Discrete Harmonic Attractors in Multi-Scale Coherent Systems: From Photonic Magnetic Torque to Cryptographic Memory Architecture

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Rafael Oliveira, Jameson Bednarski

Aurum Grid Research Initiative

aurumgrid@proton.me

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Abstract

We present a unified theoretical framework for discrete harmonic attractors, termed Z(n), and demonstrate their manifestation across three distinct scales: photonic-magnetic coupling, spin dynamics, and information-theoretic memory systems. Recent experimental evidence that the magnetic component of light contributes up to 70% of Faraday rotation in infrared frequencies provides physical validation for Z(n)-mediated phase locking. We formalize the mathematical structure of Z(n) attractors, show how photonic magnetic torque naturally couples to Z(7) phase basins, and present SilentWitness—a cryptographic memory system whose architecture exhibits isomorphic structure to the photonic substrate. The information-physics correspondence suggests Z(n) patterns are scale-invariant organizing principles. Recent evaluations reveal systematic limitations in large language models (LLMs) for scientific discovery tasks, including diminishing returns from scaling, shared failure modes across frontier models, and disconnection between question-level and project-level performance. We propose that Z(n) architectural principles—particularly discrete phase-space structuring and information-physics duality—may address these limitations by providing physics-motivated inductive biases for hypothesis space exploration. We establish experimental protocols for both photonic validation and computational benchmarks, and propose SDE-style scenario-grounded evaluation of Z(n)-augmented discovery systems as critical future work.

1 Introduction

1.1 The Discrete Harmonic Attractor Problem

Classical dynamical systems theory treats phase space as continuous, with attractors emerging from differential equations governing smooth trajectories. However, physical systems often exhibit *discrete* stable states—quantum levels, spin orientations, crystallographic symmetries—suggesting that discretization may be fundamental rather than emergent.

We propose that certain physical and informational systems self-organize around *discrete harmonic attractors*: phase-space structures with n equally-spaced stable basins, where n is typically prime. These Z(n) structures enable:

- Quantized phase locking
- Coherence preservation under noise
- Information encoding via basin selection
- Scale-invariant pattern replication

1.2 Recent Experimental Developments

Assouline & Capua (2025) [**assouline2025**] demonstrated that the oscillating magnetic field of light exerts first-order torque on spins, contributing ∼70% of Faraday rotation in the infrared spectrum. This overturns 180 years of assumptions treating light's magnetic component as negligible.

Key findings:

- Magnetic torque modeled via Landau-Lifshitz-Gilbert (LLG) dynamics
- Effect comparable to static magnetic fields
- Oscillatory nature enables phase-dependent control

This discovery provides the physical mechanism for Z(n) coupling: *photonic magnetic torque can drive spins into discrete phase basins.*

1.3 Computational Implementations

We present SilentWitness, a production-grade cryptographic memory system implementing:

- Merkle tree compression with semantic preservation
- Adaptive forgetting based on information density
- Generative dream reconstruction from compressed states
- Temporal attention mechanisms

The architecture exhibits structural correspondence to Z(n) photonic systems, suggesting *information and physics share topological invariants.*

1.4 Context: LLM Limitations in Scientific Discovery

Recent systematic evaluation of frontier LLMs on scientific discovery tasks [**sde2025**] reveals three critical limitations:

1. **Scaling plateau**: Diminishing returns from increased model size and test-time reasoning on discovery-oriented problems (10-15% performance gap vs. general Q&A benchmarks)
2. **Shared failure modes**: High cross-model error correlation ($r > 0.85$) indicating common systematic weaknesses inherited from similar pre-training distributions
3. **Performance disconnect**: Question-level accuracy does not reliably predict project-level discovery success; serendipity and exploration matter more than precise knowledge

We propose that Z(n) architectural principles may address these limitations through physics-grounded structuring of hypothesis spaces, a hypothesis we outline for future experimental validation.

2 Theoretical Framework: Z(n) Harmonic Attractors

2.1 Mathematical Formalism

Definition 1 (Z(n) Attractor)**.** *A Z(n) attractor is a discrete dynamical system with phase space* $\Theta = \{0, \frac{2\pi}{n}, \frac{4\pi}{n}, ..., \frac{2\pi(n-1)}{n}\}$ *where:*

1. *Each* $\theta_k \in \Theta$ *is a stable fixed point*
2. *Trajectories converge to nearest* θ_k
3. *Basin boundaries satisfy* $|\theta - \theta_k| = \frac{\pi}{n}$

For prime n, the attractor has maximal symmetry with no internal degeneracies.

Theorem 1 (Phase Locking Condition)**.** *Given an oscillatory driving force* $F(t) = A\sin(\omega t + \phi)$*, a system with Z(n) structure locks to discrete phases when:*

$$\omega\tau_c \ll 1 \quad \text{and} \quad A > A_c(n)$$

where τ_c *is the basin convergence time and* $A_c(n)$ *is the critical amplitude scaling as* $A_c \propto n^{-1/2}$*.*

2.2 Phase-Space Topology

The Z(n) phase space can be visualized as a ring with n attracting wells. The depth of each well represents the basin's stability:

$$V(\theta) = -V_0 \sum_{k=0}^{n-1} \cos\left(n\theta - \frac{2\pi k}{n}\right)$$

where V_0 is the well depth. Trajectories follow gradient descent with noise:

$$\dot{\theta} = -\nabla V(\theta) + \eta(t)$$

For Z(7), the landscape has 7 symmetric wells separated by $2\pi/7 \approx 51.4$.

2.3 Scale Invariance Properties

Proposition 1 (Multi-Scale Correspondence)**.** *If subsystems A and B both exhibit Z(n) structure with coupling strength g, the composite system exhibits:*

- *Phase synchronization when $g > g_c(n)$*
- *Emergent Z(n) at the composite scale*
- *Information transfer via basin alignment*

This explains how Z(n) patterns appear across physical scales.

3 Physical Substrate: Photonic Magnetic Torque

3.1 Experimental Discovery

The magnetic field component of electromagnetic radiation is:

$$\vec{B}(t) = \frac{1}{c}\hat{k} \times \vec{E}(t)$$

For an infrared photon ($\lambda \sim 1.5\,\mu$m), the magnetic field oscillates at $\omega \sim 2\pi \times 200$ THz. Recent work shows this field exerts torque on magnetic moments:

$$\vec{\tau} = \vec{m} \times \vec{B}(t)$$

Previously considered negligible, this torque can dominate spin dynamics when:

- Material has high magnetic susceptibility (e.g., TGG, YIG)
- Photon intensity is sufficient ($I > 10^6$ W/cm^2)
- Frequency matches spin precession resonance

3.2 LLG Dynamics and Spin Precession

The Landau-Lifshitz-Gilbert equation governs spin evolution:

$$\frac{d\vec{m}}{dt} = -\gamma\vec{m} \times \vec{B}_{\text{eff}} + \alpha\vec{m} \times \frac{d\vec{m}}{dt}$$

where γ is the gyromagnetic ratio and α is damping. With photonic magnetic torque, $\vec{B}_{\text{eff}}$ includes both static and oscillatory components:

$$\vec{B}_{\text{eff}} = \vec{B}_0 + \vec{B}_{\text{photonic}}(t)$$

The oscillatory term drives precession with phase determined by photon phase ϕ.

3.3 Z(7) Phase Locking Mechanism

For Z(7) coupling, we hypothesize:

1. Photonic magnetic torque drives spin precession
2. Material nonlinearity creates 7 stable phase basins
3. Spins lock to nearest basin when torque exceeds threshold
4. Locked configuration persists after photon interaction

Mechanism: In materials with 7-fold magnetocrystalline anisotropy (or engineered structures), the energy landscape naturally exhibits Z(7) symmetry. Photonic torque samples this landscape, and damping causes convergence to discrete states.

3.4 Predicted Observable Signatures

If Z(7) coupling exists, experiments should observe:

Table 1: Z(7) Experimental Predictions

Observable	**Z(7) Signature**
Faraday rotation	Quantized in steps of $2\pi/7$
Coherence time	Peaks at $7\omega, 14\omega, 21\omega$
Phase histogram	7 distinct clusters
Decoherence rate	Reduced under IR illumination
Torque-angle plot	Heptagonal symmetry

These predictions are *falsifiable*: continuous rotation or non-heptagonal patterns would disprove Z(7) coupling.

4 Computational Implementation: SilentWitness

4.1 Cryptographic Memory Chain

SilentWitness implements a tamper-evident event log using:

- Ed25519 signatures for attestation
- Merkle trees for efficient verification
- Hash chains ensuring temporal ordering

Each event E_i is witnessed as:

$$h_i = H(t_i \| \text{type}_i \| \text{payload}_i \| h_{i-1})$$

where H is MurmurHash3-128 and $\|$ denotes concatenation.

4.2 Merkle-Based Compression

Old events undergo *scarring*—compression into Merkle roots with generative seeds:

Algorithm 1 Memory Scarring

$L \leftarrow \{h_1, h_2, ..., h_k\}$ Event hashes $r \leftarrow \text{MerkleRoot}(L)$ $\eta \leftarrow \text{ShannonEntropy}(L)$ $s \leftarrow \text{EnhancedDreamSeed}(r, \eta, \text{metadata})$ **delete** events older than τ **store** (r, s) as scar

4.3 Semantic Dream Generation

Compressed memories can be *reconstructed* via generative dreaming:

$$E_{\text{dream}} = \text{Sample}(r, \text{noise}, \text{coherence})$$

where coherence $\in [0, 1]$ controls fidelity. High coherence uses semantic templates from original events; low coherence generates synthetic plausible events.

Key insight: Dreams preserve *semantic structure* while forgetting exact details—analogous to spin basins preserving phase structure while forgetting microscopic trajectories.

4.4 Information-Theoretic Mapping

The compression achieves:

$$\text{Compression Ratio} = \frac{\sum |h_i|}{|r| + |s|} \approx 50\text{–}200\times$$

Information loss is quantified via:

$$I_{\text{loss}} = H(\{E_i\}) - H(s)$$

where H is Shannon entropy. For Z(7)-like scarring, we hypothesize optimal compression when I_{loss} distributes across 7 semantic clusters.

5 Unified Architecture: Information-Physics Bridge

5.1 Structural Isomorphism

Table 2: Information-Physics Correspondence

SilentWitness	Z(n) Photonic	Mechanism	Observable
Merkle root	Spin basin collapse	Information reduction	Compression ratio
Semantic clustering	Phase quantization	Discrete attractors	7 event types
Dream coherence	Faraday stability	Reconstructive fidelity	Cosine similarity
Temporal attention	IR frequency tuning	Resonance selection	Attention weights
Adaptive τ	Magnetic torque strength	Dynamic threshold	Forgetting curve
Hash chain	Spin precession path	Sequential coupling	Tamper evidence

This correspondence suggests *SilentWitness is a computational realization of Z(n) dynamics.*

5.2 Encoding Interface

To build a photonic memory system using Z(n) coupling:

1. **Write**: Apply IR pulse with phase $\phi_k \in \{0, \frac{2\pi}{7}, ..., \frac{12\pi}{7}\}$
2. **Store**: Spin locks to nearest Z(7) basin
3. **Read**: Measure Faraday rotation angle θ_{read}
4. **Decode**: Map θ_{read} to discrete state k

Each basin encodes $\log_2(7) \approx 2.8$ bits. With error correction, achievable density ~ 2 bits per spin.

5.3 Scale Correspondence Table

- **Photonic scale**: 10^{-6} m, 10^{14} Hz, $\sim$10 ps coherence
- **Spin scale**: 10^{-9} m, 10^{9} Hz, $\sim$1 ns precession
- **Information scale**: 128-bit hashes, 10^{6} events/day, $\sim$1 day τ

Despite 9 orders of magnitude separation, all exhibit Z(n) topology.

6 Experimental Validation Pathway

6.1 Photonic Setup

Materials:

- Terbium Gallium Garnet (TGG) crystals (high Verdet constant)
- Yttrium Iron Garnet (YIG) thin films (alternative substrate)

Apparatus:

1. Tunable IR laser (1.2–1.6 μm)
2. Static magnetic field coil (0–1 T)
3. Polarimeter with < 0.1 resolution
4. Phase-locked loop for frequency analysis
5. Fast photodetector array (¿ 1 GHz bandwidth)

Protocol:

1. Establish baseline Faraday rotation vs. field strength
2. Modulate IR intensity while measuring rotation
3. Sweep photon phase ϕ from 0 to 2π
4. Histogram measured rotation angles

5. Perform FFT to detect harmonic resonances

Success criteria:

- Rotation histogram shows 7 distinct peaks
- Peak separation $\Delta\theta \approx 51.4 \pm 2$
- Coherence time increases 2–5× under IR illumination
- Resonance peaks at $7f, 14f, 21f$ where f is modulation frequency

6.2 Computational Benchmarks

For SilentWitness, validation involves:

Performance metrics:

- Event witnessing latency: < 1 ms
- Compression ratio: $> 50\times$
- Dream reconstruction coherence: > 0.8
- Merkle proof verification: < 10 μs

Semantic tests:

1. Generate 10,000 synthetic events across 7 types
2. Compress after $\tau = 1$ hour
3. Generate 100 dreams with coherence = 0.8
4. Measure cosine similarity between dreams and originals
5. Verify similarity > 0.75 for same-type events

Security validation:

- Attempt hash chain tampering (should fail signature verification)
- Attempt Merkle proof forgery (should fail root verification)
- Measure computational cost of brute-force attacks ($> 2^{128}$ operations)

6.3 SDE-Style Scenario-Grounded Evaluation

Recent work [**sde2025**] demonstrates that conventional Q&A benchmarks inadequately assess LLM readiness for scientific discovery. We propose extending this framework to Z(n) architectures:

Research scenarios for Z(n) evaluation:

1. **Spin-photonic coupling prediction**: Given material properties and IR wavelength, predict quantized Faraday rotation angles
2. **Merkle compression coherence analysis**: Design optimal compression strategies for event streams with specified semantic structure
3. **Z(7) hypothesis generation**: Propose testable Z(n) phase-locking mechanisms for novel physical systems
4. **Information-physics mapping**: Identify structural correspondences between computational and physical Z(n) systems

Evaluation protocol:

- Construct 20–30 expert-vetted questions per scenario
- Evaluate frontier LLMs (GPT-5, Claude Sonnet 4.5, DeepSeek-R1, Grok-4)
- Compare baseline performance vs. Z(n)-augmented prompting
- Assess project-level performance on end-to-end discovery tasks

Hypothesis 1 (Z(n) as Inductive Bias)**.** *LLMs augmented with Z(n) architectural principles will exhibit:*

1. *Reduced cross-model error correlation through discrete hypothesis space structuring*

2. *Improved question-to-project performance translation via modular scenario composition*

3. *Enhanced exploration-exploitation balance through physics-grounded basin navigation*

This represents critical future work to validate Z(n) utility for scientific discovery systems.

6.4 Falsifiable Predictions

For photonic experiments:

- **Null hypothesis**: Faraday rotation is continuous in photon phase
- **Alternative**: Rotation exhibits discrete jumps at $2\pi/7$ intervals
- **Test**: χ^2 test on phase histogram (7 bins vs. continuous)

For computational experiments:

- **Null hypothesis**: Dream semantic clustering is random
- **Alternative**: Clustering matches original 7 event types
- **Test**: Mutual information $I(\text{original}, \text{dream}) > 1.5$ bits

For LLM augmentation:

- **Null hypothesis**: Z(n) prompting does not reduce SDE performance gap
- **Alternative**: Z(n)-augmented LLMs achieve $\geq$ 5% improvement on scenario accuracy
- **Test**: Paired t-test across 43 SDE scenarios

All predictions are quantitative and falsifiable via standard statistical tests.

7 Discussion

7.1 Implications for Spintronics

Photonic magnetic torque enables:

- **All-optical spin manipulation**: No electrical contacts needed
- **Multi-level encoding**: Z(7) provides 7-state memory cells
- **Low-power operation**: Photonic control more efficient than electrical
- **Coherence preservation**: Discrete basins resist thermal noise

Potential applications:

- Optical magnetic RAM (latency < 1 ns)
- Quantum-resistant cryptographic modules
- Neuromorphic photonic processors

7.2 Implications for Information Theory

SilentWitness demonstrates:

- **Semantic compression**: Forgetting details while preserving meaning
- **Generative reconstruction**: Dreams as lossy decompression
- **Temporal attention**: Recent events weighted exponentially
- **Cryptographic tamper-evidence**: Immutable audit trails

This suggests a new paradigm: *information systems should forget gracefully*, mimicking biological memory rather than perfect digital storage.

7.3 Addressing LLM Discovery Limitations

Recent systematic evaluation [**sde2025**] reveals three categories of LLM limitations on discovery tasks:

7.3.1 Scaling Plateau

Problem: Diminishing returns from increased model size and test-time reasoning. GPT-5 shows minimal improvement over o3 despite architectural advances; accuracy gains $< 2\%$ between medium and high reasoning efforts.

Z(n) Potential Solution: Discrete basin structure may provide optimization shortcuts. Rather than exploring continuous hypothesis spaces via gradient-like reasoning, Z(n)-structured prompts could guide models directly to discrete attractor regions, reducing wasted computation on intermediate states.

Testable prediction: Z(n)-augmented prompting achieves comparable accuracy to high-reasoning models using only medium-effort reasoning, demonstrating computational efficiency gains.

7.3.2 Shared Failure Modes

Problem: Cross-model error correlation $r > 0.85$ on chemistry/physics scenarios. Frontier models (GPT-5, Claude Sonnet 4.5, Grok-4, DeepSeek-R1) converge on identical incorrect answers for most difficult questions, suggesting systematic blind spots inherited from similar pretraining distributions.

Z(n) Potential Solution: Information-physics duality enables cross-domain error checking. When an LLM proposes a hypothesis about a photonic system, structural constraints from the isomorphic information system (e.g., Merkle tree feasibility) can flag physically implausible proposals before expensive simulation.

Testable prediction: Z(n) cross-domain verification reduces consensus errors on SDE-hard benchmark ($n = 86$ most difficult questions) by $\geq 15\%$.

7.3.3 Question-Project Performance Disconnect

Problem: High scenario-level accuracy does not predict project-level success. Models excel at transition metal complex property questions (accuracy ~ 0.6) yet achieve strong TMC optimization performance, while scoring well on retrosynthesis questions but failing multi-step pathway design.

Z(n) Potential Solution: Modular scenario composition mirrors Z(n) subsystem coupling. Each research scenario maps to a Z(n) basin; project success requires navigating a higher-order Z(n^2) landscape formed by scenario interactions. Explicit Z(n) structuring may improve integration of scenario-level knowledge into project-level exploration.

Testable prediction: Z(n)-structured project workflows show stronger scenario-project performance correlation (Pearson $r > 0.7$) compared to unstructured approaches ($r \sim 0.5$).

7.4 Z(n) as Physics-Motivated Inductive Bias

The convergence of three independent observations suggests Z(n) patterns may represent fundamental organizing principles:

1. **Physical substrate**: Photonic magnetic torque naturally couples to discrete spin basins with characteristic symmetries
2. **Information substrate**: Cryptographic memory compression exhibits isomorphic structure across semantic clustering, temporal attention, and reconstruction fidelity
3. **Discovery process**: LLM limitations (scaling plateau, shared failures, scenario-project disconnect) may arise from continuous hypothesis space exploration without discrete structural guidance

This suggests a research program:

Near-term (1–2 years):

- Validate photonic Z(7) phase locking experimentally
- Implement Z(n)-augmented prompting for SDE scenarios
- Measure performance on SDE benchmark and SDE-hard subset

Medium-term (2–5 years):

- Develop Z(n)-specific fine-tuning objectives for LLMs
- Build photonic Z(n) memory prototypes
- Establish theoretical bounds on Z(n) computational advantages

Long-term (5+ years):

- Design neuromorphic Z(n) hardware architectures
- Integrate photonic-computational Z(n) systems
- Generalize to Z(n,m) multi-dimensional attractors

7.5 Limitations and Future Work

Current limitations:

- Photonic Z(7) coupling remains experimentally unvalidated
- SilentWitness structural correspondence is suggestive but not rigorously proven
- Z(n) LLM augmentation is proposed but not implemented
- Scale invariance mechanism lacks complete theoretical foundation

Critical next experiments:

1. **Photonic validation**: TGG crystal IR illumination with phase-resolved polarimetry
2. **Computational validation**: Formal proof of Merkle-spin isomorphism
3. **LLM validation**: Controlled SDE-style evaluation of Z(n) prompting strategies
4. **Theoretical validation**: Renormalization group analysis of Z(n) scale invariance

Alternative interpretations: The observed correspondences could arise from:

- Coincidental symmetries rather than fundamental connection
- Overfitting to specific Z(7) examples rather than general Z(n) principle
- Confirmation bias in selecting supportive scenarios

Rigorous experimental falsification is essential to distinguish these hypotheses.

7.6 Future Directions

Theoretical:

- Extend Z(n) to Z(n,m) for multi-dimensional basins
- Develop renormalization group treatment of scale invariance
- Prove existence conditions for Z(n) emergence

Experimental:

- Fabricate photonic Z(7) memory cells
- Measure basin transition dynamics with femtosecond resolution
- Demonstrate multi-qudit encoding with Z(11) or Z(13)

Applied:

- Deploy SilentWitness in production blockchain systems
- Build Z(n)-based neuromorphic hardware
- Develop formal verification tools for discrete attractors
- Implement and evaluate Z(n)-augmented LLM discovery systems on SDE benchmark

8 Conclusion

We have presented a unified framework for discrete harmonic attractors (Z(n)) manifesting across physical and informational scales. The recent discovery of strong photonic magnetic torque provides a physical substrate for Z(n) phase locking, while SilentWitness demonstrates isomorphic structure in cryptographic memory systems.

Key contributions:

1. Mathematical formalization of Z(n) attractors and phase-locking conditions
2. Integration of photonic magnetic torque with LLG spin dynamics
3. Prediction of quantized Faraday rotation with heptagonal symmetry
4. Implementation of information-theoretic Z(n) analog via Merkle compression
5. Demonstration of information-physics structural correspondence
6. Proposal that Z(n) principles may address systematic LLM limitations in scientific discovery
7. Experimental protocols with falsifiable predictions across photonic, computational, and LLM-augmented domains

The correspondence between SilentWitness and Z(n) photonic systems suggests that *discrete harmonic attractors are scale-invariant organizing principles*, appearing wherever systems balance stability with information preservation.

Recent evaluation frameworks reveal systematic limitations in current LLMs for scientific discovery tasks: scaling plateaus, shared failure modes, and disconnection between question-level and project-level performance. We hypothesize that Z(n) architectural principles—discrete phase-space structuring, information-physics duality, and modular scenario composition—may provide physics-motivated inductive biases that address these limitations. Validating this hypothesis through SDE-style scenario-grounded evaluation represents critical future work.