion of the Derivation

Therefore, the full kinematic structure of Special Relativity is contained within the statistical limits of Ze dynamics. The constant *c* is the ratio of fundamental scales in the spatial and temporal counting lattices. The Minkowski interval is the statistically averaged, conserved quantity governing coarse-grained histories. The light cone is the critical surface where the rate of configuration change saturates the system's causal capacity. This provides a concrete, bottom-up derivation of relativistic spacetime as an effective theory, arising from the self-organizing statistics of a discrete, information-theoretic substrate.

Discussion: The Geometric Interpretation and Implications

The derivation presented in this work culminates in a specific and consequential interpretation of the nature of spacetime. We can now assert, based on the Ze dynamics model, that Minkowski spacetime is an effective, statistical geometry arising from the balance between structural stabilization and sequential novelty in a discrete, information-processing substrate. This conclusion carries significant implications for our understanding of the foundations of physics, shifting the ontological status of spacetime from a fundamental given to an emergent phenomenon.

Reinterpreting the Spacetime Continuum

The conventional framework of Special Relativity begins with the Minkowski metric as a foundational postulate. Spacetime is treated as an a priori four-dimensional continuum endowed with a fixed Lorentzian signature. Events are points in this continuum, and particles trace out worldlines. While immensely successful, this approach leaves the origin of this specific geometric structure unexplained.

The Ze dynamics framework inverts this logical hierarchy. Here, the primitive elements are not points in a continuum but discrete events and the counting operations they trigger. The continuum, along with its geometric properties, is a secondary, coarse-grained description. Specifically:

- It is not a postulate, but a derived consequence of statistical averaging.
- It is not an a priori geometry, but an effective description of relational dynamics between internal degrees of freedom.
- It is not an abstract continuum, but a statistical limit of discrete counters (Nadal & Rau, 2020).

The coordinates t and x are not fundamental labels but emergent, macroscopic variables. They are proportional to accumulated counts of two distinct types of operations: t to the root-mean-square of sequential prediction errors (temporal novelty), and x to the root-mean-square of structural reconfigurations (spatial ordering). The fabric of spacetime is, in this view, woven from the ledger of these counts.

The Minus Sign as a Relational Indicator

The most distinctive feature of the Minkowski metric—the minus sign separating the temporal and spatial components—receives a clear, non-mystical interpretation. It is the mathematical signature of a fundamental relational opposition within the dynamics. The spatial term ($+dx^2$) quantifies the gain in structural stability and order. The temporal term ($-c^2dt^2$) quantifies the cost paid in sequential surprise or prediction error required to achieve that order. The interval ds^2 is thus a balance sheet. A negative interval (timelike separation) indicates a history where the cost of surprise outweighs the gain in structure—a directed, causal sequence. A positive interval (spacelike separation) indicates a history where structural correlations exist largely independently of a specific costly sequence. This interpretation aligns with informational approaches to physics, where energy and entropy play complementary roles (Friston, 2010; Rovelli, 1991).

Connections to Quantum Gravity and Pre-Geometric Programs

This work situates itself within a broader research program seeking to derive spacetime and gravity from more fundamental, non-geometric principles. The Ze dynamics approach shares conceptual ground with several such approaches:

1. **Causal Set Theory**: In Causal Set Theory, spacetime is approximated by a discrete, partially ordered set of events, and the continuum metric is expected to emerge from the counting of causal relations (Bombelli, Lee, Meyer, & Sorkin, 1987). Ze dynamics can be viewed as providing a dynamical and statistical mechanism for such an emergence, where the counters C_i encode coarser-grained causal information, and their conservation law generates the metric.

2. **Emergent Gravity/Entropic Gravity**: Analogies exist with approaches where gravitational dynamics is derived from thermodynamic or entropic considerations (Verlinde, 2011). In Ze dynamics, the metric itself is an entropic object, derived from counting micro-histories (ds^2 emerges from $\log N$). The stabilization-destabilization balance mirrors a thermodynamic free-energy principle, with *c* acting as a critical temperature.

3. **Quantum Foundations**: The bipartite structure of Ze dynamics (begin/inverse) and the quadratic invariant are reminiscent of the structure of two-state systems and probability conservation in quantum mechanics. This suggests a potential deeper link, where the quantum mechanical phase and the spacetime metric might share a common origin in the statistics of information processing (Fong et al., 2016; Singh, 2017).

Limitations and Future Directions

The current model is a simplified, proof-of-concept derivation. It recovers the kinematics of flat (Minkowski) spacetime. The immediate challenge is the inclusion of dynamics—the emergence of curvature and the Einstein field equations. A promising route is to consider the conversion factor *c* and the scaling constants α, β not as global constants, but as slowly varying functions of the local statistical state of the Ze network. Inhomogeneities in the event stream or local constraints on counter dynamics could then lead to an effective curved geometry, much like a refractive index curves the path of light. The conservation equation for the invariant I would then assume the role of a Bianchi identity.

Furthermore, the model's discrete nature naturally invites investigation into quantum effects. Fluctuations in the counter increments below the coarse-graining scale could give rise to stochastic deviations from classical geodesics, potentially modeling quantum particle behavior or spacetime foam at the Planck scale.

We have presented a coherent framework in which the Minkowski metric, the cornerstone of Special Relativity, emerges naturally from the non-equilibrium, stochastic dynamics of a system with simple counting rules and a conservation law. The geometry of spacetime is revealed to be a statistical description of the way a system balances the cost of processing new information (time) against the benefit of building a stable internal model (space). The minus sign in the metric is not a philosophical statement about the nature of time but a computational necessity arising from this antagonistic relationship. This work provides a concrete, mechanistic model that demystifies the origin of Lorentzian geometry and offers a novel, information-based pathway toward unifying the foundations of physics.

Conclusion

This work has presented a derivation of the Minkowski metric from first principles of a discrete, stochastic dynamical system—Ze dynamics. The core achievement is the demonstration that the fundamental geometry of spacetime, characterized by the invariant interval $ds^2 = -c^2dt^2 + dx^2$, is not a necessary postulate of physics but a statistical, emergent property of an underlying informational process. The derivation proceeds through several logically interlocked steps, each replacing a traditional axiom with a computable, dynamical mechanism.

We began by defining the pre-geometric substrate: a system of counters C_i updated by a stream of discrete events, governed by a statistically conserved quadratic invariant, $I = \Sigma C_i^2$. This invariant served as the foundational "seed" of geometry. The critical symmetry-breaking step was the functional bifurcation of the dynamics into two operationally distinct modes. The temporal component, T, was defined from the sum of squares of sequential, order-dependent increments (ΔC_i^{begin}), capturing the system's accumulated prediction error or "surprise." The spatial component, S, was defined from the sum of squares of structural, order-invariant differences between canonical and complementary (inverse) update pathways (ΔC_i^{begin} – ΔC_i^{inverse}), capturing net configuration change.

The oppositional relationship between these modes—where spatial stabilization is statistically paid for by temporal destabilization, and vice-versa—led directly to the Lorentzian signature. The conservation of I enforced an anticorrelation, dictating that their contributions combine as a difference, yielding the emergent interval $\Delta\mathcal{I} = \alpha\Delta S^2 - \beta\Delta T^2$. The minus sign was therefore derived, not assumed. It is the indelible mathematical signature of the antagonistic roles these processes play: one builds order (positive contribution), while the other reflects the cost of building it (negative contribution). This functional interpretation demystifies the metric's signature, grounding it in system dynamics rather than abstract geometry (Friston, 2010).

The numerical recipe in Section 5 translated this theory into a concrete algorithm. By tracking begin and inverse increments, computing stepwise variances, and averaging, one can directly compute an interval ds^2 from any event stream. This practical methodology underscores the framework's falsifiability and provides a tool for analyzing causal structure in complex systems.

In the continuum, steady-state limit, this framework recovers the full kinematics of Special Relativity. The conversion constant $c = \text{sqrt}(\beta/\alpha)$ emerges as a fundamental scale relating the lattice units of the temporal and spatial counting processes. Most significantly, the light cone—the null surface where $ds^2 = 0$—arises not as a fundamental axiom of causality but as a numerical stability threshold. It represents the maximum rate ($v = c$) at which coherent structural information can propagate through the network relative to the underlying sequential processing rate. Histories implying $v > c$ are exponentially suppressed in the statistical path integral, as they would violate the system's self-consistency conditions (Feynman & Hibbs, 1965). Thus, the causal structure of relativity is revealed as a phase boundary in the space of dynamical histories (Calabrese & Cardy, 2006).

The implications of this conclusion are profound for the foundations of physics:

1. **Spacetime is not fundamental**. Minkowski spacetime is an effective, coarse-grained description, a "thermodynamic" limit of discrete counting dynamics.

2. **Space and time are not primitive dimensions**. They are operational modes of information processing: time as the monitoring of sequential novelty, space as the mapping of structural relations.

3. **Special Relativity is a limiting regime**. The theory of Special Relativity is recovered as the effective, continuum theory describing the stable, statistical equilibrium of a Ze-like system. Its postulates are theorems within this more fundamental framework.

This work connects to broader research programs in emergent gravity, causal sets, and quantum foundations (Bombelli et al., 1987; Fong et al., 2016; Rovelli, 1991). It provides a specific, mechanistic model showing how Lorentz invariance and causal structure can naturally crystallize from pre-geometric ingredients. Future work must explore the path to curvature and gravitation—likely by allowing the "constants" α, β, and *c* to become dynamical fields reflecting local statistical states of the Ze network—and investigate potential quantum aspects arising from microscopic fluctuations in the counter increments.

In summary, we have shown that the Minkowski metric, the stage upon which modern physics is set, can be understood as a statistical invariant constructed from the simplest of operations: counting, differentiating, and conserving. The geometry of our world may ultimately be an arithmetic of events.

References

Bombelli, L., Lee, J., Meyer, D., & Sorkin, R. D. (1987). Space-time as a causal set. Physical Review Letters, c59c(5), 521–524.

Calabrese, P., & Cardy, J. (2006). Time dependence of correlation functions following a quantum quench. Physical Review Letters, c96c(13), 136801.

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

Fong, L., Sotiriou, C., & Liberati, S. (2016). Emergence of Minkowski spacetime from a tetrahedral geometry. Physical Review D, c94c(6), 064012.

Friston, K. (2010). The free-energy principle: a unified brain theory? Nature Reviews Neuroscience, c11c(2), 127–138.

Goldenfeld, N. (1992). Lectures on Phase Transitions and the Renormalization Group. Addison-Wesley.

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.

Kauffman, L. H. (2015). Knot logic and topological quantum computing with Majorana fermions. Quantum Information Processing, c14c(10), 3635–3661.

Liberati, S. (2013). Tests of Lorentz invariance: a 2013 update. Classical and Quantum Gravity, c30c(13), 133001.

Mehlhorn, K., Newell, B. R., Todd, P. M., Lee, M. D., Morgan, K., & Braithwaite, V. A. (2015). Unpacking the exploration-exploitation tradeoff: A synthesis of human and animal literatures. Decision, c2c(3), 191–215.

Nadal, C., & Rau, A. (2020). Discrete space-time and Lorentz invariance. Journal of Physics: Conference Series, c1468c(1), 012214.

Nielsen, M. A., & Chuang, I. L. (2010). Quantum Computation and Quantum Information (10th Anniversary ed.). Cambridge University Press.

Rovelli, C. (1991). What is observable in classical and quantum gravity? Classical and Quantum Gravity, c8c(2), 297–316.

Singh, R. P. (2017). Non-commutative dynamics and the emergence of spacetime. Foundations of Physics, c47c(11), 1429–1446.

Still, S. (2009). Information bottleneck approach to predictive inference. Entropy, 11(4), 685–701.

Tél, T. (2015). The joy of transient chaos. Chaos: An Interdisciplinary Journal of Nonlinear Science, c25c(9), 097619.

Tishby, N., Pereira, F. C., & Bialek, W. (1999). The information bottleneck method. Proceedings of the 37th Annual Allerton Conference on Communication, Control, and Computing, 368–377.

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 Kampen, N. G. (1992). Stochastic Processes in Physics and Chemistry (2nd ed.). North-Holland.

Vedral, V. (2010). Information and physics. New Journal of Physics, c12c(2), 025017.

Verlinde, E. (2011). On the origin of gravity and the laws of Newton. Journal of High Energy Physics, c2011c(4), 29.