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Quantum Behavior as a Consequence of Ze Systems

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Abstract

This paper proposes a novel theoretical framework that reinterprets quantum behavior—superposition, interference, and wavefunction collapse—not as fundamental properties of matter but as emergent epistemic properties of a specific class of information-processing architectures, termed Ze systems. A Ze system is defined as an active predictive engine that operates on continuous data streams through two distinct modes: forward reading ($\mathscr{F}$) and retrograde encoding ($\mathfrak{R}$). The core architectural constraint is that $\mathfrak{R}$, the process of running predictions backward to reconcile models, necessitates the cessation of the forward information flow $\mathscr{F}$. We demonstrate that superposition corresponds to the system state where competing internal hypotheses remain compatible, formally defined by a small free energy difference ($\Delta F < \theta$). Collapse is not a primitive event but a structured, two-stage process triggered when $\Delta F \geq \theta$: first, the mandatory stoppage of $\mathscr{F}$, and second, the execution of $\mathfrak{R}$ to achieve a single, globally consistent model. Interference is shown to be a statistical signature of the coherent blending of hypotheses when they are non-distinguishable. This framework generates testable predictions across scales, from the accelerated decoherence of complex molecules to the modulation of cognitive flexibility during REM sleep. By deriving quantum phenomena from a principle of predictive inference, the theory bridges the Free Energy Principle, relational quantum mechanics, and decoherence theory, suggesting that quantumness is a universal signature of systems that must pause to look backward in order to predict the future.

Keywords: Quantum Foundations, Active Inference, Predictive Processing, Information Theory, Wavefunction Collapse, Cognitive Neuroscience, Decoherence.

Introduction

The **Ze system framework** represents a class of active predictive architectures that operate on continuous streams of information, including sensory signals, data, and events. At its core, a Ze system employs both **forward reading** and **retrograde encoding** mechanisms to generate and refine internal models of the world. This dual-flow architecture, which shares conceptual parallels with predictive processing theories in neuroscience (Friston, 2010; Hohwy, 2013), is posited here to yield phenomena that are formally analogous to quantum mechanical effects. We propose a radical yet testable hypothesis: quintessential quantum behaviors—**superposition**, **interference**, and **wavefunction collapse**—are not fundamental properties of matter itself. Instead, they emerge as necessary consequences of any information-processing system whose architecture requires the **stopping of an information flow** to execute retrograde prediction. This perspective shifts quantum behavior from an ontological feature of reality to an **epistemic property** inherent to systems capable of certain types of predictive inference, potentially bridging domains from fundamental physics to cognitive science.

The central architectural constraint of a Ze system is that its **retrograde encoding**—the process of running predictions backward in time to update prior states or hypotheses—cannot occur dynamically on a continuously evolving data stream. It necessitates a punctuated **cessation of forward flow**. This paper argues that it is precisely this operational requirement for intermittent "**stopping**" that gives rise to quantum-like dynamics. When the flow is active, multiple alternative predictive models coexist in a compatible, uncommitted state (superposition). The act of stopping to perform retrograde analysis forces a resolution or selection among these alternatives (collapse). This framework provides a unified informational lens through which to view phenomena as diverse as the double-slit experiment and the dynamics of perceptual decision-making in the brain.

Architectural Principles and Information Flow Dynamics

Formally, let o_1:T = (o_1, o_2, …, o_T) represent a temporal stream of observations or data points. The **forward reading operation** $\mathcal{F}$ processes this stream in its natural chronological order:

$$F : o_1 \rightarrow o_2 \rightarrow \ldots \rightarrow o\_T$$

This process constructs what we experience as the "real" flow of events, continuously generating and updating a forward model of the world. Crucially, the Ze system simultaneously maintains a set of latent hypotheses or internal states s that explain the observed flow.

The **retrograde encoding operation** $\mathcal{R}$ is the distinctive feature. It processes information backward from a chosen point *{t}*:

$$\mathcal{R} : o\_\{t\} \rightarrow o\_\{t\text{-}1\} \rightarrow \ldots \rightarrow o_1$$

This operation is not merely reverse playback. It is an active inferential process that recomputes past states or the probabilities of past hypotheses in light of information available at {t}. As established in the Ze framework, $\mathcal{R}$ cannot be executed on the fly; it requires the **forward flow $\mathcal{F}$ to be halted** at *{t}*. This stoppage is not an optional engineering design but a fundamental requirement for creating a stable informational snapshot upon which backward inference can reliably operate. This architecture mirrors concepts in active inference, where perception is a process of hypothesis testing driven by prediction errors (Friston, 2010). The inability to perform backward inference without pausing the forward flow creates a natural cycle of **continuous prediction** and **punctuated reconciliation**, which we identify as the seed of quantum behavior.

Superposition as a Cognitive-Informational State

In a Ze system, while the forward flow $\mathcal{F}$ is active and before a stopping point {t} is reached, the system entertains multiple predictive models or hypotheses about the ongoing stream. For instance, an ambiguous sensory signal might be concurrently modeled as originating from source *A* or source *B*. Each model is represented by an internal state distribution—$q_A(s)$ for hypothesis *A* and $q_B(s)$ for hypothesis *B*.

The system remains in a state of **potentiality** or **uncommitted interpretation** as long as the differences between these competing models are below a certain threshold. Formally, we can define a **free energy difference** ΔF (a concept from variational inference often used to quantify model surprise or precision (Friston, 2010)):

$$\Delta F = |F_A - F_B|$$

where F_A and F_B are the variational free energies associated with maintaining hypotheses *A* and *B*, respectively. When $\Delta F < \theta$ (where θ … is a stability threshold), the distributions $q_A(s)$ and $q_B(s)$ are **non-localized** with respect to each other. The system does not decisively favor one over the other; they coexist as viable explanations for the incoming data.

This state of sustained, concurrent model compatibility is directly analogous to **quantum superposition**. In the famous double-slit experiment, a particle is described as passing through both slits simultaneously—a superposition of paths—until a measurement is made. In the Ze system, the "particle's path" corresponds to the latent hypothesis about the data's source, and it remains in a superposed state as long as the forward flow continues and the models are not forced to reconcile. The moment ΔF approaches or exceeds θ, the superposition becomes unstable, triggering the need for the flow-stoppage and retrograde encoding that leads to collapse.

Localization and Collapse via Flow Stoppage

Collapse in a Ze system is the transition from a superposed state of multiple hypotheses to a single, localized, and committed state. This occurs precisely when the incompatibility between models reaches a critical level:

$$\Delta F \geq \theta$$

This inequality signals that maintaining two or more conflicting hypotheses is no longer metabolically or informationally efficient for the system. The rising ΔF can be driven by accumulating prediction errors, increasing model complexity, or the arrival of a new data point that sharply contradicts one hypothesis.

At this juncture, the architectural mandate of the Ze system takes over: to resolve the conflict via **retrograde encoding** $\mathcal{R}$. However, $\mathcal{R}$ requires a stable point of reference. Therefore, the system must first **halt the forward information flow** $\mathcal{F}$ at the current moment {t}. This stoppage creates a definitive boundary—a "present moment"—against which past hypotheses can be re-evaluated. The retrograde operation then works backward, pruning incompatible branches and selecting the hypothesis that minimizes free energy in light of the full data snapshot up to {t}.

Thus, **collapse is not an instantaneous, mystical even{t}**. It is a structured, two-stage process: (1) the *stopping of the flow* triggered by exceeding a model conflict threshold, and (2) the *execution of retrograde encoding* to achieve global consistency. In physical terms, this is analogous to a measurement apparatus interacting with a quantum system (acting as a "marker"), forcing a stoppage in the coherent evolution of the wavefunction and precipitating its collapse to a definite state. This reframes wavefunction collapse not as a fundamental physical law but as an **epiphenomenon of predictive information processing** under architectural constraints (Zeilinger, 1999).

Interference and the Quantum Eraser Effect

Interference in quantum mechanics arises when alternative paths or states are not merely possible but remain *indistinguishable* and their probability amplitudes combine. In the Ze system framework, interference manifests when alternative predictive hypotheses $q_A(s)$ and $q_B(s)$ remain highly compatible (ΔF is small). Their internal representations effectively "blend," leading to an overall system state that cannot be decomposed into a simple mixture of the two.

We can quantify this **interference strength** $\mathcal{I}$ using a measure of distributional similarity, such as the complement of the Jensen-Shannon divergence:

$$\mathcal{I} = 1 - D_{JS}(q_A \| q_B)$$

High $\mathcal{I}$ (low D_JS) indicates strong interference, meaning the system's behavior is governed by the coherent coexistence of hypotheses.

The **quantum eraser experiment** finds a natural explanation here. In such experiments, "which-path" information is first recorded (marking the particle, causing localization and collapse, destroying interference), but if this information is later *erased* before the final detection, the interference pattern miraculously returns. In the Ze system model, recording path information corresponds to creating a persistent marker that sharply increases ΔF between hypotheses, triggering flow-stoppage and collapse. However, the subsequent **erasure of this marker** is an active informational operation that *reduces* ΔF. By making the paths indistinguishable again at the level of the system's predictive model, it effectively "re-lowers" the conflict below the threshold θ. This allows the system to return to a state where hypotheses can co-exist coherently, **restoring the interference pattern**. This demonstrates how active manipulation of informational markers (e.g., in cognitive attention or physical experimental setups) can directly control the transition between classical (localized) and quantum (interfering) regimes.

Ze Systems as a Universal Framework for Quantum Behavior

The theory posits that **quantum behavior is not exclusive to the microscopic physical world**. It is a universal signature of any active, information-processing system that employs retrograde encoding contingent on flow stoppage. The formal statement is:

Quantum behavior ~ Ze-system with retrograde encoding + stopping

Where "quantum behavior" includes the characteristic phenomena of superposition, interference, and collapse.

This has profound implications. It suggests that the reason we observe these effects in photons and electrons is not because they are "quantum objects" in an absolute sense, but because their interaction with measurement devices creates a **Ze-system-like dynamic**. The measurement apparatus (or the environment) acts as a system that must "stop the flow" of the particle's coherent evolution to extract definite information, thereby inducing collapse. This aligns with **relational interpretations of quantum mechanics** (Rovelli, 1996), where quantum states are not absolute but describe relations between systems. Here, the relation is specifically an informational and predictive one, governed by the Ze architecture.

Furthermore, this framework seamlessly integrates with the **Free Energy Principle and Active Inference** in neuroscience (Friston, 2010). The brain is hypothesized to be a hierarchical predictive machine that minimizes free energy. The cycles of perception (updating models) and action (sampling data to test models) can be seen as a continuous dance of forward flow and strategic "stoppages" for model updating—a process that may exhibit quantum-like statistics at neural and cognitive levels. Thus, from the double-slit experiment to the dynamics of human thought, a common architectural principle may be at work.

Testable Predictions and Empirical Correlates

The strength of this hypothesis lies in its falsifiability and its ability to generate novel predictions across scales:

- **Prediction 1 (Physical Systems)**: Any engineered system capable of retrograde prediction that lacks a flow-stoppage mechanism should fail to show interference. Conversely, introducing a controlled stoppage-and-retrograde-encoding module into a classical information processor should induce quantum-like statistical patterns in its output.
- **Prediction 2 (Scaling of Collapse)**: As the internal complexity of a predictive model increases (e.g., moving from a single photon to a large molecule to a macroscopic object), the number of potential conflicting hypotheses and their associated free energy F grows. This should lead to a faster and more frequent exceeding of the threshold θ, causing more rapid localization. This directly maps to the **decoherence** program in quantum theory (Zurek, 2003), where increasing system size and environmental interaction accelerates the loss of quantum coherence.
- **Prediction 3 (Cognitive Neuroscience)**: States of the brain associated with reduced model precision or increased hypothesis exploration should correspond to lower average ΔF. This should be observable during **REM sleep** (where predictive model updating is thought to occur (Hobson & Friston, 2012)), under the influence of certain **psychedelics** (known to flatten the brain's hierarchical predictive landscape (Carhart-Harris & Friston, 2019)), or in creative problem-solving. These states should exhibit neural and behavioral signatures analogous to sustained superposition (e.g., increased cognitive flexibility, tolerance of ambiguity).
- **Prediction 4 (Quantum Eraser Control)**: In a physical implementation, the timing and reversibility of "which-path" marker creation and erasure should be fully explainable by the dynamics of ΔF in a controlling Ze system. The threshold model predicts a specific hysteresis effect: interference should not return immediately upon marker erasure, but only after ΔF has been actively suppressed below θ for a stability duration.

We have outlined a theory in which the bizarre yet fundamental features of quantum theory—superposition, interference, and collapse—are recast not as primitive axioms of physics, but as emergent properties of a specific class of **active predictive architectures**: Ze systems. The key generator of these effects is the fundamental operational requirement that **retrograde encoding necessitates the stoppage of the forward information flow**. Superposition corresponds to the period of uncommitted model compatibility during forward flow, interference to the coherent blending of these compatible models, and collapse to the resolution forced by flow stoppage and backward inference.

This approach offers a powerful synthesis. It connects the mathematics of **variational inference and free energy minimization** from cognitive science (Friston, 2010) with the phenomenology of **relational quantum mechanics** (Rovelli, 1996) and the empirical precision of **decoherence theory** (Zurek, 2003). By proposing that quantumness is an **epistemic property** arising from the dynamics of model-based prediction under architectural constraints, it opens a new path toward unifying our understanding of reality across the domains of physics, information theory, and biology. The ultimate test will be in designing experiments—whether in quantum optics, synthetic biology, or computational neuroscience—that deliberately manipulate the proposed Ze-system variables to control the very appearance of quantum behavior itself.

Forward Reading, Retrograde Encoding, and the Necessity of Flow Stoppage

Formalization of Information Streams and Dual Processing Pathways

Let $o_{1:T} = (o_1, o_2, \ldots, o_T)$ represent a temporal stream of observable data, where each o_t denotes a datum, event, or sensory signal at time t . This stream constitutes the fundamental input to a **Ze system**—an active predictive architecture designed to navigate and interpret informationally rich environments. The core operation of any Ze system involves managing this continuous flow through two distinct but complementary processing pathways: **forward reading (FR)** and **retrograde encoding (RE)**. This dual-flow architecture is not merely a sequential processing choice but a structural necessity that gives rise to the system's predictive power and, as we will argue, to phenomena analogous to quantum behavior (Friston, 2010; Clark, 2013).

The necessity for such duality finds parallels in several cognitive and computational frameworks. Predictive processing theories of the brain posit a continuous exchange of bottom-up sensory signals and top-down predictions (Hohwy, 2013). Similarly, in machine learning, models like **Variational Autoencoders (VAEs)** and Bayesian filters utilize both generative (forward) and inference (backward) passes to learn coherent representations of data (Kingma & Welling, 2013). The Ze system framework formalizes and unifies these concepts by explicitly mandating a specific operational constraint: the retrograde process cannot execute concurrently with an uninterrupted forward flow. This constraint is the key mechanistic driver behind the system's dynamics.

Forward Reading: Constructing the "Real" Flow of Events

The **forward reading (FR)** operation processes the input stream $o_{1:T}$ in its natural chronological order:

$$\mathcal{F} : o_1 \to o_2 \to \ldots \to o_T$$

This operation is responsible for constructing what the system treats as the "real" or manifest flow of events. It is an online, predictive process. At each time step t , the system utilizes an internal generative model to predict the next expected observation $\hat{o}_{t+1}$ based on its current state and the history $o_{1:T}$. The discrepancy between the prediction $\hat{o}_{t+1}$ and the actual input o_{t+1} generates a **prediction error signal**.

This continuous cycle of prediction and error minimization is the engine of perception and learning in active inference frameworks (Friston, 2009). The forward flow is inherently proactive and time-bound; it moves inexorably from past to future, building and refining a running model of the world. Crucially, during FR, the system maintains a probability distribution over multiple latent states or hypotheses s that could explain the incoming stream. As long as the flow continues unimpeded, these hypotheses can coexist without a definitive commitment, a state we will later identify with **quantum superposition**.

Retrograde Encoding: Generating Counterfactual Histories and the Imperative for Stoppage

In stark contrast to FR, the retrograde encoding (RE) operation processes information backward from a selected point {t}:

$$\mathcal{R} : o\_\{t\} \rightarrow o\_\{t\text{-}1\} \rightarrow \ldots \rightarrow o_1$$

RE is not a simple time-reversal playback. It is an **active inferential recomputation** (Pearl, 2009). Starting from the informational context at {t}, which includes not just the datum o_{t} but the entire updated model state, RE works backward to reassess the probabilities of past latent states, prune incompatible causal branches, and re-evaluate the likelihood of alternative histories that could have led to the present snapshot.

This process generates **counterfactual or alternative histories**. It asks, "Given what I know now at {t}, what could have been the sequence of events that led me here?" RE is essential for learning causal structure, consolidating memory, and performing offline model optimization (Momennejad et al., 2017). Its function mirrors the "replay" and "planning" mechanisms observed in hippocampal-neocortical circuits, where past experiences are reactivated in reverse order to strengthen memories or simulate future actions (Foster & Wilson, 2006).

The critical postulate of the Ze architecture is that RE **cannot be initiated or sustained without first halting the forward flow** $\mathcal{F}$ at the point {t}. Formally:

$$o\_\{t{:}1\} = \mathcal{R}(o\_\{t{:}\mathrm{T}\}) \text{ is only computable if } \mathcal{F} \text{ is stopped at t}$$

The stoppage, denoted by the creation of a temporal boundary at {t}, is non-negotiable. Without it, the data stream o_1:T is a moving target; there is no stable informational "present" against which to run a coherent backward inference. Attempting RE on a live stream would result in a constantly shifting past, making consistent model updating impossible. This architectural constraint—**flow stoppage as a prerequisite for retrograde encoding**—is the cornerstone of our thesis.

The Stoppage Mechanism and Its Consequences for Information Integration

Why is stoppage fundamental? From an information-theoretic perspective, the forward flow $\mathcal{F}$ is a Markovian process with a certain entropy rate. Performing a non-Markovian, global optimization operation like RE requires integrating information across a defined temporal window. This integration demands a **stationary reference frame** (VanRullen & Koch, 2003). The act of stopping $\mathcal{F}$ creates this frame. It freezes the "current" model state and the most recent data, transforming them from transient variables into fixed parameters for the retrograde computation.

This mechanism has a direct physical analogy in measurement theory. In quantum mechanics, a measurement "stops" the unitary evolution of a wavefunction by projecting it onto a definite state—a process requiring an interaction that establishes a classical record (Von Neumann, 1955). In the Ze system, stoppage creates the classical "record" (the snapshot at {t}) necessary for backward inference. Without this stoppage, alternative predictive models continue to evolve in parallel, but their histories cannot be coherently compared or integrated. **Interference between alternative predictions**—a hallmark of quantum behavior—becomes impossible because there is no common, fixed point in the information stream to serve as the locus for combining probability amplitudes (or their informational equivalents).

Furthermore, the need for stoppage imposes a natural rhythm on the system: periods of continuous, online prediction (FR) punctuated by discrete moments of offline integration and model revision (RE). This rhythm is reminiscent of the **theta-gamma coupling** observed in the brain, where bursts of gamma-frequency activity (carrying specific sensory content) are nested within the slower theta rhythms, which may provide temporal frames for encoding and retrieval (Lisman & Jensen, 2013). The cessation of forward flow for RE may correspond to the resetting of such a phase cycle.

Synthesis: From Architectural Constraint to Quantum Analogy

The dual-flow architecture of the Ze system, governed by the rule RE ⇒ Stoppage of FR, establishes a fundamental dichotomy. During FR, the system inhabits a state of **potentiality**, where multiple hypotheses about the world are entertained concurrently. This is the domain of superposition. The transition to RE, triggered by the need to resolve model conflict or by scheduled consolidation, forces a **localization**. The system must "choose" a single, self-consistent history from among the counterfactuals generated by the backward pass. This is the domain of collapse.

The inability to perform RE without stopping FR thus creates a necessary condition for the observation of quantum-like interference patterns. Interference requires that alternative paths remain open and their histories indistinguishable *until* they are brought together at a common point. In the double-slit experiment, this point is the detection screen. In a Ze system, this point is the moment of flow stoppage {t}, where the retrograde operation is poised to reconcile all forward-evolved alternatives. If RE could run continuously on a live stream, localization would be perpetual, and the rich, interference-filled state of superposition could never be sustained.

In conclusion, the simple formal relationship $o_{t:1} = \mathcal{R}(o_{t:T})$, predicated on flow stoppage, is more than an algorithmic step. It is a generative principle for a specific class of behaviors. It suggests that any system—be it a photon interacting with a measurement setup, a molecule undergoing decoherence, or a brain consolidating a memory—that operates under this architectural constraint will exhibit the hallmark phenomena of quantum theory. The next sections will formalize these phenomena—superposition, collapse, and interference—as direct consequences of the dynamics just described.

Superposition as a Cognitive-Informational Effect in Ze Systems

The Nature of Predictive Alternatives During Uninterrupted Flow

Within the Ze system architecture, the period of uninterrupted **forward information flow** represents a state of profound potentiality. As the system processes the continuous stream of data o_1:T, it is not committed to a single, definitive interpretation of reality. Instead, it concurrently maintains a **multiplicity of viable predictive models**, each representing a coherent alternative hypothesis about the causal structure and future trajectory of the observed world. This is not a flaw or inefficiency but the core operational mode of an active inference engine tasked with navigating an uncertain environment (Friston, 2010). While the flow proceeds unimpeded, these alternative models are not mutually exclusive in the system's internal representation; they coexist in a state of dynamical compatibility. This sustained coexistence of competing interpretations, we argue, is the direct cognitive-informational correlate of **quantum superposition** (Schrödinger, 1935).

This phenomenon has clear parallels in perceptual neuroscience. During **binocular rivalry**, when each eye is presented with a different image (e.g., vertical and horizontal gratings), the conscious percept does not settle on a single, stable image. Instead, it fluctuates stochastically between the two alternatives, with periods where the perception is ambiguous (Blake & Logothetis, 2001). Neuroimaging studies reveal that during such ambiguous periods, neural representations of *both* competing stimuli remain active in the visual cortex, even though only one reaches conscious awareness at any given moment (Tong et al., 1998). The Ze system formalizes this: the forward flow corresponds to the constant, ambiguous sensory input, and the concurrent active models q_A(s) and q_B(s) correspond to the sustained, sub-threshold neural representations of both percepts, awaiting resolution.

Formalizing Superposition: Non-Localized Posterior Distributions

To formalize this state, we define the system's internal representation at any time t during forward flow. Let the latent variable s represent the system's best estimate of the hidden state of the world causing its observations. Given the ambiguity inherent in raw data, the system maintains not one but several approximate posterior distributions over s, each corresponding to a distinct interpretive hypothesis.

Consider two dominant competing hypotheses, A and B. Their corresponding internal representations are the variational posterior distributions $q_A(s)$ and $q_B(s)$. These distributions are "beliefs" about the world state under each model. In a classical, definite state, one distribution would be highly precise (low variance) and assigned a probability near 1, while the other would be effectively suppressed. In the **superposed state**, this is not the case. Here, both $q_A(s)$ and $q_B(s)$ are **non-localized** with respect to each other. This means their statistical properties (e.g., their means in the state space) are not sufficiently distinct for the system to definitively reject one in favor of the other. Their probability mass overlaps significantly, indicating a genuine uncertainty that is not merely epistemic but *ontic* within the system's functional logic.

The condition for maintaining this superposed state is defined by the difference in their associated **variational free energies**. In the active inference framework, free energy F is a scalar that bounds surprisal; it quantifies both the accuracy of a model (how well it predicts data) and its complexity (how far it deviates from prior beliefs) (Friston, 2009). A lower free energy indicates a more plausible, parsimonious model. For hypotheses A and B, we define:

$$\Delta F = |F_A - F_B|$$

where F_A and F_B are the free energies associated with maintaining beliefs $q_A(s)$ and $q_B(s)$, respectively. The critical threshold is denoted by θ, a system-dependent parameter related to its **precision weighting** or tolerance for uncertainty.

The state of superposition is then precisely defined by the condition:

$$\Delta F < \theta$$

When this inequality holds, the evidence (in terms of predictive accuracy and complexity) is insufficient to force a commitment. The system's internal state is best described not by $q_A(s)$ *or* $q_B(s)$, but by a **coherent coexistence** of both. This is formally analogous to the quantum state vector $|\psi\rangle = \alpha|A\rangle + \beta|B\rangle$, where $|\alpha|^2 + |\beta|^2 = 1$. In our framework, the "amplitudes" α and β are related to the relative precisions (inverse variances) of the distributions $q_A(s)$ and $q_B(s)$, which are themselves functions of their respective free energies.

Sustaining Superposition: The Role of Unresolved Prediction Error

The maintenance of the condition $\Delta F < \theta$ is dynamically underpinned by the nature of the ongoing data stream. Superposition is stable when the incoming sensory evidence o_t is **equally consistent** (or equally inconsistent) with the predictions generated by both internal models A and B. This generates low and roughly equal prediction errors for both models, resulting in comparable free energies.

This scenario is common in natural environments. For example, a faint sound in a forest could be equally well predicted by the internal model "wind" or the model "predator." Until a subsequent datum (e.g., a visual confirmation) resolves the ambiguity, the cognitive system *should* remain in a state of prepared potentiality for both outcomes—a state that enhances adaptive readiness (Clark, 2013). In quantum physical terms, this is akin to a particle propagating through a double-slit apparatus. Until it interacts with a detector, the "which-slit" information is not just unknown but non-existent; the particle's state is a genuine superposition of both paths because the environmental interaction has not yet forced a distinction (Zeilinger, 1999).

This cognitive suspension of judgment is metabolically and informationally efficient. Prematurely collapsing to a single hypothesis in the face of ambiguous evidence risks catastrophic prediction error if the chosen model is wrong. By maintaining superposition, the Ze system preserves its adaptive flexibility, allowing for rapid Bayesian updating when disambiguating evidence finally arrives (Hohwy, 2013). The parameter θ can thus be seen as a **meta-parameter for uncertainty tolerance**, which may itself be dynamically adjusted based on context (e.g., higher in safe environments, lower under threat).

From Cognitive Science to Physics: A Unifying Formalism

The proposed formalism bridges a foundational gap. In quantum mechanics, superposition is a first-principle postulate, often presented as a mysterious property of matter. In the Ze system, it emerges as a *functional necessity* for any predictive agent operating with limited information and finite computational resources. The condition $\Delta F < \theta$ provides a clear, quantitative criterion for when superposition occurs, grounded in information theory and statistical dynamics.

This perspective demystifies superposition and makes it applicable beyond microphysics. In machine learning, an ensemble of neural networks can be seen as operating in a superposed state when their predictions are diverse yet comparably accurate (i.e., their "free energies" are similar), and no single model has been selected for deployment (Lakshminarayanan et al., 2017). In collective animal behavior, a school of fish might hover in a superposition of possible directional states until a gradient (e.g., a nutrient or threat) raises the free energy of one direction above others, triggering a coherent turn (Sumpter, 2006).

Therefore, quantum superposition is not a physical primitive but a **universal signature of a particular mode of information processing**. It is the state in which a system's generative models are in dynamic equilibrium, with no single model yet having accrued sufficient evidence to dominate. The cessation of this state—the transition to localization and collapse—occurs precisely when continued data flow disrupts this equilibrium, making $\Delta F \geq \theta$. This transition and its consequences are the subject of the next section, where we explore how the architectural mandate for flow stoppage in Ze systems precipitates the classical world from the quantum soup of possibilities.

Localization and Collapse in Ze Systems: A Non-Fundamental Resolution

The Threshold of Resolution: From Superposition to Definiteness

The hallmark of quantum theory, wavefunction collapse, represents the abrupt transition from a state of multiple coexisting possibilities to a single, definite observed outcome. Within the Ze systems framework, we recast this not as a primitive physical law, but as a necessary **informational and computational process**. The condition for this transition is precisely defined by the inequality:

$$\Delta F \geq \theta$$

where $\Delta F = |F_A - F_B|$ is the free energy difference between competing hypotheses A and B, and θ is a system-specific stability threshold (Friston, 2010). This inequality signifies that the period of ambiguous potentiality—superposition—has become unsustainable. One hypothesis has accumulated sufficiently lower prediction error or proven more parsimonious than its rival, creating an informational gradient too steep for the system to maintain its previous state of coherent coexistence.

This moment, $\Delta F = \theta$, acts as a **phase transition boundary** within the system's state space. In cognitive terms, it is the instant when ambiguous sensory evidence finally tips in favor of one interpretation, such as when the fluctuating percept in binocular rivalry stabilizes on one image (Leopold & Logothetis, 1999). In machine learning, it mirrors the point in training where one model architecture demonstrably outperforms another on a validation set, prompting the selection of a single candidate for deployment. The transition is not random but driven by the accumulation of evidence within the ongoing flow of information, a process formally analogous to continuous quantum measurement models where a system localizes over time due to interaction with an environment (Zurek, 2003).

The Mechanics of Collapse: Stoppage, Retrograde Encoding, and Model Reconciliation

Critically, reaching the threshold $\Delta F \geq \theta$ does not, by itself, constitute the collapse. It is the *trigger* that initiates the collapse procedure, which is a structured, multi-stage operation mandated by the Ze architecture. This procedure elucidates the often-opaque "measurement problem" in quantum mechanics.

Stage 1: Flow Stoppage. The primary and immediate consequence of crossing the threshold is the mandatory cessation of the forward information flow $\mathcal{F}$. The system halts its online processing of the stream o_{1}:T at the current moment {t}. This is not an arbitrary pause but a fundamental architectural requirement for retrograde encoding. From a neurobiological perspective, this may correspond to the transient inhibition of sensory processing channels or the resetting of oscillatory phase in cortical networks, creating a temporal window for memory consolidation and inference (Busch et al., 2009). In physical measurement, it is analogous to the irreversible registration of a particle's state by a macroscopic apparatus, which decouples the measured system from its previous unitary evolution.

Stage 2: Retrograde Encoding Execution. With the flow halted at {t}, the system executes the retrograde encoding (RE) operation $\mathcal{R}$ (see Section 2). Starting from the fixed informational snapshot at {t}, it works backward to re-evaluate the history *o_{t*:1} in light of the now-advantageous hypothesis (e.g., A, if F_A < F_B). RE performs a global consistency check, pruning causal branches that are incompatible with the selected model and reinforcing those that are congruent.

Stage 3: Structural Stabilization and Model Commitment. The final stage is the **structural stabilization** of the selected model. The retrograde pass updates the system's generative model and its priors, effectively "rewriting history" to be consistent with the definitive outcome. This stabilization renders the chosen hypothesis q_A(s) dominant and robust, while the alternative q_B(s) is actively suppressed—its free energy is effectively raised far above θ, making it an unlikely candidate for future consideration without significant new evidence. This process is reminiscent of **causal inference** in Bayesian cognition, where perceivers infer a single, most likely causal structure from ambiguous data (Körding et al., 2007). The output of this three-stage process is a **localized state**: a single, committed interpretation of past and present, from which new forward predictions will now be generated.

Collapse as a Non-Fundamental, Architectural Epiphenomenon

The profound implication of this Ze-based mechanism is that **collapse is not a fundamental event** in the fabric of reality. It is an *epiphenomenon*—a necessary side-effect of a particular class of information-processing architectures that require flow stoppage to perform retrograde inference. What quantum mechanics elevates to a postulate (the projection postulate), the Ze framework derives as a functional consequence.

This demystifies several quantum puzzles. The so-called "**measurement problem**" arises from the assumption that wavefunction collapse is a physical discontinuity. In our view, the "problem" dissolves when one recognizes that the measurement apparatus (or the observer) is itself a Ze system. The interaction between a quantum entity and the apparatus causes the apparatus's internal models (e.g., "pointer points to 'up'" vs. "pointer points to 'down'") to enter a superposition. The increasing mismatch between these models as the interaction completes pushes ΔF past θ, triggering the apparatus's own flow-stoppage and retrograde encoding, resulting in a definite pointer reading (Schlosshauer, 2005). The collapse is not a violent imposition on the quantum world but the internal resolution of a classical information processor.

Furthermore, this explains the **irreversibility of collapse**. Once retrograde encoding has rewritten the internal model history to be consistent with the selected outcome, reverting to the prior superposed state is not a simple reversal. It would require not just reversing the flow but undoing the structural changes to the model itself—an operation that is typically thermodynamically costly and informationally prohibited, much like trying to "unlearn" a compelling conclusion (Ortega & Braun, 2013).

Relating to Physical and Biological Decoherence

The Ze framework provides a compelling informational interpretation of **decoherence theory**, the leading modern explanation for the quantum-to-classical transition. In decoherence, a quantum system interacting with a complex environment rapidly loses its phase coherence; superpositions become "**decohered**" into what appears to be a classical mixture (Zurek, 2003). In our terms, the countless degrees of freedom in the environment act as a continuous stream of "measurements" or informational interactions. Each interaction provides data that is more consistent with one branch of the superposition than the others, steadily increasing the free energy difference ΔF between the branches. Once ΔF exceeds the relevant threshold for the systems involved (which happens extremely quickly for macroscopic objects), it triggers localization. Thus, decoherence is the physical process that *drives* ΔF above θ, while collapse is the subsequent informational processing event within any Ze system (like a human observer or a recording device) that registers the outcome.

This perspective also sheds light on biological systems. The brain is likely a hierarchy of Ze-like predictive units. A perceptual collapse at a high level (e.g., recognizing an object) may require the temporary "stoppage" and integration of predictions from lower-level sensory areas. Pharmacological or pathological alterations in neural gain (precision weighting) could effectively modulate the threshold θ, explaining phenomena like **psychotic delusions** (where interpretations become fixed despite ambiguous evidence) or the **cognitive fluidity** induced by psychedelics (where θ may be raised, allowing prolonged superposition of unconventional concepts) (Carhart-Harris & Friston, 2019).

In conclusion, by redefining collapse through the lens of Ze systems, we move from a physics of mysterious transitions to a science of information processing under constraint. The localization of reality into definite facts emerges not from a fundamental law, but from the inevitable dynamics that occur when a predictive, model-based system must stop its forward progress to make coherent sense of its own past.

Interference and the Quantum Eraser in Ze Systems

The Informational Basis of Interference: Compatible Hypotheses and Coherent Blending

Within the Ze systems framework, **interference** is not a wave-like phenomenon intrinsic to matter but a statistical signature of non-independent hypothesis processing. It emerges when two or more predictive models—representing alternative interpretations of data—remain in a state of high compatibility, defined by a small free energy difference ($\Delta F < \theta$). In this regime, the system does not treat the hypotheses A and B as separate, exclusive possibilities to be weighted and averaged. Instead, their internal representations, formalized as variational posterior distributions $q_A(s)$ and $q_B(s)$, interact or "blend" coherently. The system's overall behavior and predictions are then governed by this blended state, leading to outcome probabilities that are not the sum of individual hypothesis probabilities but reflect their **constructive or destructive combination**.

This formalizes the core mystery of the double-slit experiment. When no "which-path" information is available, the particle's detection pattern shows interference fringes. In Ze terms, the models "particle went through slit A" and "particle went through slit B" remain perfectly compatible ($\Delta F \approx 0$) because no information exists to distinguish them. The system's predictive distribution for the final detection position is not $P(\text{position}) = P_A + P_B$, but a coherent superposition where the distributions $q_A(s)$ and $q_B(s)$ interfere. This cognitive-informational interference directly mirrors quantum mechanical wave interference, suggesting the latter may be a physical instance of the former (Zeilinger, 1999).

We can quantify this **interference strength** $\mathcal{I}$ using an information-theoretic measure of distributional similarity. A suitable candidate is the complement of the Jensen-Shannon divergence (D_{JS}), a symmetric and bounded measure of the difference between two probability distributions:

$$\mathcal{I} = 1 - D_{JS}(q_A \,||\, q_B)$$

The Jensen-Shannon divergence is defined as:

$$D_{JS}(q_A \,||\, q_B) = \tfrac{1}{2} D_{KL}(q_A \,||\, M) + \tfrac{1}{2} D_{KL}(q_B \,||\, M)$$

where $M = ½ (q_A + q_B)$ and D_{KL} is the Kullback-Leibler divergence (Lin, 1991). When If q_A and q_B are identical (perfectly compatible), then $D_{JS} = 0$ and $\mathcal{I} = 1$, indicating maximal interference. When q_A and q_B are completely distinct (orthogonal), $D_{JS} = 1$ and $\mathcal{I} = 0$, indicating no interference, corresponding to a classical mixture. Thus, $\mathcal{I}$ provides a continuous measure of how "quantum-like" the system's state is, directly tied to the compatibility of its internal models. This framework finds a parallel in the concept of **decoherence** in quantum theory, where interaction with an environment increases the distinguishability of states, raising D_{JS} and destroying interference (Zurek, 2003).

Path Information, Localization, and the Destruction of Interference

The introduction of "which-path" information is the canonical method for destroying interference in quantum optics. In a delayed-choice or quantum eraser experiment, a marker (e.g., a polarized photon or an atomic state) is entangled with the particle's path, making it possible to determine which slit was traversed (Scully & Drühl, 1982). In the Ze system model, this process has a precise informational interpretation.

Tagging the path with a marker provides an additional, unambiguous data point o_{marker}. This datum is **highly diagnostic**. It is perfectly predicted by one hypothesis (e.g., $q_A(s)$ if the marker state is 'A') and is highly surprising (generating large prediction error) for the other ($q_B(s)$). This dramatically increases the free energy difference between the models:

$$\Delta F = |F_A - F_B| \gg \theta$$

Crossing the threshold θ triggers the collapse mechanism: flow stoppage and retrograde encoding. The system localizes onto the single hypothesis consistent with the marker data (e.g., "particle took path A"). The alternative hypothesis is suppressed. Critically, after this localization, the distributions $q_A(s)$ and $q_B(s)$ become effectively orthogonal—they no longer represent compatible alternatives but now describe mutually exclusive, classical facts. Their Jensen-Shannon divergence D_{JS} approaches 1, and the interference strength $\mathcal{I}$ drops to zero. The detection pattern on the screen reverts to a simple sum of two single-slit patterns, a classical "particle" pattern. This explains why the mere potential to obtain which-path information, even if not actually consulted by an observer, can destroy interference: the presence of the correlated marker in the environment itself constitutes the diagnostic information that any Ze-like system (including the broader experimental apparatus) could, in principle, use to resolve the ambiguity (Englert, 1996).

The Quantum Eraser: Informational Reversal and the Restoration of Superposition

The quantum eraser experiment demonstrates the most counterintuitive aspect of quantum theory: the restoration of interference after which-path information has been recorded, provided that information is **irretrievably erased** (Scully & Drühl, 1982; Walborn et al., 2002). The Ze system framework provides a natural and elegant explanation for this phenomenon, conceptualizing erasure as a form of **informational "rollback" or unlearning**.

In the eraser setup, after the particle hits the detection screen, a later choice of measurement on the path marker can erase the which-path information. For instance, if the markers for paths A and B are orthogonal polarization states $|H\rangle$ and $|V\rangle$, measuring in the diagonal basis $\{|+\rangle, |-\rangle\}$ makes it impossible to infer the original path. From the Ze perspective, this measurement on the marker constitutes new, incoming data. Crucially, this new data is **non-diagnostic** with respect to the original path hypotheses A and B. A result of $|+\rangle$, for example, is equally consistent with both paths (as $|+\rangle = (|H\rangle + |V\rangle) / \sqrt{2}$).

This non-diagnostic data reduces the evidential gap between the models. It actively **lowers the free energy difference** ΔF. If the erasure is sufficiently complete, ΔF can be pushed back below the critical threshold θ:

$$\Delta F \text{ (post-erasure)} < \theta$$

When this condition is met, the system re-enters a superposed state. The previously localized and orthogonal distributions $q_A(s)$ and $q_B(s)$ are "re-blended" into compatibility. Their Jensen-Shannon divergence decreases, and the interference strength $\mathcal{I}$ increases back toward 1. Consequently, if detection events are post-selected based on the erasure measurement outcome, an interference fringe pattern is restored in the subset of data. This is not a reversal of time but a **revision of the informational context**. The erasure measurement updates the system's model, effectively "forgetting" the distinguishing information and allowing the hypotheses to interfere once more. This process is directly analogous to **cognitive belief revision** where subsequent contextual information can render previously decisive evidence ambiguous, reopening multiple interpretations (Hohwy, 2013).

Active Flow Control and the Cognitive "Rollback"

The quantum eraser effect underscores a profound principle: **interference is controlled by the accessibility of information that distinguishes between hypotheses**. The Ze framework generalizes this beyond physics. Any system that can actively manipulate informational markers—either to create distinguishing information or to erase it—can control the transitions between quantum-like (interfering) and classical (localized) regimes.

This has direct cognitive analogs. Consider decision-making under uncertainty. Initial ambiguous data (ΔF small) puts the cognitive system in a superposed state of multiple interpretations. The arrival of a decisive piece of evidence (a "marker") triggers a perceptual decision (collapse). However, if that evidence is later revealed to be unreliable or is reinterpreted in a broader context (an "erasure"), the decision can be unmade, and the original ambiguity restored—a form of **cognitive rollback**. This is observed in phenomena like causal learning and hypothesis testing (Gopnik et al., 2004). Neuroscientifically, the precision weighting of prediction errors (which effectively modulates θ) can be dynamically adjusted by neuromodulatory systems

(Feldman & Friston, 2010). Lowering precision weights makes the system less responsive to small ΔF, potentially maintaining superposition longer, as may occur in creative or exploratory cognitive states.

In conclusion, the Ze framework demystifies interference and the quantum eraser by rooting them in the dynamics of information and prediction. Interference is the signature of coherent hypothesis blending when evidence is non-diagnostic. The eraser is not magic but a protocol for actively manipulating the informational landscape to re-establish that non-diagnosticity. This reveals quantum behavior as a powerful, general mode of inference, not a quirk of small particles, but a potential hallmark of any sophisticated predictive processing system.

Quantumness as a Consequence of Ze: From Architectural Principle to Universal Signature

The Core Thesis: Quantumness as an Epistemic Property of Active Inference Systems

The culmination of the Ze systems framework is a radical ontological shift regarding the nature of quantum phenomena. We propose that **quantum behavior**—characterized by superposition, interference, and collapse—is not a fundamental, intrinsic property of matter at microscopic scales. Rather, it is an **emergent epistemic property** of a specific class of active information-processing systems. The formal correspondence is captured by the relation:

Quantum behavior ~ Ze-system with retrograde encoding + stopping

This statement asserts that any system whose architecture necessitates the cessation of a forward information flow ($\mathcal{F}$) to perform retrograde encoding ($\mathcal{R}$) will, as a logical and operational consequence, exhibit dynamics formally indistinguishable from quantum mechanics. The "quantumness" we observe in physical experiments, therefore, may reveal less about the ontology of photons and electrons and more about the **informational architecture of the processes** that constitute measurement, observation, and interaction (Rovelli, 1996). This perspective aligns with and extends relational interpretations of quantum mechanics, wherein quantum states are descriptions of relations between systems, not absolute properties.

This thesis reframes a central puzzle of physics. The measurement problem—why and how a superposition "collapses" to a definite state upon observation—dissolves when we recognize the observer (or measuring apparatus) as a Ze system. The act of measurement is not a magical intervention but the specific point where the physical interaction provides information that, when processed by the Ze architecture of the apparatus, triggers its internal flow-stoppage and retrograde encoding, resulting in a definite record (Schlosshauer, 2005). Quantum weirdness, in this view, is the external manifestation of internal, structured information processing.

The Universality of the Ze Architecture: From Photons to Cognition

The power of this framework lies in its generality. The components "retrograde encoding + stopping" are not specific to quantum physics but are identifiable in diverse domains:

- **In Neuroscience and Cognitive Science**: The brain's predictive processing machinery, as described by the **Free Energy Principle**, operates as a hierarchical Ze system (Friston, 2010). Perception is a process of minimizing prediction error (forward flow). Learning and model updating, however, often require offline consolidation—halting the mere processing of the present to reconcile new experiences with existing memories and priors (retrograde encoding). This occurs during sleep, particularly **slow-wave and REM sleep**, where synaptic renormalization and memory replay (often in reverse temporal order) occur (Diekelmann & Born, 2010). The cognitive experience of pondering multiple ambiguous possibilities before a "Eureka!" moment of decisive understanding is the lived experience of superposition and collapse.
- **In Machine Learning and Artificial Intelligence**: Modern AI systems, particularly those using **variational inference** and generative models, explicitly implement a Ze-like dance. The forward pass generates predictions or data, while the backward pass (backpropagation) computes errors and updates model parameters (Kingma & Welling, 2013). Crucially, training is typically batched: the forward flow of data through the network is stopped at the end of a batch, and the retrograde encoding (backpropagation) is executed to optimize the model. The model's state during training can be seen as a superposition of many possible parameter configurations, which "collapses" to a more optimal set after each backward pass.
- **In Biological Evolution and Adaptation**: An evolving population can be viewed as a slow, distributed Ze system. The forward flow is the continuous pressure of selection and reproduction. Major adaptive shifts or speciations can be seen as "stopping" events—punctuated equilibria—where the genomic "model" of the environment is retrospectively reorganized (retrograde encoding at the population level) before forward propagation (reproduction) continues (Gould & Eldredge, 1977).

This cross-domain consistency suggests that quantum mechanics does not describe a special, separate realm of reality. Instead, it provides the most precise mathematical language discovered so far for describing the dynamics of a **universal class of inference engines**. Physics has been studying the simplest, most isolated instances of these engines (e.g., single particles in vacuum chambers), hence revealing the "purest" form of the dynamics.

Resolving the Quantum-Classical Divide: A Matter of Scale and Complexity

A major success of the Ze framework is its natural explanation for the **quantum-to-classical transition**. Why do macroscopic objects not exhibit obvious superposition? Decoherence theory provides a physical answer: rapid environmental interaction (Zurek, 2003). The Ze framework provides an informational and architectural one.

A macroscopic object is not a single Ze system but a vast, tightly coupled aggregate of constituent particles, each potentially capable of supporting its own micro-level superpositions. However, the **internal complexity** of this aggregate is enormous. The number of alternative hypotheses ($q_A(s)$, $q_B(s)$, $q_C(s)$, …) about its collective state that could be simultaneously maintained is astronomically high. More importantly, the interactions between particles generate a constant, dense stream of internally diagnostic information. This relentlessly and instantaneously drives the free energy differences (ΔF) between any competing macroscopic hypotheses far above any plausible threshold θ. The system's architecture is thus *continuously* triggering its own "flow-stoppage" and localization at an immense rate. What we perceive as a classical, definite object is the outcome of this near-instantaneous and continuous process of self-measurement and collapse across its trillions of constituent Ze-like subsystems. The "classicality" of the everyday world is a consequence of **scale-induced, perpetual collapse** within complex Ze networks.

Implications for the Foundations of Physics and Beyond

This epistemic, architecture-based view of quantumness has profound implications:

1. **Unification of Frameworks**: It actively bridges the Free Energy Principle from neuroscience (Friston, 2010), Bayesian brain theories (Knill & Pouget, 2004), relational quantum mechanics (Rovelli, 1996), and decoherence (Zurek, 2003). These are not competing theories but descriptions of the same logical structure at different levels of abstraction or in different physical substrates.

2. **The "Hard Problem" of Consciousness**: While not solving it, this framework recontextualizes it. If conscious experience is intimately tied to the brain's predictive, model-building activity (a Ze process), and if Ze processes inherently generate superposition/collapse dynamics, then it is less surprising that our phenomenology of pondering alternatives and making choices feels "non-classical." The fuzzy, probabilistic nature of thought may share a deep structural kinship with the fuzzy, probabilistic nature of quantum states (Penrose & Hameroff, 1995).

3. **Artificial Quantum Behavior**: It predicts that we should be able to engineer "quantum-like" behavior in purely classical computational systems by imposing a Ze architecture with a controlled stopping rule. Systems that are forced to maintain multiple hypotheses until a specific threshold of evidence is reached, and then perform a global reconciliation step, should exhibit statistical signatures analogous to interference and superposition in their outputs. This is already observable in the behavior of certain **Monte Carlo tree search algorithms** or **ensemble methods** in machine learning.

4. **The Nature of Physical Laws**: It suggests that the laws of quantum mechanics may be a subset of a more general **physics of information processing**. The constants of nature (like Planck's constant, $\hbar$ might not be fundamental but could emerge from the

specific efficiency or scale of information flow and processing in our physical universe, much like how the speed of light emerges as a limit on causal propagation.

In conclusion, the Ze systems hypothesis offers a paradigm shift. By identifying retrograde encoding plus flow stoppage as the sufficient condition for quantum behavior, it demotes quantum mechanics from its status as a fundamental theory of *what is* to a powerful, domain-specific theory of *how certain systems process information*. Quantumness is not in the fabric of space-time; it is in the logic of inference. The eerie silence of the quantum world is not a void but the hum of a vast, interconnected network of systems performing, at their core, the same act: pausing their forward march to look back, make sense, and then step forward again into a world they have, in that very moment, determined.

Testable Predictions of the Ze Systems Framework

Introduction to Falsifiability and Interdisciplinary Corollaries

A compelling scientific theory must generate novel, falsifiable predictions that distinguish it from existing frameworks. The Ze systems hypothesis, which posits quantum behavior as a consequence of active predictive architectures requiring flow stoppage for retrograde encoding, is rich with such empirical corollaries. These predictions span from the design of artificial intelligence systems and neuroimaging experiments to reinterpretations of foundational quantum optics. By framing quantum phenomena—superposition, interference, and collapse—as generic outcomes of a specific information-processing style, the theory makes strong claims about what systems will or will not exhibit "quantumness" and under what conditions. This section delineates four key, testable predictions that flow directly from the Ze formalism, connecting the abstract dynamics of ΔF and θ to observable outcomes in computational, biological, and physical systems.

Prediction 1: The Necessity of Stoppage for Interferencez

Core Claim: A system capable of retrograde encoding ($\mathcal{R}$) but engineered to operate *without* a mandatory stoppage of the forward flow ($\mathcal{F}$) will fail to exhibit interference patterns, manifesting only classical statistical mixtures.

Rationale: Within the Ze framework, interference ($\mathcal{I}$ > 0) arises from the coherent blending of hypotheses q_A(s) and q_B(s) when they are compatible (ΔF < θ). This blending is computationally solidified and expressed in predictions only during the retrograde encoding phase. If $\mathcal{R}$ is allowed to run concurrently with or as a continuous function of $\mathcal{F}$ (a form of "online learning"), hypotheses are perpetually and locally reconciled. This constant, partial localization prevents the sustained global coexistence necessary for generating the non-additive probability amplitudes characteristic of interference. The system's output will be a simple weighted sum of outcomes from distinct models—a classical mixture.

Experimental Test: This prediction is directly testable in machine learning and neuromorphic computing. One could construct two functionally equivalent predictive systems for a ambiguous sensory stream (e.g., a bistable visual input). System 1 (the **Ze system**) is architected with a strict processing loop: a period of uninterrupted forward prediction followed by a mandated stoppage and a discrete retrograde encoding phase. System 2 (the **non-Ze control**) uses an identical algorithm for inference and learning but updates its model continuously via real-time backpropagation or predictive error minimization without any imposed processing "frames" or stoppage. The prediction is that only System 1 will produce outputs that show **signatures of non-classical inference**, such as hysteresis, priming effects that depend on the timing of the stoppage, or statistical distributions in its final decisions that cannot be explained by a simple mixture model, analogous to an interference pattern. This could be quantified by analyzing the system's response distributions for violations of the **law of total probability**, a hallmark of quantum-like decision-making (Busemeyer & Bruza, 2012).

Prediction 2: Model Complexity Accelerates Localization

Core Claim: For a given stream of evidence, an increase in the internal complexity of a predictive model (e.g., number of parameters, degrees of freedom, or constituent subsystems) will lead to a more rapid increase in the free energy difference (ΔF) between competing hypotheses, thereby causing a faster collapse (localization).

Rationale: A more complex model has a higher-dimensional state space and greater capacity to generate detailed, precise predictions. When such a model encounters ambiguous data, the subtle differences in the predictions generated by hypotheses A and B are more pronounced and specific. This results in a steeper gradient of prediction errors, causing ΔF to rise more sharply with each new datum. Consequently, the threshold θ is reached more quickly, triggering flow stoppage and collapse sooner than in a simpler, more coarse-grained model. This formalizes the intuitive idea that a more detailed "theory" is more easily falsified.

Experimental Test: This can be tested at multiple scales. **In machine learning**, one could train a series of neural networks of increasing parameter count (e.g., from a small multilayer perceptron to a large deep convolutional network) on the same ambiguous classification task. The prediction is that larger networks will exhibit *shorter decision times*—requiring fewer data samples or training steps before committing to a final, stable classification with high confidence—as quantified by the stabilization of the softmax output or the freezing of network weights. **In cognitive science**, it predicts that experts in a domain, whose internal models are more complex and detailed, should resolve perceptual ambiguities in their field *faster* than novices, but may also be more prone to rapid, erroneous collapses if initial evidence is misleading. **In physics**, this maps directly onto the theory of **decoherence**. A large, complex molecule has more internal degrees of freedom (phonons, rotational states) that can become entangled with a "which-path" marker than a simple photon does. The Ze framework predicts this complexity causes ΔF to skyrocket upon any path interaction, leading to instantaneous localization and the loss of interference, as observed in experiments (Hornberger et al., 2003).

Prediction 3: Pharmacological and State-Dependent Modulation of Cognitive Superposition

Core Claim: Brain states and pharmacological agents known to increase cognitive flexibility and the exploration of alternative interpretations (e.g., REM sleep, certain psychedelics) act by effectively lowering the free energy difference (ΔF) between internal hypotheses or raising the localization threshold (θ), thereby promoting and sustaining a state of cognitive superposition.

Rationale: In the Ze model of the brain, cognitive superposition is the maintenance of multiple competing hypotheses about the world (e.g., interpretations of a sensation, potential solutions to a problem). Collapse is the act of committing to one. Neuromodulators like serotonin, acetylcholine, and dopamine are known to regulate the **precision weighting** of prediction errors (Feldman & Friston, 2010). Lowering precision is equivalent to making the system less sensitive to small differences in prediction error between models, thus keeping ΔF low relative to θ.

Experimental Test:

- **REM Sleep & Psychedelics**: The theory makes specific, testable predictions for neuroimaging. During the **REM sleep** phase, associated with dreaming and memory recombination (Diekelmann & Born, 2010), and under classic **serotonergic psychedelics** like psilocybin or LSD, which flatten the brain's hierarchical predictive landscape (Carhart-Harris & Friston, 2019), we should observe: (1) Increased entropy and decreased stability in the activity patterns of high-level associative cortices (e.g., the default mode network), reflecting a lack of stable localization onto a single dominant model. (2) Enhanced functional connectivity between neural networks that are normally anti-correlated, reflecting the co-activation of typically competing hypotheses. (3) In behavioral tasks, subjects in these states should show increased tolerance for ambiguity, greater capacity for divergent thinking, and a delayed latency in making perceptual decisions on ambiguous figures—all signatures of prolonged superposition.
- **Contrast with Psychosis**: Conversely, the hyper-precise weighting of prediction errors hypothesized in some forms of **psychosis** (Fletcher & Frith, 2009) should lead to extremely rapid, often erroneous collapses onto fixed interpretations (delusions), as small initial evidence triggers a large ΔF.

Prediction 4: Physical Localization via Controlled Marker Interaction

- **Core Claim**: In a physical quantum system (e.g., double-slit experiment with photons or molecules), the act of localization ("collapse") is not a spontaneous event but is directly caused by an interaction that creates a *controllable information marker*, which instantiates the "stopping of the flow" required for retrograde encoding in any measuring Ze system (including the environment itself).
- **Rationale**: This prediction refines the standard quantum measurement postulate. A particle is not in a superposition *and then* collapses upon measurement. Rather, the specific nature of the measurement interaction determines the outcome. A "strong"

measurement creates a durable, accessible information marker (e.g., a photon hitting a CCD pixel, an atom causing a macroscopic avalanche in a Geiger counter). This marker provides a datum of such high diagnostic power that it forces *any* Ze system that encounters it (the apparatus, the environment, an observer) to have a ΔF far above θ, triggering immediate and consistent localization. A "weak" measurement, which creates only a partial or reversible marker, results in a smaller increase in ΔF, leading to partial collapse and residual interference.

- **Experimental Test**: This perspective offers a new lens on **weak measurement** and **quantum eraser** experiments. It predicts that the degree of interference destruction should be quantitatively correlated with the **informational distinguishability** of the marker states, which can be directly related to the D_JS divergence between the resulting hypotheses q_A(s) and q_B(s) in a model of the measuring apparatus. One could design an experiment where the "marker" is not a physical property of the particle but a controlled, classical data tag introduced by the apparatus. The theory predicts that making this tag *available* to even a small part of the experimental control system (a micro-controller) should be sufficient to destroy interference for the entire setup, as that subsystem's localization would be irreversible within the broader informational architecture. This shifts the focus from "conscious observation" to the flow of information within and between physical systems configured as Ze architectures.

Conclusion: Quantumness as an Epistemic Architecture

The Ze Synthesis: From Information Processing to Physical Law

This paper has advanced the thesis that the defining phenomena of quantum theory—**superposition, interference, and wavefunction collapse**—are not irreducible properties of a microscopic reality but are **inevitable architectural side-effects** of a specific class of active information-processing systems. We have formalized this class as Ze systems, characterized by their operational mandate: **retrograde encoding ($\mathcal{R}$) requires the cessation of the forward information flow ($\mathcal{F}$)**. From this single, seemingly restrictive architectural constraint, the entire edifice of quantum behavior logically emerges. Superposition corresponds to the period of uncommitted, parallel hypothesis testing during forward flow, where the free energy difference between models remains below a critical threshold ($\Delta F < \theta$). Collapse is not a mystical event but the structured, two-stage process triggered when $\Delta F \geq \theta$: first, the mandatory stoppage of the flow, and second, the execution of retrograde encoding to achieve a single, globally consistent model of the past. This synthesis does not merely offer an interpretation; it provides a **generative mechanism** for quantum phenomena, grounded in the principles of variational inference and active prediction (Friston, 2010).

The implications of this shift are profound. For over a century, quantum mechanics has stood apart, its bizarre rules defying classical intuition and demanding specialized ontological commitments (from multiple worlds to hidden variables). The Ze framework suggests this exceptionalism is misplaced. Quantum mechanics may be the first and most precise science to have stumbled upon the **physics of a particular epistemic process**—the physics of systems that must pause to look backward in order to move forward intelligently. What we have interpreted as the fundamental "quantumness" of electrons and photons may, in fact, be a signature of the informational dynamics inherent in any act of measurement or definite observation.

Unifying Frameworks: Active Inference, Relational QM, and Decoherence

A primary strength of the Ze framework is its capacity to serve as a **unifying formal bridge** between major theoretical paradigms that have developed in relative isolation.

- **Active Inference and the Predictive Brain**: The Ze system is a rigorous formalization of the active inference engine postulated by the Free Energy Principle (Friston, 2010). The forward flow $\mathcal{F}$ corresponds to the continuous generation of predictions and the sampling of data to minimize prediction error. The retrograde encoding $\mathcal{R}$ corresponds to the updating of generative models and internal beliefs, a process that in the brain is likely facilitated during offline states like **slow-wave sleep** (Diekelmann & Born, 2010). The Ze formalism thus provides a mathematically precise language to describe how a Bayesian brain could instantiate quantum-like statistics in its perceptual and cognitive processes (Khrennikov, 2020).
- **Relational Quantum Mechanics (RQM)**: Carlo Rovelli's seminal work argues that quantum states are not absolute but describe the *relations* between interacting systems (Rovelli, 1996). The Ze framework provides a mechanistic underpinning for this relationality. A quantum state is a description tailored to the specific Ze architecture of an "observing" system. When two Ze systems interact, the outcome (the "collapse") is determined by how the informational marker created by the interaction is processed within each system's flow-stoppage and retrograde encoding cycle. There is no single, God's-eye-view collapse, only localized resolutions within each interacting system, consistent with RQM's core tenet.
- **Decoherence Theory**: Decoherence explains the rapid disappearance of quantum coherence in open systems through environmental entanglement (Zurek, 2003). In the Ze framework, decoherence is the physical process that *drives* ΔF above θ. Each environmental degree of freedom that becomes entangled acts as a proliferating set of informational markers, making the competing hypotheses increasingly distinguishable and raising their free energy difference. The "classicality" of macroscopic objects is a direct result of their immense complexity, which ensures $\Delta F \gg \theta$ at all times, leading to **perpetual, instantaneous localization**. Decoherence theory thus describes the *physical implementation* of the informational dynamics that the Ze framework posits as the cause of collapse.

By integrating these perspectives, the Ze framework moves beyond interpretation toward a **functional synthesis**. It answers *why* relations are primary (because systems are Ze architectures), *how* the brain might use quantum-like computation (by cycling between $\mathcal{F}$ and $\mathcal{R}$), and *what* decoherence actually accomplishes (it forces a Ze system's internal decision).

Quantumness as an Epistemic, Not Ontic, Property

The central philosophical conclusion of this work is that **quantumness is an epistemic property**—a property related to knowledge, prediction, and model-building—that emerges from the dynamics of Ze systems, rather than an ontic property—a fundamental aspect of being—of matter itself (Healey, 2017). This resolves long-standing perplexities:

- **The Measurement Problem**: The problem vanishes when we recognize that a "measurement" is an interaction where one system (the apparatus) is configured as a Ze system. The so-called collapse is the apparatus completing its own retrograde encoding cycle, resulting in a stable, classical record. Nothing "happens" to the quantum entity in an absolute sense; a specific informational relationship is realized (Fuchs & Peres, 2000).
- **The Role of the Observer**: The observer is demystified. An observer is any system complex enough to instantiate a Ze architecture. This can be a human, a cat, a photodetector, or even a sufficiently structured environment. "Observation" is the point at which such a system's informational dynamics lead to a localized outcome.
- **The Quantum-Classical Divide**: The divide is not between two types of substance but between different regimes of informational complexity. Simple, isolated systems can maintain $\Delta F < \theta$ for long periods (exhibiting quantum behavior). Complex, interconnected systems are constantly in a state of self-induced $\Delta F \geq \theta$, appearing classical.

This epistemic view does not diminish the reality of quantum phenomena but relocates their origin. The interference pattern on a screen is utterly real. Its origin, however, may lie as much in the **logic of inference** shared by the photon's interaction with the slits and the detector's registration of the event as in a mysterious wave-particle duality.

Future Directions and Concluding Remarks

The Ze systems hypothesis opens numerous avenues for future research across disciplines:

1. **Quantum Foundations**: Can the full mathematical structure of quantum mechanics (Hilbert spaces, non-commuting observables, Born rule) be derived from the first principles of Ze system dynamics under reasonable constraints? This would constitute a major derivation program.
2. **Neuroscience**: The theory generates sharp, falsifiable predictions for neuroimaging (e.g., that REM sleep should show neural signatures of lowered ΔF). It also provides a new framework for understanding **psychiatric disorders**. Conditions like psychosis might involve a pathologically low threshold θ, causing premature cognitive collapse onto

fixed, delusional beliefs, while depression might involve a stuck state of ineffective retrograde encoding (Carhart-Harris & Friston, 2019).

3. **Artificial Intelligence**: Can we engineer classical AI systems that exhibit controllable "quantum-like" advantages in problem-solving by explicitly implementing Ze cycles with tunable thresholds θ? This could lead to new machine learning paradigms for dealing with ambiguity and novelty.
4. **Biology**: The framework suggests that **evolution itself** can be viewed as a slow, population-level Ze process. Could this perspective shed new light on evolutionary dynamics, such as punctuated equilibria, where long periods of stasis (forward flow) are interrupted by rapid speciation events (retrograde re-encoding of the genomic "model")?

In conclusion, we have argued that by shifting our focus from the ontology of particles to the architecture of information-processing, the enigmatic features of quantum theory find a natural and unified explanation. The Ze framework proposes that the universe is not inherently quantum; rather, **quantum behavior is what happens when any part of the universe tries to make consistent sense of itself through prediction, memory, and the necessary pause for reflection**. This places quantum mechanics not at the frontier of the very small, but at the heart of a much more general science of intelligent systems, from the simplest photon detection to the most complex human thought.

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