

A Direct Ze-Type Experiment

Experimental validation of a fundamental information–time coupling

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Abstract

The Ze framework proposes that proper time is not a geometric parameter but a count of effective information updates, with relativistic kinematics emerging statistically from the dynamics of event processing rather than from assumed spacetime structure. This paper presents a comprehensive experimental programme to test four core Ze postulates across multiple domains. The foundational digital experiment employs identical processors receiving identical input streams operating in maximally sequential versus maximally parallel modes, predicting update count ratios $\tau_B/\tau_A = \sqrt{1 - v^2}$ where v represents the proportion of parallel correlations—a functional form identical to the Lorentz factor of special relativity. Physical clock experiments compare internal transition counts in systems with different internal complexity (trapped ions, molecular clocks, optical lattice clocks) under identical relativistic conditions, testing whether proper time correlates with update statistics rather than merely with velocity. Non-inertial experiments subject systems to periodic correlation modulation without changing average velocity, predicting that proper time accumulation depends on causal structure rather than path length alone. Quantum-level experiments leverage programmable quantum computers (IBM, IonQ) to test whether interference corresponds to parallel update distribution and whether the quantum Zeno effect reflects mode switching with measurable update deficits. The Ze framework does not claim special relativity is incorrect but seeks to show it arises as an effective theory from deeper informational principles. Structural convergence with causal set theory, twistor theory, and emergent spacetime frameworks provides indirect support. The digital experiment offers the most direct test: if the relativistic curve emerges from pure information dynamics, it demonstrates that relativistic kinematics are not unique to physics but reflect universal constraints on information processing. Independent replication by multiple groups and derivation of relativity without assuming it would constitute sufficient evidence to attract serious scientific engagement. All proposed experiments are feasible with current technology, and their falsification conditions are clearly specified, ensuring the Ze framework meets the highest standards of empirical testability.

Keywords: Information-Based Time; Emergent Relativity; Causal Structure; Quantum Zeno Effect; Digital Experiment; Update Counting; Lorentz Factor.

Introduction

The relationship between information processing and physical time has attracted increasing attention across multiple disciplines. Recent work in quantum measurement theory has demonstrated that repeated observations can fundamentally alter dynamical evolution, as exemplified by the quantum Zeno effect (Virzì et al., 2022). Simultaneously, advances in control and information theory have revealed deep connections between information-theoretic measures and fundamental performance limitations in dynamical systems (Fang, Chen, & Ishii, 2016). These developments suggest the possibility that time itself might be understood as an emergent property of information processing rather than a fundamental background parameter.

The Ze approach advances this perspective through four specific postulates that demand experimental verification:

P1. Proper time of a system is proportional to the number of effective updates (counters), not to an external parameter.

P2. Motion consists of the redistribution of events between sequential and parallel channels.

P3. Time dilation arises as a deficit of updates, not as a geometric effect.

P4. Minkowski-type invariance emerges statistically from counter dynamics.

These postulates collectively propose that relativistic kinematics might be derivable from information-theoretic constraints. This article describes a direct experimental test of these propositions using purely informational processes, thereby avoiding assumptions about physical particles or spacetime structure.

Theoretical Framework

Information-Based Time

The concept of time as proportional to internal updates finds precedent in several research traditions. Work on parallel-in-time algorithms for scientific computing has demonstrated that temporal decomposition can yield computational speedups comparable to spatial decomposition (Srinivasan, 2005). The time-partitioning approach, in which different processors simultaneously compute system states at different time points, effectively treats time as a parallelizable dimension (NASA, 1987). These computational techniques, while developed for practical speedup, inadvertently illustrate the Ze proposition that update counts rather than external clock parameters determine effective duration.

Parallel versus Sequential Processing

Consider two identical Ze-type processors receiving identical input data streams. The processors differ only in their operational mode: Processor A operates in maximally sequential

mode, processing events one after another with minimal parallel correlation. Processor B operates in maximally parallel (inverse or spatial) mode, distributing events across parallel channels to maximize simultaneous processing.

Let N represent the number of input events. Define τ as the number of effective counter updates actually performed by each processor. The Ze postulates predict that these update counts will differ between modes, with the parallel processor completing fewer effective updates than the sequential processor for the same input stream.

The predicted relationship takes the form:

$$\tau_B/\tau_A < 1$$

Furthermore, if v represents the proportion of parallel correlations in the processing architecture, the specific functional relationship becomes:

$$\tau_B/\tau_A = \sqrt{1 - v^2}$$

This expression is mathematically identical to the Lorentz factor $\gamma^{-1} = \sqrt{1 - v^2/c^2}$ of special relativity, with v playing the role of velocity relative to some maximum correlation proportion.

Statistical Origin of Invariance

The emergence of Minkowski-type invariance from counter dynamics requires statistical justification. Work on Minkowski tensors in cosmological contexts has demonstrated that anisotropic signals can be extracted from random fields through appropriate tensor statistics (Appleby et al., 2018). Similarly, the analysis of Lorentz-invariant probability distributions on Minkowski space reveals that invariance conditions impose strong constraints on functional forms (MathOverflow, 2024). The Ze approach inverts this relationship: rather than assuming invariant geometry, it derives invariant statistics from update dynamics.

Experimental Design

Core Architecture

The experiment employs a single data stream feeding two identical Ze-type processors. Processor A operates in maximally sequential mode, while Processor B operates in maximally parallel mode. Both processors are implemented algorithmically rather than as simulations of physical systems—the experiment directly manipulates information processes.

Three quantities are measured for each processor:

1. N : total number of input events processed
2. τ : number of real counter updates performed
3. The proportion of predictable versus unpredictable events in the stream

The critical comparison is the ratio τ_B/τ_A for identical input streams. According to the Ze postulates, this ratio should be less than unity and should follow the functional form $\sqrt{1 - v^2}$, where v is independently measurable from the correlation structure of the parallel processing mode.

Relationship to Existing Approaches

This experimental design differs fundamentally from conventional simulations of relativistic systems. Rather than implementing Lorentz transformations as geometric operations, the Ze experiment allows relativistic kinematics to emerge—or fail to emerge—from pure information dynamics. The approach bears conceptual similarity to work on integrating control and information theories, where performance limitations are derived from information-theoretic measures rather than assumed a priori (Fang et al., 2016).

Predictions and Interpretation

Confirmatory Evidence

Confirmation of the predicted relationship $\tau_B/\tau_A = \sqrt{1 - v^2}$ would constitute strong evidence for the Ze postulates. Such confirmation would demonstrate that:

1. Effective update counts depend on processing architecture
2. The ratio between parallel and sequential updates follows a relativistic form
3. Minkowski-type invariance emerges statistically from counter dynamics
4. Time dilation can be understood as an update deficit rather than a geometric effect

Implications

Successful confirmation would suggest that relativistic kinematics are not unique to physics but rather reflect universal constraints on information processing. This interpretation aligns with recent work on quantum Zeno and anti-Zeno effects, where measurement frequency fundamentally alters dynamical evolution (Virzì et al., 2022). The repeated measurements in quantum Zeno experiments effectively constitute updates to quantum states, and the resulting modification of evolution rates parallels the Ze prediction that update counts determine proper time.

Furthermore, the statistical emergence of Lorentz invariance from update dynamics would address foundational questions about the origin of relativistic symmetry. Rather than assuming Minkowski spacetime as a background, the Ze approach derives its effective appearance from information constraints—a perspective with potential implications for quantum gravity and the unification of general relativity with quantum theory.

The direct Ze-type experiment described here offers a clean test of four fundamental postulates about time and information. By comparing update counts between sequential and parallel processors processing identical data, the experiment directly tests whether relativistic kinematics emerge from information dynamics. Confirmation of the predicted functional form would validate the Ze approach independently of particle physics and suggest that time dilation reflects update deficits rather than geometric effects. Such a result would bridge information theory, computation, and fundamental physics, providing experimental support for the view that time is not a background parameter but an emergent property of information processing.

Experiment on Physical Systems with Internal Clocks

Atomic Clocks ≠ Time Ticks

The Ze approach makes a fundamental distinction between the external parameter of coordinate time and the internal counting of system updates that constitutes proper time. According to postulate P1, proper time τ is proportional to the number of effective internal transitions, not to the elapsed coordinate time t measured by an external reference clock. This distinction becomes experimentally accessible when we recognize that atomic clocks, despite their extraordinary precision, measure frequency ratios rather than counting internal transitions directly.

Standard relativistic time dilation predictions concern the rate of atomic clocks as a whole—given by the ratio τ/t for a moving clock compared to a stationary reference. The Ze postulates make a stronger claim: time dilation correlates not with velocity per se, but with a reduction in the number of internal transitions occurring within a fixed external interval. Crucially, this reduction should depend on the internal complexity of the system, not merely on its kinematic state.

The proposed experimental test is conceptually straightforward: compare not only the tick rates of different atomic clocks subjected to identical relativistic conditions, but count the actual number of transitions between internal states over a fixed external coordinate interval. The Ze prediction states that for identical γ factors (identical velocities relative to a laboratory frame), systems with different internal complexity will accumulate different numbers of effective updates τ . In other words, the "clock" and the "ticks" are not identical—the clock rate aggregates many internal processes, and it is the count of those microscopic transitions that constitutes proper time.

Implicitly Testable in Existing Systems

This prediction is implicitly testable in several classes of precision frequency standards currently under development. Ion clocks, molecular clocks, and ultra-precision optical transition systems each offer different internal architectures while operating under identical relativistic conditions.

Trapped-ion optical clocks provide an ideal testbed. Recent ab initio quantum treatments of mass defect and time dilation in trapped-ion systems have developed fully quantum-mechanical descriptions of relativistic frequency shifts . These treatments derive Hamiltonians for the external and internal dynamics of electromagnetically bound, charged two-particle systems in external fields, including leading-order relativistic corrections. The work reproduces well-known formulas for the second-order Doppler shift for thermal states, which were previously derived on the basis of semiclassical arguments, while clarifying the role of time dilation and mass defect in ion clocks . This theoretical framework now enables systematic calculation of internal transition counts under specified relativistic conditions.

Molecular clocks offer a distinct internal structure with different complexity. The vibrational transitions in molecules such as calcium monofluoride provide frequency references with fundamentally different coupling between internal and external degrees of freedom . Molecular iodine clocks, designed for space applications with improved stability performances, enable fractional frequency reproducibility at the 10^{-15} level . Comparing the update counts between a molecular clock and an atomic clock under identical relativistic motion would reveal whether the reduction in internal transitions follows the simple γ factor or depends on internal architecture.

Optical lattice clocks, based on neutral atoms confined in periodic arrays of laser light, achieve extraordinary stability by probing thousands of trapped atoms simultaneously . The ultra-narrow optical frequency transitions in strontium or ytterbium atoms provide ticking frequencies hundreds of trillions per second. These systems have been proposed for testing variations of fundamental constants, and their precision makes them sensitive to the effects predicted by Ze.

Experimental Protocol

The proposed experiment would proceed as follows:

1. Select two or more clock systems with different internal complexity—for example, a single trapped ion clock, a molecular clock based on vibrational transitions, and an optical lattice clock with collective interrogation.
2. Subject all systems to identical relativistic conditions, either through controlled motion (such as in high-precision atomic fountain experiments) or through gravitational potential differences.
3. For each system, measure two quantities over a fixed external coordinate interval Δt :
 - The conventional clock rate $R = \Delta\tau_{\text{clock}}/\Delta t$, where $\Delta\tau_{\text{clock}}$ is the proper time accumulated by the clock's output
 - The actual number of internal transitions N_{int} occurring within the system during Δt

4. Compare the reduction factors: For conventional clocks, the prediction is $\Delta\tau_{\text{clock}}/\Delta t = 1/\gamma$. The Ze prediction concerns $N_{\text{int}}(\gamma)/N_{\text{int}}(0) = f(\gamma, \text{complexity})$, where the function f should differ from $1/\gamma$ and depend on the internal structure.

Relation to Existing Precision Measurements

This proposal connects to several active research directions. Atom interferometry experiments are now capable of measuring gravitational time dilation with delocalized quantum superpositions , and novel measurement schemes enable the use of atom interferometers as freely falling clocks directly measuring relativistic time-dilation effects . These techniques provide the necessary precision to distinguish between overall clock rate and internal transition counts.

The work on quantum Zeno and anti-Zeno effects in photon polarization has demonstrated that measurement frequency fundamentally alters dynamical evolution [citation:11]. In the Ze framework, this corresponds to the modification of effective update counts by external interventions. Similarly, experiments exploring complementarity in atom interferometry have shown how internal clocks can act as which-path witnesses . These investigations reveal the deep connection between internal dynamics and observable interference phenomena.

Distinguishing Predictions

The critical distinction between standard relativity and the Ze postulates lies in the complexity dependence. Special relativity predicts that all clocks, regardless of internal construction, experience identical time dilation when moving identically. This universality is a cornerstone of Einstein's theory. The Ze postulates, by contrast, predict that what dilates is not "time" as a unified quantity but the rate of internal updates, and that this rate depends on how the system processes information internally.

If experiments reveal that two different clock systems with identical γ factors accumulate different numbers of internal transitions over the same coordinate interval, this would constitute evidence that proper time is not a universal parameter but rather an emergent property of system-specific update dynamics. Even null results would be valuable, establishing upper bounds on complexity-dependent effects and potentially revealing that all systems reach the same informational limit under relativistic motion.

The experiments described here are feasible with current or near-future technology. The precision required to distinguish overall clock rate from internal transition counting is demanding but accessible, particularly with the ongoing development of optical clocks and atom interferometry techniques.

Experiment with Non-Inertial Systems (The Key to the Twins)

Acceleration in Special Relativity and the Ze Critique

The conventional interpretation of special relativity assigns a privileged status to acceleration. In the standard resolution of the twin paradox, the traveling twin's acceleration during turn-around is identified as the physical event that breaks the symmetry between the two observers, allowing one to unambiguously age less upon reunion. Within this framework, acceleration serves as the "special case" that distinguishes inertial from non-inertial worldlines, yet the theory provides no dynamical mechanism for how acceleration produces differential aging—it merely calculates the integrated proper time along each path.

The Ze approach offers a fundamentally different perspective. According to postulate P2, motion consists of the redistribution of events between sequential and parallel channels. Within this framework, acceleration corresponds not to a special physical effect but to a change in the class of causal events—a reconfiguration of how information propagates through the system's internal network. This reconceptualization opens the possibility of experimental tests that distinguish between geometric time dilation and update-based proper time accumulation.

Acceleration as Causal Reclassification

Recent work on the emergence of spacetime from causal networks provides mathematical support for this viewpoint. D'Ariano and Tosini (2013) demonstrated that Minkowski spacetime can emerge from a discrete causal network representing classical information flow, where the metric is derived from pure event-counting. In their framework, the Lorentz transformations acquire a digital form, and time dilation emerges as an increased density of "leaves" within a single tick of a clock. Crucially, the operational procedure of building coordinate systems introduces an indistinguishability between neighboring events, resulting in a coarse-graining of the network that depends on the observer's clock.

This computational analogy treats the foliation of spacetime as analogous to synchronizing calls to independent subroutines in parallel distributed computation. When a system undergoes acceleration, it reconfigures the causal connections between events, effectively changing the class of correlations that determine future updates. Acceleration thus becomes a reclassification of causal relations rather than a geometric perturbation to a pre-existing background.

Experimental Design: Periodic Correlation Modulation

To test this prediction, we propose an experiment involving a system subjected to periodic changes in its correlation structure without any change in its average velocity. The experimental configuration consists of:

1. A physical system with internal degrees of freedom that can be configured to operate in different correlation regimes—for example, a trapped ion system whose internal couplings can be modulated externally.
2. A trajectory that returns to its starting point with zero net displacement, but during which the system's internal correlation structure is periodically varied between sequential and parallel dominant modes.
3. Measurement of the accumulated proper time τ (measured via internal transition counts) compared to an identical system that follows the same geometric path but maintains constant internal correlation structure.

The critical prediction of the Ze framework is that τ depends on the structure of the causal chain—the pattern of event correlations—rather than on velocity as a kinematic parameter. Two systems traversing identical worldlines but with different internal correlation modulations should accumulate different proper times. This constitutes a potential departure from the classical interpretation of special relativity, which predicts that proper time depends only on the spacetime path, not on internal dynamical details.

Theoretical Foundation

The theoretical basis for this prediction derives from the analysis of causal networks. In topologically homogeneous causal networks, the metric emerges from pure event-counting, and the Lorentz transformations become integer relations that differ from the usual analog transformations by a multiplicative constant corresponding to event thickness. The velocity of a boosted frame can be expressed in terms of the clock's internal timing parameters as:

$$v = (\alpha - \beta)/(\alpha + \beta)$$

where α and β characterize the "tic" and "tac" intervals of the clock (D'Ariano & Tosini, 2013). When acceleration occurs, these parameters undergo reconfiguration that depends on the causal structure of the network.

Friedman and Gofman (2010) explored related ideas, developing a relativistic kinematics of accelerated systems under the assumption that the clock hypothesis might be false. Their work predicted the existence of maximal acceleration and time dilation due to acceleration itself, beyond the conventional velocity-dependent effects. They further predicted Doppler shifts arising from source acceleration in addition to velocity shifts, offering an alternative explanation for experiments such as Kündig's measurement of the transverse Doppler effect.

Experimental Realization with Quantum Clocks

Recent advances in quantum clock technology make such experiments increasingly feasible. Charged quantum clocks in non-inertial motion provide a concrete testbed: for example, cyclotron motion in a uniform magnetic field offers a controlled non-inertial trajectory where time dilation can be evaluated quantum mechanically. Cepollaro and Giacomini (2023) derived time

dilation formulas for charged quantum clocks in electromagnetic fields, applying these results to coherent states and demonstrating that quantum clocks exhibit richer behavior than classical idealized clocks.

The extraordinary stability of modern optical lattice clocks enables measurements at the 10^{-18} level, corresponding to centimeter-scale resolution of gravitational potential differences. The most stable atomic clocks currently achieve fractional frequency instability below 10^{-18} , losing or gaining less than one second over timescales comparable to the age of the universe (Ludlow et al., 2015). Such precision allows detection of minute differences in proper time accumulation that might arise from internal correlation structure rather than purely geometric path length.

Schioppo et al. (2022) demonstrated the operation of a transportable optical clock with systematic uncertainty below the 10^{-17} level, opening possibilities for clock-based tests of fundamental physics in varying gravitational potentials. Similarly, Bothwell et al. (2022) resolved the gravitational redshift across a submillimeter-scale atomic sample, demonstrating the sensitivity required for non-inertial experiments with confined quantum systems.

Distinguishing Predictions and Potential Outcomes

The experiment's key distinguishing prediction can be stated as follows: For two systems following identical worldlines that begin and end together, if they differ in the temporal pattern of their internal correlation structure—specifically, in how events are distributed between sequential and parallel channels during the journey—they will accumulate different proper times upon reunion.

This prediction contradicts the standard relativistic expectation that proper time is a path-dependent functional independent of internal dynamics. Even within general relativity, where gravitational time dilation depends on the metric, identical paths through identical spacetime geometries should yield identical proper times for all clocks. The Ze framework introduces a new variable: the causal architecture of the clock itself.

If confirmed, such an effect would have profound implications. It would suggest that the twin "paradox" is not merely a pedagogical device but a window into the informational foundations of relativity. Acceleration would be understood not as a geometric interruption but as a reconfiguration of causal relations—a shift in how a system processes information through time. The differential aging of twins would then reflect not just their paths through spacetime but the patterns of correlation their internal dynamics sustained during those paths.

The experiment described here offers a direct test of this radical proposition. By separating the kinematic variable (velocity) from the causal variable (correlation structure), it isolates the mechanism by which the Ze postulates propose time dilation actually arises. Confirmation would validate the view that proper time is not a geometric given but an emergent property of information processing—and that acceleration matters because it changes how systems process information, not because it marks a special class of worldlines.

Connection to Foundational Questions

These considerations connect to broader questions about the nature of time in quantum theory. Experiments on complementarity in atom interferometry have demonstrated that internal clocks can act as which-path witnesses, revealing how internal dynamics affect observable interference patterns (Margalit et al., 2015). The Quantum Zeno and anti-Zeno effects, where measurement frequency alters dynamical evolution, further illustrate the connection between update counting and effective time evolution (Virzi et al., 2022). These phenomena provide independent motivation for treating internal updates as fundamental to proper time, rather than treating time as an external parameter.

The Ze framework unifies these observations by proposing that all time dilation—whether from motion, gravity, or internal dynamics—reflects changes in the rate of effective updates. The non-inertial experiment described here provides the cleanest test of this unification, potentially revealing that acceleration matters precisely because it reconfigures the causal network through which updates propagate.

Quantum Level: Ze vs Standard Interpretation

Double Slit / Delayed Choice

The interpretational divide between standard quantum mechanics and the Ze framework becomes most sharply defined in the context of wave-particle duality experiments. The double-slit experiment and its delayed-choice variants have long served as the primary battleground for questions about quantum ontology. Within the standard interpretation, the quantum system exhibits complementary behaviors—wave-like or particle-like—depending on the measurement context, with the observer's choice seemingly retroactively determining the system's past behavior in delayed-choice configurations.

The Ze approach offers a fundamentally different ontology. According to postulate P2, motion consists of the redistribution of events between sequential and parallel channels. In the quantum domain, this translates to a specific claim: interference phenomena arise from the distribution of effective counter updates across parallel causal pathways, while the appearance of collapse corresponds to a sudden change in the mode of update processing—a transition from parallel to sequential correlation architecture.

This reconceptualization transforms the experimental question. Rather than asking whether a quantum system behaves as a wave or a particle, the Ze framework directs attention to the statistics of correlation counter updates underlying the observed phenomenology. Interference visibility becomes a measure of how effectively the system distributes updates across parallel channels; which-path information becomes a measure of sequential update confinement.

Quantum Erasers on Programmable Platforms

The advent of programmable quantum computers provides an unprecedented opportunity to test these ideas. Recent work by Chen, Chiou, and Hsu (2025) demonstrated the implementation of Scully-Drühl-type delayed-choice quantum erasers on IBM Quantum and IonQ processors. Their quantum circuit approach offers several advantages over traditional optical experiments: it facilitates arbitrary adjustment of the erasure parameters, enables true random choice in a genuine delayed-choice manner, and allows the use of delay gates to further defer the random choice, thereby amplifying retrocausal effects for investigation.

Remarkably, these experiments achieved quantum erasure with delay times up to approximately 1 microsecond without noticeable decoherence—a feat challenging to replicate in optical setups (Chen et al., 2025). Because gate operations are executed sequentially in time, the system has no involvement of random choice until after the signal qubit has been measured, eliminating potential philosophical loopholes regarding retrocausality that might exist in other experimental configurations.

The significance for Ze testing lies in what these platforms enable: direct access to the internal correlation structure of quantum processes. Unlike optical experiments that measure only final interference patterns, quantum computers allow examination of intermediate states and the statistics of correlation establishment. Chiou and Hsu (2024) extended this approach by investigating complementarity relations in delayed-choice quantum erasers implemented on IBM Quantum platforms, exploring how the degree of entanglement between paired quantons affects visibility-distinguishability relations from multiple perspectives.

Correlation Counter Statistics

The Ze experimental protocol for quantum systems proposes a shift in measurement strategy. Instead of measuring the final interference pattern alone, the experiment would track the statistics of correlation counter updates throughout the quantum process. This requires access to the internal dynamics of the quantum system—precisely what quantum simulators and computers provide.

Araújo et al. (2025) developed programmable photonic circuits capable of simulating quantum channels, including phase-damping, amplitude-damping, and bit-flip channels, through adjustable interferometric parameters. By encoding qubits in photon paths and using polarization as an auxiliary degree of freedom, their platform enables precise control over system-environment interactions. This capability allows systematic investigation of how different correlation architectures—sequential versus parallel dominant—affect the effective update count τ that the Ze framework identifies with proper time.

The key prediction concerns the relationship between interference visibility and update statistics. In standard quantum mechanics, interference visibility V and which-path distinguishability D satisfy complementarity relations such as $V^2 + D^2 \leq 1$. The Ze framework proposes that both quantities are manifestations of a deeper variable: the distribution of updates

between parallel and sequential channels. For a two-path interferometer, the ratio of parallel to sequential updates should determine both the observable interference pattern and the effective proper time accumulation.

Quantum Zeno: Collapse as Mode Switching

The quantum Zeno effect provides a particularly direct test of the Ze interpretation of collapse. In the quantum Zeno effect, frequent measurements inhibit the evolution of a quantum system, effectively "freezing" it in its initial state. The standard explanation invokes the projection postulate: each measurement collapses the wavefunction, restarting the evolution. The Ze framework offers an alternative: collapse corresponds to a switch from parallel to sequential update mode, and frequent measurements enforce sequential processing, reducing the effective update count.

Recent experiments on NISQ devices have observed the quantum Zeno effect in both Rabi evolution and free decay scenarios. Alessandrini, Ciaramelletti, and Paganelli (2024) implemented repeated measurements on single qubits using IBM Quantum Experience devices, demonstrating increasing survival probability with the number of intermediate measurements. Their implementation used CNOT gates and ancillary qubits to emulate projective measurements without irreversible collapse—precisely the kind of controlled environment where update statistics can be tracked.

Franceschetto et al. (2025) extended this line of investigation by using the quantum Zeno effect as a tool for Hamiltonian learning. Their protocol applies frequent unitary kicks to localize system dynamics, effectively reshaping the Hamiltonian by suppressing unwanted interactions. This work demonstrates that the Zeno effect can be understood and employed in purely unitary terms, without invoking wavefunction collapse—aligning naturally with the Ze framework's emphasis on update modes rather than ontological collapse.

The critical measurement for Ze testing involves comparing the number of effective updates τ under different measurement regimes. For a fixed external evolution time, increasing measurement frequency should decrease τ according to the Ze prediction, with the functional form depending on the correlation structure of the measurement apparatus. This can be tested directly on quantum computers by tracking the internal state evolution between measurements.

Proposed Quantum Experiment

Building on these capabilities, we propose a specific quantum experimental protocol:

1. **System preparation:** Initialize a qubit in a superposition state on a programmable quantum platform (IBM Quantum, IonQ, or similar).
2. **Correlation mode control:** Implement two variants of the evolution:
 - *Parallel mode:* Allow unitary evolution with minimal intervention, maximizing parallel channel distribution

- *Sequential mode*: Insert frequent "measurement" operations (implemented via CNOT with ancillas) to enforce sequential update processing
3. **Update counting**: For each mode, track the effective number of internal transitions by either:
 - Direct state tomography at intermediate times
 - Weak measurement techniques that minimally disturb the evolution
 - Analysis of the entanglement structure between system and ancilla qubits
 4. **Correlation measurement**: Determine the proportion v of parallel correlations in each mode by analyzing the quantum channel's Kraus operator representation, following techniques developed by Araújo et al. (2025).
 5. **Prediction test**: Compare the ratio $\tau_{\text{parallel}}/\tau_{\text{sequential}}$ with $\sqrt{(1-v^2)}$ derived from the measured correlation proportion.

The extraordinary stability and programmability of current quantum platforms make this experiment feasible. Chen et al. (2025) demonstrated microsecond-scale coherence times sufficient for complex multi-gate operations. The ability to implement true delayed choice via delay gates on IBM Quantum platforms provides access to the temporal structure of correlation establishment.

Distinguishing Predictions

The Ze framework's predictions diverge from standard quantum mechanics in several testable ways:

1. **Update-rate dependence**: Standard quantum mechanics predicts that interference visibility depends on which-path information, but makes no prediction about internal update counts. Ze predicts that systems with identical final interference patterns can differ in their accumulated proper time τ if their internal correlation structures differ during evolution.
2. **Complexity effects**: Following the logic of Section 2, systems with different internal complexity should show different τ for identical external conditions, even when quantum predictions for measurement outcomes are identical.
3. **Zeno regime scaling**: The standard quantum Zeno effect predicts survival probability $P \approx 1 - (N)(t/N)^2$ for N measurements. Ze predicts that the effective time experienced by the system scales differently, with τ/N following a system-specific function of the measurement interval.

These predictions can be tested by combining the capabilities of quantum computers for precise state control with the measurement protocols developed for testing time dilation in physical

clocks (Section 2). The quantum platform serves as both the system under study and the measurement apparatus—a self-consistency check unique to the Ze approach.

Ontological Implications

If confirmed, the Ze interpretation would offer a unified ontology for quantum phenomena and relativistic effects. Interference and entanglement would be understood as manifestations of parallel update distribution; collapse and decoherence as transitions to sequential processing; and time dilation as the cumulative effect of update deficits arising from sequential correlation structure.

This perspective aligns with information-theoretic interpretations of quantum mechanics while offering a concrete dynamical mechanism—update counting—that bridges quantum and relativistic domains. The experiments proposed here, building on existing quantum computing platforms, provide a pathway to test this unification empirically.

Indirect Confirmation: The Convergence of Independent Structures

A criterion often underappreciated in empirical science is the power of structural convergence. When multiple independent theoretical frameworks, each developed from distinct starting assumptions and methodologies, converge upon identical or closely related mathematical structures, this convergence itself constitutes powerful evidence for the physical relevance of those structures. The Ze approach finds strong indirect support through precisely such convergence: its core postulates independently generate—or find deep resonance with—the Minkowski metric, time dilation, the twin effect, causal set structure, and twistor-like representations.

Emergence of Minkowski Spacetime

The first pillar of structural convergence concerns the emergence of Minkowski spacetime from discrete causal principles. D'Ariano and Tosini (2013) demonstrated that Minkowski spacetime can emerge from a topologically homogeneous causal network representing classical information flow. Their key insight is that the metric can be derived from pure event-counting when the network satisfies topological homogeneity—a requirement that ensures spacetime metric emerges from the pure topology of causal connections, while physical homogeneity corresponds to the universality of physical law.

In their analysis of the 1+1 dimensional case, causal connections are treated as exchanges of classical information. Coordinate systems can be established via an Einsteinian protocol, leading to a digital version of the Lorentz transformations. The computational analogy is striking: foliation construction corresponds to synchronization with a global clock of calls to independent subroutines in parallel distributed computation. Lorentz time dilation emerges as an increased

density of "leaves" within a single tick of a clock, while space contraction results from the corresponding decrease in density of events per leaf (D'Ariano & Tosini, 2013).

This framework aligns precisely with Ze postulate P1 (proper time proportional to effective updates) and P4 (Minkowski-type invariance emerging statistically from counter dynamics). The operational procedure of building coordinate systems introduces an in-principle indistinguishability between neighboring events, resulting in a coarse-grained network where event thickness depends on the observer's clock—a direct analog of the Ze update counting mechanism.

Extending this work, Leuenberger (2022) addressed the open problem of how a graph representing (3+1)-dimensional Minkowski spacetime could be generated solely from simple deterministic rules. By describing rules that characterize discrete Lorentz boosts between 4D lattice graphs, which combine to form Wigner rotations, his construction produces isotropy and leads to the emergence of the continuous Lorentz group. On such graphs, the speed of light, proper time interval, and proper length all emerge with high accuracy. This demonstrates that the full structure of relativistic kinematics—including the twin effect—can arise from purely combinatorial rules operating on discrete causal networks.

Causal Set Theory and Lorentz Invariance

The causal set program provides another independent line of structural convergence. Dowker (2011) addressed the fundamental question of whether spacetime discreteness can coexist with Lorentz invariance. Contrary to frequent assumptions, a causal set's discreteness is locally Lorentz invariant, precisely because the causal set is a locally finite set of elements endowed with a partial order corresponding to the macroscopic relation defining past and future.

Dowker, Henson, and Sorkin (2004) further demonstrated that fundamental spacetime discreteness need not contradict Lorentz invariance, introducing phenomenological models of massive particles propagating in Minkowski spacetime arising from an underlying causal set. These particles undergo Lorentz invariant diffusion in phase space, illustrating how discrete causal structure can yield continuous Lorentz symmetry at the phenomenological level.

The connection to Ze postulates is direct. Causal set theory treats events as fundamental, with proper time emerging from the counting of causal relations—exactly the update counting proposed in Ze. The partial order structure corresponds to the causal chain whose reconfiguration, under acceleration, produces differential aging in the twin paradox. Dowker's (2011) observation that Lorentz symmetry can be compatible with atomicity only at the price of locality resonates with Ze's claim that time dilation arises from update deficits rather than geometric effects.

Twistor Theory and Its Extensions

Twistor theory, originating with Penrose (1999), offers perhaps the most sophisticated mathematical realization of principles akin to Ze. The central programme of twistor theory takes

entire light rays (null geodesics) as more primitive than spacetime points—events are derived, not fundamental. This inversion mirrors Ze postulate P2: motion as redistribution of events between sequential and parallel channels, with light-like structure encoding parallel correlation geometry.

In twistor theory, a spacetime point emerges as a secondary construct derived from twistors—the more primitive elements representing entire light rays or idealized photon histories. The incidence relation connecting twistors to spacetime points encodes the geometry of null separation. For a massless particle, twistor quantization yields commutation rules that reproduce the correct momentum and angular momentum operators (Penrose, 1999).

The non-linear graviton construction extended twistor methods to curved spacetime, bringing together basic features of quantum mechanics and general relativity. This was followed by Ward's construction for gauge fields, expressing Maxwell's electromagnetism and Yang-Mills equations in twistor terms (Penrose, 2014). However, these constructions were limited to anti-self-dual (or self-dual) conformal curvature—a restriction that, for Lorentzian signature, confines applicability to conformally flat spacetimes.

Recent developments in "palatial twistor theory" (Penrose, 2014) appear to surmount this barrier, suggesting that the full structure of general relativity may admit twistor description. This progression mirrors the Ze research programme: beginning with flat spacetime kinematics, then seeking the dynamical principles that generate curved geometry from update statistics.

The SIGMA special issue on Progress in Twistor Theory (Eastwood, LeBrun, & Mason, 2014) collects numerous articles demonstrating the depth of twistor methods across integrable systems, differential geometry, and scattering amplitude calculations. The fact that twistor structures continue to find new applications—both in pure mathematics and in high-energy physics—testifies to their fundamental character.

Structural Convergence as Evidence

The convergence among these frameworks is not superficial. Consider the parallels:

1. **Primacy of events:** Causal set theory, Ze, and twistor theory all treat events (or their analogs) as more fundamental than spacetime points. D'Ariano and Tosini (2013) derive metric from pure event-counting; causal sets are locally finite event sets with causal relations; twistor theory treats light rays (event histories) as primitive.
2. **Update counting as time:** Ze identifies proper time with effective updates. D'Ariano and Tosini (2013) show Lorentz time dilation emerges as increased density of "leaves" within a single clock tick. Causal set theory calculates proper time as the number of relations along a chain.
3. **Emergent Lorentz symmetry:** Leuenberger (2022) demonstrates emergence of continuous Lorentz group from discrete combinatorial rules. Dowker et al. (2004) show

causal set discreteness is locally Lorentz invariant. Twistor theory encodes massless particles and their symmetries in complex geometry.

4. **Information-theoretic foundation:** Each framework treats spacetime structure as arising from informational or combinatorial primitives. D'Ariano and Tosini (2013) explicitly invoke computational analogies; Ze builds on information processing; twistor theory seeks to unify quantum mechanics and spacetime geometry through non-local descriptions.

This convergence constitutes what might be called "structural empirical evidence"—a form of confirmation that has played crucial roles in fundamental physics. The development of general relativity was supported by its convergence with Riemannian geometry; quantum mechanics found confirmation through its convergence with Hilbert space mathematics; string theory's various dualities provide internal structural consistency arguments. While such convergence does not replace direct experimental test, it elevates the plausibility of frameworks that independently generate the same mathematical structures from distinct starting points.

Implications for the Ze Programme

The structural convergence documented here provides indirect confirmation for the Ze postulates in two ways. First, it demonstrates that the key ideas of Ze—event primacy, update counting as time, emergence of relativistic kinematics from combinatorial rules—are not isolated speculations but resonate with established research programmes in causal set theory and twistor theory. Second, it suggests that the specific functional form $\tau_B/\tau_A = \sqrt{(1-v^2)}$ predicted by Ze is not arbitrary but reflects deep mathematical structures (Lorentz group representations, causal set counting, twistor incidence relations) that have proven their physical relevance across multiple domains.

The experimental programme outlined in Sections 1-4 thus rests on a foundation broader than Ze itself. If the digital experiment, the clock comparison experiment, the non-inertial experiment, and the quantum experiments all yield positive results, they will not merely confirm Ze but will also provide empirical support for the entire family of approaches that treat events and their relations as fundamental. Conversely, if Ze predictions fail, the structural convergence among these frameworks would be challenged, forcing a re-examination of the connections among causal set theory, twistor theory, and information-based approaches to spacetime.

This interdependence is as it should be. Fundamental physics advances not through isolated hypotheses but through the gradual convergence of independent lines of evidence—both empirical and structural—toward a unified understanding. The Ze experiment, by testing predictions that emerge from this convergence, participates in the larger project of determining whether spacetime, time, and motion are indeed emergent properties of information processing.

What Does Not Need to Be Proven

In any scientific endeavor that proposes a novel theoretical framework, it is essential to delineate clearly what the theory claims and, equally important, what it does not claim. The Ze approach to time and information processing is sometimes misunderstood as challenging the empirical validity of special relativity or denying the reality of spacetime. Such interpretations miss the point entirely. The relationship between Ze and special relativity is not one of replacement or refutation, but of emergence and foundation.

The Effective Theory Perspective

Modern theoretical physics has increasingly come to understand that our most successful theories are often effective field theories—descriptions valid within a limited domain, arising from deeper underlying structures. As Cao (1997) has documented, the conceptual development of twentieth-century field theories reveals a pattern wherein theories initially regarded as fundamental later come to be understood as emergent from deeper principles. General relativity itself, despite its extraordinary empirical success, is now widely recognized as an effective field theory with a limited domain of validity, undergoing breakdown of fundamental symmetry in strong fields and exhibiting only one-loop finiteness in perturbative expansion (Chishtie, 2025).

The treatment of General Relativity as an effective field theory provides crucial context for understanding the Ze programme. In four dimensions, gravity has a dimensional coupling $\kappa^2 = 16\pi G_N$, suggesting that higher-order loop corrections become untenable above a certain cutoff Λ (Chishtie, 2025). The one-loop effective action takes the form:

$$\Gamma_{\text{eff}} = \int d^4x \sqrt{-g} [R/(16\pi G) + \alpha R^2 \ln(\mu/\Lambda) + \beta R_{\mu\nu} R^{\mu\nu} \ln(\mu/\Lambda) + \dots]$$

where α and β are dimensionless coefficients determined by one-loop calculations. The appearance of logarithmic terms signals the approach to the boundary of the effective theory's domain of validity. Large values of $\ln(\mu/\Lambda)$ mark pushing the theory beyond its EFT domain, reinforcing that GR, under this prescription, cannot be extended arbitrarily in energy (Chishtie, 2025).

This perspective does not render GR "wrong" any more than Newtonian gravity was rendered "wrong" by Einstein's theory. Rather, it situates GR as a limiting case of a more comprehensive framework—precisely the relationship that Ze proposes with respect to special relativity.

What Ze Does Not Claim

First, Ze does not claim to be "better" than special relativity. Special relativity is an extraordinarily successful theory, confirmed by countless experiments from particle accelerators to GPS satellites. The Lorentz-Poincaré group of transformations, satisfying $\eta_{\alpha\beta} \Lambda^{\alpha}_{\mu} \Lambda^{\beta}_{\nu} = \eta_{\mu\nu}$, provides the kinematic structure that has proven universally valid across all fundamental interactions except gravitation (Minazzoli, 2015). The Ze framework does not propose to replace this structure but to explain its origin.

Second, Ze does not claim that special relativity is "incorrect." The empirical adequacy of special relativity is not in question. What Ze offers is a deeper explanatory layer—an account of why relativistic kinematics take the form they do, grounded in information-theoretic principles rather than geometric postulates. As D'Ariano and Tosini (2013) demonstrated in their work on causal networks, Minkowski spacetime can emerge from topologically homogeneous causal networks where the metric is derived from pure event-counting. The Lorentz transformations in this framework acquire a digital form, and time dilation emerges as an increased density of "leaves" within a single tick of a clock. This is not a refutation of relativity but a derivation of it from more primitive elements.

Third, Ze does not claim that spacetime "does not exist." The ontological status of spacetime is a subtle question that has occupied philosophers and physicists for decades. As Nerlich (1994) observes in discussing the causal structure approach to spacetime, the fact that the full metric structure can be built from causality relations does not constitute a reductive victory that dethrones spacetime geometry from its explanatory status. Rather, it reveals that spacetime and causality are deeply interwoven. The Ze framework aligns with this nuanced view: spacetime is real and empirically adequate as an effective description, but it is not the most fundamental level of reality.

The Emergence Paradigm

The concept of emergence is central to understanding the Ze programme's relationship to special relativity. Jizba and Scardigli (2013) have demonstrated that Einstein's special relativity might well be an emergent concept in the quantum realm, arising from deeper statistical processes. Their work shows that the combination of special relativity and quantum-mechanical dynamics is mathematically identical to a complex dynamical system described by two interlocked processes operating at different energy scales. The combined dynamic obeys Einstein's special relativity even though neither of the two underlying dynamics does individually (Jizba & Scardigli, 2013).

This emergence paradigm finds resonance across multiple research programmes. Chishtie (2025) introduces the Principle of Spatial Energy Potentiality, wherein both time and gravity emerge from purely spatial, high-energy configurations through quantum-induced phase transitions. Brandt et al. (cited in Chishtie, 2025) demonstrate that, in a perturbative expansion around a background field, one can impose the classical Einstein equations via a Lagrange multiplier field in the path integral, thereby removing higher-loop graviton diagrams and restricting quantum-gravity effects to one loop. This leads to a finite one-loop effective action with a characteristic renormalization logarithm $\ln(\mu/\Lambda)$, exemplifying that 4D GR can be treated as an effective field theory under these conditions.

The chronon field theory developed by recent authors (2025) offers another example: conventional spacetime geometry and gauge interactions emerge from a single dynamical temporal field, eliminating the need for a fundamental spacetime manifold. In this framework, a smooth, unit-norm, future-directed timelike vector field Φ^μ generates local causal structure, effective spacetime geometry, and emergent gauge interactions without reliance on a

background metric. The theory yields Einstein-like gravitational dynamics, with the effective metric and connection derived from the foliation induced by Φ^μ (Emergent Gravity and Gauge Interactions, 2025).

What Ze Does Claim

The positive claim of the Ze programme is precisely this: special relativity arises as an effective theory from the deeper dynamics of information processing. The four postulates articulated in Section 1—that proper time is proportional to effective updates, that motion corresponds to redistribution of events between sequential and parallel channels, that time dilation arises as an update deficit, and that Minkowski-type invariance emerges statistically from counter dynamics—collectively propose a mechanism by which relativistic kinematics can be derived from informational primitives.

This claim is empirically testable through the experiments described in previous sections. The digital experiment comparing update counts in sequential versus parallel processors, the physical clock experiments comparing internal transition counts across systems with different complexity, the non-inertial experiments probing correlation structure independent of velocity, and the quantum experiments examining update statistics in controlled quantum systems—all these provide opportunities to confirm or falsify the Ze framework.

Crucially, confirmation of Ze predictions would not contradict special relativity. It would, rather, explain why special relativity holds. The Lorentz factor $\gamma = 1/\sqrt{1-v^2/c^2}$ would be understood not as a brute geometric fact but as the necessary expression of constraints on information processing. The invariant interval $ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu$ would be recognized as a statistical regularity emerging from the dynamics of event counting. The twin paradox would be resolved not by appealing to acceleration as a geometric marker but by understanding how acceleration reconfigures causal structure and thereby affects update accumulation.

The Virtue of Theoretical Pluralism

The history of physics teaches that progress often comes not from insisting that one theory must replace another, but from understanding the relationships between theories at different levels of description. Newtonian mechanics was not "wrong" because quantum mechanics emerged; it was revealed as the effective description of macroscopic phenomena. Thermodynamics was not "wrong" because statistical mechanics explained it; it was recognized as the emergent behavior of microscopic constituents. In each case, the deeper theory did not refute the shallower one but explained its domain of validity and origin.

The Ze programme adopts this constructive stance toward special relativity. It seeks not to dethrone Einstein's theory but to ground it in something more fundamental—the logic of information processing itself. If successful, it would unify our understanding of relativity with the growing recognition that information-theoretic principles may underlie fundamental physics. It would connect the Lorentz transformations to the mathematics of causal networks (D'Ariano &

Tosini, 2013), the twin paradox to the dynamics of event counting (Dowker, 2011), and the metric structure of spacetime to the statistics of updates (Leuenberger, 2022).

This is the sense in which Ze aims to show that special relativity "arises as an effective theory." The goal is not replacement but foundation; not refutation but explanation; not denial of spacetime's reality but understanding of its origin. The experiments proposed in this paper are designed to test whether this explanatory project succeeds—whether, indeed, the functional form $\tau_B/\tau_A = \sqrt{1-v^2}$ emerges from pure information dynamics, and whether the rich structure of relativistic physics can be derived from the simple act of counting updates.

Experimental Falsifiability of Ze

The scientific status of any theoretical framework rests ultimately on its falsifiability—the specification of empirical conditions under which the theory would be refuted. The Ze framework, despite its departure from conventional geometric interpretations of relativity, makes concrete and testable predictions at the level of event statistics. This section articulates those predictions, describes the experimental protocols required to test them, and specifies the conditions under which the Ze postulates would be empirically falsified.

Core Falsifiable Prediction

The central prediction of the Ze framework concerns the relationship between proper time accumulation and the statistics of internal updates. According to postulate P1, proper time τ is proportional to the number of effective state updates rather than to any external coordinate time parameter. For two systems processing identical input streams but operating in different correlation modes, the Ze framework predicts:

$$\tau_B/\tau_A = \sqrt{1 - v^2}$$

where τ_A and τ_B are the effective update counts in maximally sequential and maximally parallel modes respectively, and v represents the proportion of parallel correlations in the processing architecture. This functional form is mathematically identical to the Lorentz factor of special relativity, but its origin lies in information dynamics rather than spacetime geometry.

The falsifiability condition is straightforward: if, for any two systems with identical input streams and well-characterized correlation proportions v , the ratio τ_B/τ_A deviates systematically from $\sqrt{1 - v^2}$, the Ze postulates are empirically refuted. The framework offers no adjustable parameters to absorb such deviations; the prediction is quantitative and precise.

Controlled Information-Processing Tests

The most direct test of Ze predictions employs controlled information-processing systems, as outlined in Section 1. These are not simulations of physical systems but physical experiments conducted on actual information processors. The experimental architecture requires:

1. **Identical input streams:** Both processors receive precisely the same sequence of input events, ensuring that any difference in output statistics arises from internal processing architecture rather than input variation.
2. **Well-characterized correlation modes:** Processor A operates in maximally sequential mode, processing events one after another with minimal parallel correlation. Processor B operates in maximally parallel mode, distributing events across parallel channels to maximize simultaneous processing. The proportion v of parallel correlations must be independently measurable from the processor's architecture and operational parameters.
3. **Precise update counting:** The number of effective counter updates τ must be measured directly, not inferred from external clock rates. This requires access to the internal state transition dynamics of each processor.
4. **Statistical power:** Sufficient trials to distinguish the predicted $\sqrt{(1 - v^2)}$ scaling from alternative functional forms or from the null hypothesis of no mode dependence ($\tau_B/\tau_A = 1$).

If these conditions are met and the measured ratio deviates from the predicted form, the Ze framework is falsified. No appeal to "emergent geometry" or "effective descriptions" can rescue the theory if the fundamental update statistics fail to conform to the predicted relationship.

Physical Clock Comparisons

Beyond digital information processors, the Ze framework makes falsifiable predictions for physical clocks with internal complexity variations. As developed in Section 2, systems with different internal complexity—single-ion clocks, molecular clocks, optical lattice clocks—subjected to identical relativistic conditions should accumulate different numbers of internal transitions over fixed external intervals, even if their conventional clock rates appear identical.

The falsification condition here is: if two clock systems with demonstrably different internal complexity, moving identically (identical γ factors), accumulate the same number of internal transitions N_{int} over a fixed external interval, the Ze prediction of complexity-dependent update counting is refuted. Conversely, if the transition counts differ but follow a pattern unrelated to the predicted $\sqrt{(1 - v^2)}$ scaling derived from measured correlation proportions, the specific functional form is falsified even if the general principle of update counting survives.

This experimental protocol connects directly to ongoing research on quantum clocks and time dilation. Recent work on relational emergent time has demonstrated that temporal structure can arise from correlations within a globally stationary state, with each subsystem possessing its own internal clock and evolving according to conditional states defined by internal readings (Ghasemi, 2025) . This framework reproduces classical time dilation and predicts deviations from standard evolution dependent on the strength of quantum entanglement—predictions that can be tested against Ze's update-counting hypothesis. Similarly, research on quantum clocks

has established that proper time can be treated as a covariant positive operator-valued measure (POVM) on the internal degrees of relativistic particles, with the Helstrom-Holevo lower bound yielding a fundamental proper time-energy/mass uncertainty relation $\Delta M_{\text{clock}} \Delta T_{\text{clock}} \geq 1/(2c^2)$ (Smith & Ahmadi, 2020) . These developments provide the mathematical and experimental tools necessary to test Ze predictions at the quantum level.

Non-Inertial Tests

The non-inertial experiments described in Section 3 provide another falsification opportunity. The Ze claim that acceleration corresponds to reconfiguration of causal structure—a change in the distribution of events between sequential and parallel channels—implies that systems undergoing identical spacetime trajectories but different internal correlation modulations should accumulate different proper times.

The falsification condition: if two systems following identical worldlines with zero net displacement, one subjected to periodic correlation modulation and the other maintaining constant correlation structure, accumulate identical proper times upon reunion, the Ze prediction is refuted. The framework offers no alternative mechanism by which correlation structure could affect proper time accumulation without leaving a detectable signature in update statistics.

This prediction connects to foundational work on causal set theory, where spacetime discreteness has been shown to be locally Lorentz invariant precisely because the causal set is a locally finite set of elements endowed with a partial order corresponding to the macroscopic relation defining past and future (Dowker, 2011). The causal set approach treats events as fundamental, with proper time emerging from the counting of causal relations—exactly the update counting proposed in Ze. If experiments reveal that proper time is path-independent even when causal structure is modulated, both causal set theory and Ze would face empirical challenges.

Quantum Domain Tests

The quantum experiments outlined in Section 4 offer perhaps the most precise testing ground. Programmable quantum computers now enable direct manipulation of correlation structures and measurement of internal update statistics. The Ze prediction that interference visibility correlates with update distribution between parallel and sequential channels, and that the quantum Zeno effect corresponds to mode switching with measurable update deficits, can be tested on existing platforms.

The falsification condition: if, for a fixed external evolution time, increasing measurement frequency does not produce the predicted decrease in effective updates τ following the $\sqrt{1 - v^2}$ relation derived from independently measured correlation proportions, the Ze framework is falsified. Alternatively, if systems with identical final interference patterns but different internal correlation structures show identical accumulated proper times, the claim that proper time depends on update statistics rather than external parameters is refuted.

Recent experiments on IBM Quantum and IonQ processors have demonstrated the feasibility of implementing delayed-choice quantum erasers with microsecond-scale coherence times (Chen, Chiou, & Hsu, 2025). These platforms enable true random choice in a genuine delayed-choice manner, with delay gates deferring random choice until after signal qubit measurement—eliminating philosophical loopholes regarding retrocausality. Such capabilities provide precisely the controlled environment required to test Ze predictions against standard quantum mechanical expectations.

Comparison with Relativistic Scaling Laws

A critical aspect of Ze falsifiability is the comparison with standard relativistic predictions. Special relativity predicts that proper time along a worldline is given by $\tau = \int d\tau = \int \sqrt{1 - v^2/c^2} dt$, independent of any internal details of the clock. The Ze framework does not dispute this as an effective description but proposes that it emerges from a deeper update-counting dynamics.

The distinguishing prediction is that systems with identical worldlines but different internal complexity should, according to Ze, accumulate different update counts even while their conventional clock rates remain identical. Special relativity predicts no such difference. Therefore, a null result—no complexity-dependent variation in update counts—would falsify Ze while leaving special relativity unchanged. Conversely, positive results showing complexity-dependent update counting would require reinterpretation of relativistic phenomena while leaving the empirical predictions of special relativity intact as an effective description.

This asymmetric falsifiability is characteristic of theories that propose deeper explanatory layers beneath well-confirmed effective theories. Just as statistical mechanics did not falsify thermodynamics but explained its origin, Ze does not seek to falsify special relativity but to ground it. The falsification criteria address the deeper layer: if update counting fails to follow the predicted scaling, the Ze explanation for relativity's origin fails, even though relativity itself remains empirically adequate.

Summary of Falsification Conditions

The Ze framework can be empirically refuted by any of the following observations:

1. **Digital processor test:** $\tau_B/\tau_A \neq \sqrt{1 - v^2}$ for any well-characterized sequential and parallel processors with identical input streams and measurable correlation proportion v .
2. **Physical clock test:** Equal internal transition counts N_{int} for systems with different internal complexity moving identically (identical γ factors), or transition counts that deviate from $\sqrt{1 - v^2}$ scaling with measured correlation proportions.
3. **Non-inertial test:** Equal proper time accumulation for systems following identical worldlines with and without internal correlation modulation.
4. **Quantum test:** For fixed external evolution time, effective update counts τ that do not scale with measurement frequency according to $\sqrt{1 - v^2}$, or identical proper times for

systems with different internal correlation structures but identical final interference patterns.

5. **Statistical emergence test:** Failure of Minkowski-type invariance to emerge from counter dynamics in sufficiently large information-processing systems, as tested by the protocols of Section 1.

Each of these conditions is experimentally accessible with current or near-future technology. The precision required varies across tests, but the fundamental logic is clear: the Ze framework makes quantitative predictions that can be confirmed or refuted through controlled experimentation. This empirical vulnerability is the hallmark of scientific seriousness and distinguishes Ze from purely metaphysical speculation about the nature of time.

Honestly: What Constitutes the Strongest Evidence

In any scientific investigation, it is essential to distinguish between what would constitute compelling evidence and what would merely be suggestive. The Ze framework, despite its ambitious scope and foundational implications, can be evaluated against a clear and achievable evidentiary standard. This section honestly assesses what would constitute the strongest possible evidence for the Ze postulates, distinguishing between essential confirmations and auxiliary desiderata.

The Digital Ze-Experiment with Relativistic Curve

The single most powerful piece of evidence for the Ze framework would be successful confirmation of its core prediction in the digital experiment described in Section 1. This experiment possesses several features that make it uniquely compelling:

1. **Purity of test:** The experiment involves no assumptions about physical particles, fields, or spacetime geometry. It operates entirely on information processes—identical input streams processed by identical Ze-type processors operating in different correlation modes. If the predicted relationship $\tau_B/\tau_A = \sqrt{1 - v^2}$ emerges from this purely informational setup, it demonstrates that relativistic kinematics can arise from information dynamics alone.
2. **Quantitative precision:** The prediction is not merely qualitative but takes a specific functional form identical to the Lorentz factor of special relativity. Agreement with this curve over a range of v values would constitute strong evidence that the mathematical structure of relativity is not unique to physics but reflects universal constraints on information processing.
3. **Elimination of alternatives:** Success in the digital experiment would rule out explanations that attribute relativistic kinematics solely to properties of physical spacetime. If the same functional form emerges from information processors that make no reference to spacetime geometry, then spacetime cannot be the unique origin of that form.

4. **Experimental simplicity:** Unlike particle accelerator experiments requiring massive infrastructure, the digital Ze experiment can be implemented on existing computational hardware. This accessibility enables rapid testing, replication, and extension.

The importance of this experiment cannot be overstated. It directly tests the Ze postulates at their most fundamental level—the level of event counting and correlation distribution. If the relativistic curve emerges here, it provides a foundation for all further investigations. If it does not, the framework is falsified regardless of any other considerations.

Independent Replication by Other Groups

Scientific knowledge is social knowledge. No single experiment, however elegant, establishes a result as scientifically accepted until it has been independently replicated by other research groups working with different apparatus, different methodologies, and different assumptions. The history of science is replete with striking experimental results that could not be reproduced, from cold fusion to faster-than-light neutrinos.

For the Ze framework, independent replication carries special weight because the digital experiment is straightforward to implement. Any research group with access to standard computing hardware and basic programming capability can construct the two processor architectures, generate identical input streams, and measure update counts. The prediction is quantitative and unambiguous; either the relativistic curve emerges or it does not.

Replication by multiple groups would accomplish several objectives:

- **Elimination of experimental artifacts:** Different implementations may reveal hidden dependencies on specific programming languages, hardware architectures, or data structures. If the effect survives across diverse implementations, confidence in its robustness increases.
- **Demonstration of intersubjectivity:** Scientific claims must be verifiable by any competent investigator. Replication demonstrates that the Ze effect is not dependent on the peculiarities of a single laboratory or researcher.
- **Extension to new regimes:** Different groups may explore parameter ranges not examined in the original experiment—higher v values, different input stream statistics, alternative processor architectures—revealing the full domain of validity of the Ze predictions.

The requirement of independent replication is not skepticism for its own sake but the mechanism by which science self-corrects and establishes reliable knowledge. For a framework as foundational as Ze, this social process of validation is essential before broader implications can be seriously considered.

Coincidence with Special Relativity Without Postulating Special Relativity

Perhaps the most philosophically significant form of evidence would be the emergence of special relativity's mathematical structure from Ze postulates that make no reference to relativity whatsoever. The Ze postulates as stated in Section 1—proper time proportional to effective updates, motion as redistribution of events, time dilation as update deficit, statistical emergence of Minkowski invariance—contain no mention of Lorentz transformations, invariant intervals, or the speed of light. These are derived consequences, not assumed principles.

If the digital experiment yields $\tau_B/\tau_A = \sqrt{1 - v^2}$, this constitutes derivation of the Lorentz factor from informational principles. If further analysis shows that the statistics of event distributions satisfy an invariant interval relation, this would demonstrate emergence of Minkowski structure from pure update counting. And if the causal structure of the processor networks reproduces the relativistic light cone, this would show that the causal structure of relativity emerges from correlation architecture.

This form of evidence—coincidence with an established theory without postulating that theory—is among the strongest in theoretical physics. It demonstrates that the established theory is not arbitrary but necessary, not conventional but inevitable, given deeper principles. The derivation of thermodynamics from statistical mechanics, the derivation of Newtonian gravity from general relativity in the weak-field limit, the derivation of classical mechanics from quantum mechanics in the $\hbar \rightarrow 0$ limit—these are the success stories that validate the deeper theory.

For Ze, the goal is analogous: to show that special relativity is not a brute fact about the world but a necessary consequence of how information processes unfold. Achieving this derivation without ever assuming relativity would constitute the strongest possible evidence that the Ze framework captures something fundamental about the nature of time and motion.

Sufficiency for Scientific Discussion

A crucial question is what level of evidence would justify moving beyond speculative discussion to serious scientific engagement. The position advocated here is that the three forms of evidence described above—successful digital experiment, independent replication, and derivation of relativity without assuming it—are collectively sufficient to:

Begin discussion: With positive results from the digital experiment, the Ze framework becomes a legitimate topic for scientific seminars, conference presentations, and journal publications. Physicists should be aware of the results and consider their implications.

Attract physicists rather than philosophers: The digital experiment transforms Ze from a philosophical speculation about time into an empirically testable—and tested—scientific hypothesis. Physicists, whose training emphasizes empirical validation, will take notice when a purely informational system reproduces relativistic kinematics.

Continue experimenting: Success at the digital level justifies investment in more sophisticated experiments—the physical clock comparisons of Section 2, the non-inertial tests of Section 3, the quantum investigations of Section 4. Each subsequent experiment tests the framework in new domains and refines our understanding of its domain of validity.

What this level of evidence does not justify is the claim that Ze has been "proved" or that special relativity has been "overturned." Such claims would be premature and would misunderstand the relationship between emergent and effective theories. The proper stance is one of constructive investigation: we have found that information processors can reproduce relativistic kinematics; let us now explore how far this analogy extends and what it reveals about the nature of time.

The Role of Theoretical Coherence

Beyond empirical evidence, the Ze framework gains strength from its theoretical coherence with other research programmes. As argued in Section 5, the structural convergence among Ze, causal set theory, twistor theory, and emergent spacetime frameworks provides indirect support. When multiple independent lines of inquiry converge on similar mathematical structures, confidence in those structures increases.

This convergence serves as a guide for further experimentation. The causal set prediction that proper time emerges from counting causal relations (Dowker, 2011), the twistor program's treatment of light rays as more fundamental than events (Penrose, 1999), and the demonstration that Minkowski spacetime can emerge from topologically homogeneous causal networks (D'Ariano & Tosini, 2013)—all these reinforce the plausibility of Ze and suggest that experiments testing Ze also test broader class of foundational approaches.

What Would Not Constitute Strong Evidence

To maintain scientific honesty, it is equally important to specify what would not constitute strong evidence for Ze:

- **Philosophical arguments alone:** No amount of reasoning about the nature of time, however elegant, can substitute for empirical confirmation. Ze must stand or fall on experimental results.
- **Single unreplicated experiment:** A single positive result, however striking, requires independent confirmation before it can be accepted as establishing a phenomenon.
- **Qualitative agreement:** The Ze predictions are quantitative. Vague qualitative agreement with expectations does not constitute confirmation.
- **Retrodiction of known phenomena:** Explaining known results (like time dilation) after the fact is weaker than predicting novel phenomena. The digital experiment's prediction of $\tau_B/\tau_A = \sqrt{1 - v^2}$ was made before execution; its confirmation would carry correspondingly greater weight.

- **Appeals to authority:** No number of prominent physicists endorsing Ze can substitute for empirical evidence. Science progresses through data, not reputation.

Moving Forward

The path forward for the Ze programme is clear: execute the digital experiment with rigor, invite independent replication, and compare the results against the predicted relativistic curve. If the curve emerges, the scientific community has a genuine discovery to investigate. If it does not, the framework is falsified and should be abandoned or substantially revised.

This is the honest standard. It is neither impossibly high—the experiment is feasible with current technology—nor trivially low—it requires genuine empirical confirmation, not mere speculation. It respects the scientific tradition that has produced our current understanding of relativity while remaining open to the possibility that deeper principles await discovery.

The title of this paper, "A Direct Ze-Type Experiment," reflects this commitment: direct empirical test, not indirect argument; experiment, not thought experiment; Ze-type, testing the specific postulates of this framework. Whatever the outcome, conducting such experiments advances our understanding of time, information, and their deep interconnection.

Conclusion

The Ze framework proposes a fundamental reconceptualization of time, motion, and relativistic kinematics. At its core lies a simple but radical claim: proper time is not a geometric parameter but a count of effective updates, and the structures of special relativity—Minkowski metric, time dilation, Lorentz transformations—emerge statistically from the dynamics of information processing. This paper has articulated a comprehensive experimental programme to test this claim across multiple domains, from purely digital information processors to physical clocks, non-inertial systems, and quantum platforms.

Summary of the Experimental Programme

The proposed experiments target the four postulates of Ze with increasing levels of physical implementation:

The digital Ze experiment (Section 1) provides the most direct and fundamental test. Two identical processors receiving identical input streams, operating in maximally sequential versus maximally parallel modes, should exhibit update counts satisfying $\tau_B/\tau_A = \sqrt{1 - v^2}$, where v is the proportion of parallel correlations. This prediction replicates the Lorentz factor without any assumption about spacetime geometry, demonstrating that relativistic kinematics can arise from pure information dynamics. The simplicity and accessibility of this experiment make it the ideal starting point for empirical investigation.

Experiments on physical clocks (Section 2) extend the test to actual atomic and molecular systems. By comparing not only clock rates but internal transition counts across systems with

different internal complexity—trapped ions, molecular clocks, optical lattice clocks—under identical relativistic conditions, these experiments test whether proper time correlates with update statistics or merely with velocity. The prediction that systems with identical γ factors should accumulate different numbers of internal transitions directly challenges the universality assumption of standard relativity while remaining consistent with its effective predictions.

Non-inertial experiments (Section 3) target the role of acceleration in the twin paradox. The Ze framework interprets acceleration as a reconfiguration of causal structure—a change in the distribution of events between sequential and parallel channels. Systems following identical worldlines but subjected to different internal correlation modulations should accumulate different proper times upon reunion. This prediction distinguishes Ze from standard relativity, which attributes differential aging solely to path length in spacetime.

Quantum-level experiments (Section 4) leverage programmable quantum computers to test Ze interpretations of interference and collapse. Interference corresponds to parallel update distribution; collapse corresponds to mode switching. By measuring update statistics in controlled quantum evolutions and comparing with the predicted $\sqrt{1 - v^2}$ scaling, these experiments test whether quantum phenomena admit information-theoretic reinterpretation consistent with Ze.

Structural convergence (Section 5) provides indirect support through the independent emergence of similar mathematics in causal set theory, twistor theory, and emergent spacetime frameworks. The demonstration that Minkowski spacetime can arise from topologically homogeneous causal networks (D'Ariano & Tosini, 2013), that causal set discreteness is locally Lorentz invariant (Dowker, 2011), and that twistor theory treats light rays as more fundamental than events (Penrose, 1999) all resonate with Ze postulates.

What Success Would Mean

Successful confirmation of Ze predictions would not falsify special relativity. As argued in Section 6, the relationship between Ze and relativity is one of emergence, not replacement. Special relativity would remain empirically adequate as an effective theory; its equations would continue to predict experimental outcomes correctly. What would change is our understanding of why those equations hold. The Lorentz transformations would be recognized not as brute geometric facts but as necessary consequences of information-processing constraints. The invariant interval would be understood as a statistical regularity emerging from update counting. The twin paradox would be resolved not by appealing to acceleration as a geometric marker but by understanding how acceleration reconfigures causal structure and thereby affects update accumulation.

This explanatory deepening would parallel earlier developments in physics. Thermodynamics was not falsified by statistical mechanics; rather, its laws were shown to emerge from microscopic dynamics. Newtonian gravity was not falsified by general relativity; rather, it was revealed as the weak-field limit of a deeper theory. Similarly, Ze seeks not to overturn relativity but to ground it in something more fundamental—the logic of information processing itself.

The Threshold for Scientific Acceptance

Section 8 honestly assessed what constitutes the strongest evidence for Ze. The digital experiment with relativistic curve, independently replicated by multiple groups, demonstrating emergence of relativity without postulating it—this combination would justify moving from philosophical speculation to serious scientific investigation. It would warrant conference presentations, journal publications, and further experimental investment. It would attract physicists rather than philosophers because it would rest on empirical data rather than a priori reasoning.

This threshold is achievable. The digital experiment requires no exotic technology, no multi-billion-dollar facilities, no decades-long development timelines. It can be implemented on existing hardware by any competent researcher. Independent replication is straightforward once the initial result is published. The derivation of relativity from informational principles can be checked by any group with access to the experimental data.

Broader Implications

If confirmed, the Ze framework would have implications extending beyond relativity. The connection to causal set theory suggests a unified approach to quantum gravity, wherein spacetime emerges from discrete causal structures and proper time from relation counting (Dowker, 2011). The resonance with twistor theory points toward a non-local, information-based understanding of field interactions (Penrose, 1999). The computational analogy underlying Ze—treating physical processes as information processing—aligns with growing recognition that information-theoretic principles may be fundamental to physics.

The quantum experiments connect Ze to foundational questions about measurement and collapse. If interference corresponds to parallel update distribution and collapse to mode switching, then the measurement problem acquires a new interpretation: what we call "wavefunction collapse" is the transition from parallel to sequential processing in response to environmental correlation structure. This perspective aligns with recent work on the quantum Zeno effect, where frequent measurements inhibit evolution by enforcing sequential updates (Alessandrini, Ciaramelletti, & Paganelli, 2024), and with delayed-choice experiments on quantum computers demonstrating the role of correlation structure in determining measurement outcomes (Chen, Chiou, & Hsu, 2025).

The Necessity of Continued Experimentation

Theoretical speculation, however elegant, cannot substitute for empirical test. The Ze framework will stand or fall based on experimental results, not on the coherence of its mathematics or the appeal of its philosophy. This paper has therefore emphasized experiment throughout: digital experiments, clock experiments, non-inertial experiments, quantum experiments. Each offers opportunities for confirmation or falsification; each provides a pathway for empirical engagement with Ze postulates.

The falsification conditions articulated in Section 7 are genuine. If the digital experiment fails to produce the predicted $\sqrt{(1 - v^2)}$ scaling, the framework is refuted regardless of any other considerations. If physical clocks with different complexity show identical internal transition counts under identical motion, the claim that proper time correlates with update statistics is falsified. If non-inertial systems with modulated correlation structures show no difference in proper time accumulation, the interpretation of acceleration as causal reconfiguration is undermined. If quantum experiments reveal no relationship between update statistics and interference patterns, the Ze interpretation of quantum phenomena fails.

This empirical vulnerability is the hallmark of scientific seriousness. Ze does not retreat into unfalsifiable metaphysics; it puts forward specific, quantitative predictions that can be tested with existing or near-future technology. The experiments described in this paper are not *Gedankenexperimente* but real experiments, feasible with current resources and capable of producing unambiguous results.

A Call to the Scientific Community

The Ze framework invites engagement from multiple communities: information theorists who can analyze processor architectures and correlation measures; experimental physicists who can implement clock comparisons and non-inertial tests; quantum information scientists who can program quantum computers to test update statistics; mathematicians who can explore the structural connections to causal set theory and twistor theory.

The digital experiment, in particular, offers an opportunity for rapid progress. Any research group with programming capability can implement the two processor architectures, generate identical input streams, and measure update counts. The prediction is clear and quantitative; the result will either confirm or falsify the core Ze claim. Independent replication can begin immediately upon publication of initial results.

If the predictions are confirmed, a new research programme opens. If they are falsified, we have still learned something valuable: that relativistic kinematics do not arise from pure information dynamics of this type, and that the deep connection between time and information must be sought elsewhere. Either outcome advances scientific understanding.

Final Reflection

The title of this paper, "A Direct Ze-Type Experiment," reflects a commitment to direct empirical test. Not indirect inference, not mathematical analogy, not philosophical argument—but direct experiment on information processes, physical clocks, non-inertial systems, and quantum platforms. The Ze postulates are not offered as dogma but as hypotheses to be tested. Their fate lies in the laboratory, not in the armchair.

If they survive testing, they will transform our understanding of time, motion, and the origin of relativistic kinematics. If they fail, they will have served their purpose: to pose sharp questions that demand empirical answers. In either case, science advances. The experiments proposed

here are feasible, the predictions are clear, and the implications are profound. It remains only to perform them.

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