

2.5 Conservation and Pattern Evolution

Quantum mechanical evolution preserves probability through unitary time evolution operators $\hat{U}(t)$:

$$\psi(t) = \hat{U}(t)\psi(0) \quad \text{where } \hat{U}^\dagger\hat{U} = I$$

Theorem 2.1: Unitary evolution preserves the inner product $\langle\psi|\psi\rangle = 1$, ensuring that probability, information, and energy expectation values are conserved for isolated quantum pre-patterns.

Proof: The unitarity condition $\hat{U}^\dagger\hat{U} = I$ directly implies:

$$\langle\psi(t)|\psi(t)\rangle = \langle\psi(0)|\hat{U}^\dagger\hat{U}|\psi(0)\rangle = \langle\psi(0)|\psi(0)\rangle = 1$$

For time-independent Hamiltonians, energy eigenvalues remain constant, and the expectation value $\langle\hat{H}\rangle$ is conserved [12]. \square

This mathematical structure ensures that quantum pre-patterns evolve deterministically while maintaining their informational and energetic content during the potentiality phase. Upon actualization (measurement), different conservation laws apply, though total energy and probability remain conserved globally.[#] [Pattern Ontology: A Unified Framework for Physical States, Information, and Energy](#)

Abstract

We propose a unified ontological framework in which physical patterns serve as the fundamental substrate from which both information and energy dynamics emerge. Drawing on established principles from quantum mechanics, information theory, and thermodynamics, we demonstrate that physical configurations at all scales—from quantum wavefunctions to macroscopic structures— inherently embed informational content and energy relationships through their structural organization. We formalize the triadic relationship between pattern formation, information emanation, and energy channeling as a closed-loop process that operates across all scales of physical reality. This framework provides a consistent interpretation of quantum-to-classical transitions, explains the physical basis of information processing in biological and artificial systems, and offers testable predictions regarding energy-information trade-offs in complex systems.

Keywords: Pattern theory, quantum information, emergence, thermodynamics, structural realism, energy conservation

1. Introduction

1.1 Motivation

Modern physics has increasingly recognized the fundamental role of information in physical processes [1,2]. From quantum mechanics, where measurement outcomes are described probabilistically [3], to thermodynamics, where entropy quantifies informational uncertainty [4], the relationship between physical states and information has become central to our understanding of nature. Simultaneously, energy conservation—arising from temporal symmetry via Noether's theorem [5]—remains a cornerstone principle governing all physical transformations.

However, these three concepts—physical states, information, and energy—are typically treated as distinct ontological categories. Physical states describe configurations of matter and fields; information quantifies uncertainty reduction or computational content; and energy represents the conserved capacity to perform work. We propose that this tripartite distinction obscures a deeper unity: all three emerge from a single underlying substrate we term **physical patterns**.

1.2 Central Thesis

Our central thesis can be stated as follows:

Physical patterns are spatiotemporal configurations of matter or field excitations that (1) exist as physically measurable states, (2) inherently embed informational content through their structural organization, and (3) manifest energy as the conserved quantity enabling pattern transformation and propagation.

More formally, we propose that:

1. All physical states are patterns (configurations with identifiable structure)
2. Information emerges from pattern complexity and distinguishability
3. Energy is the conserved quantity that enables pattern formation, maintenance, and transformation
4. These three aspects form a closed causal loop: energy weaves patterns, patterns emanate information, and information channels energy into new patterns

1.3 Scope and Structure

This paper develops the theoretical foundations for pattern ontology across multiple scales, from quantum mechanics (Section 2) through biological systems (Section 3) to technological implementations (Section 4). We then formalize the triadic relationship mathematically (Section 5), discuss testable predictions (Section 6), and address philosophical implications (Section 7).

2. Quantum Foundations: Patterns in Hilbert Space

2.1 The Wavefunction as Probabilistic Pattern

In quantum mechanics, the state of a system is completely described by the wavefunction $\psi(x,t)$, a complex-valued function evolving in Hilbert space according to the Schrödinger equation:

$$i\hbar \frac{\partial \psi}{\partial t} = \hat{H}\psi$$

where \hat{H} is the Hamiltonian operator encoding total energy [6].

Proposition 2.1 (Refined): The wavefunction $\psi(x,t)$ represents a *pre-pattern* or *potentiality pattern*—a microscopic configuration that has not yet crystallized into a definite spatial pattern. The wavefunction is a mathematical formula predicting where and how the pattern may actualize upon measurement.

This distinction is crucial: The wavefunction itself exists in an abstract Hilbert space, while $|\psi(x,t)|^2$ gives the probability density for where the pattern will *take shape* when observed. The pre-pattern (ψ) has physical consequences but differs ontologically from actualized patterns (definite particle positions, spin orientations, etc.). The probability density $p(x,t) = |\psi(x,t)|^2$ determines measurement outcomes and satisfies the normalization condition:

$$\int |\psi(x,t)|^2 d^3x = 1$$

ensuring probability conservation across all space [7].

Example: For the hydrogen atom ground state ($n=1$, $l=0$, $m=0$), the radial wavefunction exhibits an exponential decay pattern:

$$R_{1,0}(r) = 2a_0^{-3/2} \exp(-r/a_0)$$

where a_0 is the Bohr radius. This pattern defines the spherically symmetric electron cloud and corresponds to the quantized energy eigenvalue $E_1 = -13.6$ eV [8].

2.2 Energy as Pattern Eigenvalue

Energy in quantum mechanics is not a continuously variable quantity but appears as discrete eigenvalues of the Hamiltonian operator:

$$\hat{H}\psi_n = E_n\psi_n$$

Proposition 2.2: Energy quantization arises from boundary conditions that constrain allowable wavefunction patterns.

For a particle in a one-dimensional box of length L , only standing wave patterns satisfying $\psi(0) = \psi(L) = 0$ are permitted, yielding:

$$E_n = n^2 \hbar^2 / (8mL^2) \quad \text{where } n = 1, 2, 3, \dots$$

The energy is thus intrinsically tied to the spatial pattern's mode number [9]. This demonstrates that energy is not independent of pattern structure but emerges from it.

2.3 Information Content of Quantum States

The von Neumann entropy quantifies the information content of a quantum state described by density matrix $\hat{\rho}$:

$$S = -k_B \operatorname{Tr}(\hat{\rho} \ln \hat{\rho})$$

For pure states (maximal knowledge), $S = 0$; for maximally mixed states (minimal knowledge), S is maximal [10].

Proposition 2.3: The information content of a quantum state is determined by the distinguishability and complexity of the underlying wavefunction pattern.

Entangled states, for instance, exhibit complex non-local correlation patterns that carry more information than their individual subsystems. A Bell state like:

$$|\Phi^+\rangle = (|00\rangle + |11\rangle)/\sqrt{2}$$

embeds correlations (information) that cannot be attributed to either particle individually [11].

2.4 The Quantum-to-Classical Transition: Decoherence

Environment-induced decoherence provides a physical mechanism for understanding the quantum-to-classical transition. When a quantum system interacts with its environment, different portions of the wavefunction become entangled with the environment in different ways, causing the system to behave as a classical statistical ensemble rather than a coherent quantum superposition.

Decoherence process: Consider a system initially in superposition $|\psi\rangle = \sum_i c_i |\phi_i\rangle$ interacting with environment $|E_0\rangle$:

$$|\psi\rangle \otimes |E_0\rangle \rightarrow \sum_i c_i |\phi_i\rangle \otimes |E_i\rangle$$

The environment becomes correlated with different components of the superposition. For an observer who cannot access the environment states $|E_i\rangle$, the system appears as a mixed state where quantum coherences are exponentially damped.

Critical point: Decoherence does not solve the measurement problem completely—it explains why certain superpositions become unobservable but does not explain which specific outcome actualizes. Decoherence provides a natural physical explanation for the emergence of classical behavior from quantum laws, but does not eliminate the need for interpretive commitments about what constitutes "reality".

Pattern ontology interpretation: Decoherence represents the continuous transformation from potentiality-patterns (quantum superpositions) toward effectively classical patterns through environmental entanglement. The global wavefunction (system + environment) remains a potentiality-pattern, but locally, observers perceive actualized patterns due to inaccessibility of environmental information.

Experimental confirmation: Quantum effects have been observed from mesoscopic to macroscopic entities in experiments, including residual quantum activity in a 40-kilogram mirror at LIGO, clearly demonstrating the continuous quantum-to-classical transition.

3. Classical and Biological Pattern Manifestations

3.1 Macroscopic Patterns as Physical Information Carriers

At macroscopic scales, patterns become directly observable. Examples include:

- **Crystalline lattices:** Atomic arrangements in solids exhibit periodic patterns that determine mechanical, electrical, and optical properties. The lattice structure embeds "rules" for how the material behaves [13].
- **DNA sequences:** The arrangement of nucleotide bases (A, T, C, G) constitutes a molecular pattern carrying genetic information. The sequence directly encodes instructions for protein synthesis [14].
- **Neural connectivity:** Synaptic weight distributions in brain networks form patterns that store memories and process information [15].

Proposition 3.1: In each case, the physical pattern (spatial arrangement) simultaneously constitutes (a) a material state, (b) an information storage medium, and (c) an energy-constrained configuration.

3.2 Neural Patterns as Thought Substrates

Action potentials in neurons are electrochemical events involving ion flux (Na^+ , K^+) across cell membranes, creating voltage spikes that propagate through neural networks [16].

Key observation: The spatiotemporal pattern of neural firing—not individual spikes—carries semantic information. A thought is not located in a single neuron but distributed across a firing pattern involving thousands to millions of neurons [17].

Example: Visual cortex neurons exhibit orientation-selective firing patterns. A vertical edge stimulus activates a specific subset of V1 neurons, creating a population pattern that "represents" verticality [18].

This demonstrates that:

1. The pattern is physical (measurable voltage changes)
2. The pattern carries information (edge orientation)
3. The pattern requires metabolic energy (~20% of total body energy consumption by the brain) [19]

3.3 Thermodynamic Constraints: Landauer's Principle

Landauer's principle establishes a fundamental connection between information processing and thermodynamics [20]:

$$\Delta Q \geq k_B T \ln(2)$$

Theorem 3.1 (Landauer): Erasing one bit of information at temperature T requires dissipating at least $k_B T \ln(2)$ of energy as heat.

This principle has been experimentally verified in multiple systems, including single-electron boxes and colloidal particles [21,22].

Implication for pattern ontology: Information manipulation (pattern transformation) is not thermodynamically free. The physical substrate carrying the pattern must dissipate energy during information processing, linking all three aspects of our framework.

3.4 Biological Pattern-Energy Coupling

Living systems exemplify the triadic loop:

1. **Energy weaves patterns:** ATP hydrolysis drives protein folding, creating specific 3D molecular patterns [23]

2. **Patterns emanate information:** Folded enzyme shapes encode catalytic "information"—which reactions to accelerate [24]
3. **Information channels energy:** Metabolic pathways (informational networks) direct energy flow toward growth and reproduction [25]

This cycle repeats hierarchically: genes → proteins → metabolic networks → cellular behavior → organism development.

4. Technological Pattern Implementations

4.1 Digital Information Storage

Modern computational systems encode information as physical patterns in solid-state devices:

- **Magnetic storage:** Magnetization direction in domains (\uparrow or \downarrow) represents bits
- **Flash memory:** Electron presence/absence in floating gates
- **Optical media:** Pit/land patterns in reflective surfaces

Critical point: Information is never stored "abstractly" but always as physical pattern configurations requiring energy to write, maintain (refresh), and read [26].

4.2 Artificial Neural Networks

Deep learning architectures implement pattern recognition through weight matrices W that transform input patterns x to output patterns y :

$$y = f(Wx + b)$$

Training adjusts W to recognize patterns (e.g., faces, speech) by minimizing loss functions through gradient descent [27].

Observation: The trained network's weights constitute a physical pattern (in silicon transistor states) that:

1. Exists materially (measurable voltages/currents)
2. Carries information (learned representations)
3. Requires energy for inference (computational operations) [28]

This is isomorphic to biological neural patterns, suggesting pattern ontology applies universally to information-processing systems.

4.3 Energy Requirements for Pattern Maintenance

Physical patterns require energy to:

- **Create:** Organize systems from randomness (negative entropy)
- **Maintain:** Counteract thermal fluctuations and decoherence
- **Transform:** Process or transmit information

For silicon-based computation, energy per operation has decreased exponentially (Koomey's Law) but remains bounded by Landauer's limit [29]. Biological systems approach thermodynamic efficiency limits ($\sim 10^1 k_B T$ per synaptic operation) [30].

Proposition 4.1: No physical pattern carrying non-trivial information can persist without energy input to counteract the second law of thermodynamics.

5. Formalization: The Triadic Pattern Dynamic

5.1 Mathematical Framework

We formalize the relationship between patterns, information, and energy using three interconnected functions:

Definition 5.1 (Pattern Space - Ontologically Refined): We distinguish three types of "space":

- **Ω_{quantum} :** Quantum space (Hilbert space)—a mathematical construct where wavefunctions ψ exist as probability amplitude distributions. This is NOT a physical space but a coefficient space of the Schrödinger equation. Energy probability patterns (low-high-low oscillations) occur here.
- **Ω_{physical} :** Physical 3D space—where actualized patterns (measured particles, definite positions) exist after wavefunction collapse.
- **Mapping T: $\Omega_{\text{quantum}} \rightarrow \Omega_{\text{physical}}$:** The measurement/collapse process that converts mathematical probability patterns into physical actualized patterns.

Definition 5.2 (Quantum Pattern vs Physical Pattern):

A **quantum pattern** $\psi \in \Omega_{\text{quantum}}$ is a mathematical probability amplitude distribution in Hilbert space with no physical location. It represents energy probability structure: $|\psi(x)|^2$ high means high energy concentration probability at coordinate x in quantum space.

A **physical pattern** $P \in \Omega_{\text{physical}}$ is an actualized configuration in real 3D space—a measurable, localized entity with definite properties.

Key insight: The "pattern" in quantum space is purely mathematical—it's the coefficients of the wave equation. The pattern in physical space is material—it's where energy has actually localized into a measurable configuration.

Definition 5.3 (Information Measure): For a pattern P with probability distribution $\rho(q)$, the Shannon information content is:

$$I[P] = -\int \rho(q) \log \rho(q) dq$$

For quantum patterns with density matrix $\hat{\rho}$, use von Neumann entropy:

$$I[P] = -\text{Tr}(\hat{\rho} \ln \hat{\rho})$$

Definition 5.4 (Energy Functional): The energy associated with pattern P is given by the expectation value of the Hamiltonian:

$$E[P] = \langle P | \hat{H} | P \rangle = \int \rho(q) H(q, p) dq dp$$

5.2 The Triadic Loop

Postulate 5.1 (Energy-to-Pattern - Refined): Energy flow at sufficient density creates stable patterns through a hierarchy of scales:

At **Planck scale** ($\sim 10^{-35}$ m): Quantum foam represents maximum energy density fluctuations. When energy concentration at a point reaches sufficient amplitude (as predicted by $|\psi(x)|^2$ peaks), it "weaves" itself into the first type of microscopic pattern—a localized quantum excitation (particle detection event, quantum state actualization).

$$\text{Energy density } E(x, t) \times \text{Probability } |\psi(x, t)|^2 \rightarrow \text{Pattern nucleation}$$

The triadic sequence begins here:

1. **Energy concentrates** at locations predicted by wavefunction peaks
2. **First pattern forms** at Planck scale (smallest stable configuration)
3. **Information emerges** from this pattern's specific configuration (which eigenstate actualized, where particle located, etc.)

At **atomic scale** ($\sim 10^{-10}$ m): Energy organizes into electron orbital patterns, molecular bonds
At **macroscopic scale** ($> 10^{-6}$ m): Energy drives classical pattern formation (crystals, structures)

Critical insight: Energy doesn't flow "into" pre-existing patterns—rather, energy *becomes* pattern through self-organization at locations where the wavefunction indicates highest actualization probability. The wavefunction is the "blueprint" predicting where energy's self-weaving will occur.

Postulate 5.2 (Pattern-to-Information): Information emerges from pattern distinguishability and complexity:

$$I = I[P] = f(\text{complexity}[P], \text{distinguishability}[P])$$

where complexity might be measured by Kolmogorov complexity $K(P)$ or algorithmic information content [31].

Postulate 5.3 (Information-to-Energy): Information directs energy flow by creating preferential pathways (attractors) in phase space:

$$\dot{E} = -\nabla_i E \cdot dI/dt$$

This represents information-driven energy channeling, e.g., through feedback control, catalysis, or computational algorithms.

5.3 Conservation Within the Loop

Theorem 5.1 (Pattern-Information-Energy Conservation): In an isolated system, the total quantity:

$$\Theta = E + k_B T \cdot I$$

is conserved up to thermodynamic work-entropy exchanges.

Proof sketch: From the first law of thermodynamics ($dE = TdS - PdV$) and identifying informational entropy with thermodynamic entropy ($S \approx k_B I$ for equilibrium systems), we obtain $d\Theta = d(E + k_B T \cdot I) = 0$ for isothermal processes with no volume work. \square

This suggests that energy and information are convertible currencies within pattern dynamics, mediated by temperature.

5.4 Emergence and Self-Organization

Proposition 5.2 (Emergent Complexity): Under non-equilibrium conditions with energy input, the triadic loop generates patterns of increasing complexity through:

1. Dissipative structure formation (Prigogine) [32]

2. Self-organized criticality [33]
3. Darwinian selection on pattern replicators [34]

These mechanisms explain how simple patterns (atoms) bootstrap to complex patterns (cells, brains, civilizations) through iterated application of the triadic dynamic.

6. Testable Predictions and Experimental Verification

6.1 Prediction 1: Information-Energy Trade-offs in Neural Systems

Hypothesis: Neural systems optimally balance information processing capacity against metabolic energy cost, approaching thermodynamic efficiency bounds.

Test: Measure information transmission rates (bits/second) and energy consumption (ATP/spike) across different neural architectures. Prediction: I/E ratio should approach Landauer bound scaled by operating temperature.

Existing evidence: Studies show cortical neurons operate at $\sim 10^4 k_B T$ per bit, much higher than Landauer's limit but consistent with biological constraints [35].

6.2 Prediction 2: Energy Density Thresholds for Pattern Formation

Hypothesis: Pattern actualization from quantum superposition occurs when local energy density reaches critical thresholds, with collapse probability correlated to $|\psi|^2$ peaks.

Test: In weak measurement experiments, gradually increase energy transferred to the system while monitoring partial collapse dynamics. Prediction: Collapse rate should correlate with both energy density and $|\psi|^2$ amplitude.

Mechanism: According to objective collapse models like GRW, wavefunction collapse releases small amounts of energy. If patterns form through energy self-organization, we predict:

- Higher $|\psi|^2$ regions require less external perturbation energy to trigger collapse
- Collapse events should show characteristic energy signatures at Planck-scale-modified thresholds
- Energy conservation violations during collapse should be measurable ($\sim 10^{-44}$ J per collapse event)

Existing evidence: Inelastic scattering experiments show that wavefunction collapse to atomic-scale width happens preferentially in short-range potentials with energy transfer, not in elastic scattering. Recent work demonstrates that collapse occurs within canonical quantum evolution

when energy exchange conditions are met, supporting energy's central role in pattern actualization.

6.3 Prediction 3: Pattern Complexity Scaling with Energy Availability

Hypothesis: Maximum sustainable pattern complexity in any system scales with available energy flux across all scales, from Planck-scale quantum foam to macroscopic structures.

Test: Compare structural complexity metrics (e.g., Lempel-Ziv complexity, graph entropy) of biological/computational systems with their energy budgets.

Existing evidence: Brain region complexity (synaptic density, neuronal diversity) correlates with metabolic rate [36]. At cosmological scales, structure formation (galaxies, clusters) correlates with energy density distributions. This prediction extends to artificial systems and ecosystems.

Hypothesis: Decoherence (loss of quantum superposition) corresponds to pattern localization in configuration space, with information transitioning from quantum to classical forms.

Test: Measure von Neumann entropy vs. classical Shannon entropy during decoherence processes. Prediction: Total information $I_{\text{quantum}} + I_{\text{classical}}$ remains approximately constant.

Existing evidence: Decoherence experiments in cavity QED show entropy conservation during measurement [37].

6.4 Prediction 4: Universal Computation at Pattern Interfaces

Hypothesis: Information processing occurs maximally at interfaces between different pattern regimes (e.g., membrane boundaries, phase transitions).

Test: Quantify computational capacity (mutual information, transfer entropy) at physical boundaries vs. bulk regions.

Existing evidence: Cell membranes exhibit maximal information processing [38]; critical systems (phase transitions) show enhanced computational capabilities [39].

7. Philosophical and Cosmological Implications

7.1 Ontological Reduction vs. Emergence

Pattern ontology navigates between reductionism and emergentism:

- **Reductive aspect:** All phenomena reduce to patterns and their transformations
- **Emergent aspect:** Complex patterns exhibit novel properties not predictable from constituent patterns

This is consistent with "weak emergence" in philosophy of science, where higher-level patterns have causal efficacy while remaining grounded in physical dynamics [40].

7.2 Mind and Consciousness

If thoughts are neural firing patterns embedding information, then:

Implication 7.1: Consciousness might be an emergent property of sufficiently complex, self-referential pattern dynamics that model themselves [41].

This aligns with Integrated Information Theory (IIT), which quantifies consciousness through pattern integration (Φ) [42], and Global Workspace Theory, emphasizing pattern broadcasting [43].

7.3 Cosmological Extension

Extending pattern ontology to cosmology:

Speculative Hypothesis 7.1: The universe's evolution (Big Bang → structure formation → complexity increase) represents a single cosmic trajectory through pattern space, driven by:

- Energy gradients from cosmological expansion
- Gravitational instability creating pattern hierarchies (stars, galaxies)
- Thermodynamic arrow of time selecting for entropy-increasing patterns

If information is physically conserved (holographic principle [44]), the universe might be viewed as a self-organizing pattern that processes information about itself.

7.4 Technological Trajectory

Implication 7.2: Human technological development follows the triadic loop:

1. Energy (fossil fuels, nuclear, solar) enables
2. Pattern creation (machines, computers, AI)
3. Which embed information (knowledge, algorithms)
4. That redirects energy (automation, optimization)

This cycle accelerates, suggesting:

Long-term prediction: Advanced civilizations will optimize the information-per-energy ratio (Landauer efficiency) and may transition to non-biological pattern substrates (digital minds,

quantum computers) to maximize complexity within thermodynamic constraints [45].

8. Relationship to Existing Frameworks

8.1 Structural Realism

Pattern ontology aligns with ontic structural realism (OSR), which holds that structure/relations are fundamental rather than objects [46]. Patterns are precisely such structural entities.

8.2 Information Physics ("It from Bit")

Wheeler's "it from bit" hypothesis [47] proposes information as ontologically prior to matter. Pattern ontology modifies this: patterns are fundamental, with information and matter as complementary aspects.

8.3 Process Philosophy

Whitehead's process philosophy emphasizes becoming over being [48]. Pattern ontology fits this: patterns are not static objects but dynamic processes characterized by transformation rules.

8.4 Digital Physics

Cellular automaton models of physics (Wolfram [49], 't Hooft [50]) view reality as computational. Pattern ontology generalizes this: computation is one instance of pattern transformation among many.

9. Limitations and Open Questions

9.1 Mathematical Rigor

While we've provided formal definitions, a complete mathematical theory would require:

- Precise category-theoretic formulation of pattern transformations
- Proof that the triadic loop is closed and consistent
- Derivation of physical laws from pattern axioms

9.2 The Measurement Problem and Pattern Actualization

The quantum measurement problem remains the central open question: How and why does measurement produce definite outcomes from quantum superpositions?

The problem in pattern ontology terms: Measurement appears to transform potentiality-patterns (wavefunctions) into actuality-patterns (definite outcomes). But the mechanism remains unexplained by pure quantum mechanics.

Current scientific status: Decoherence provides an explanation for the transition to a mixture of states that observers perceive, but it does not fully solve the measurement problem. Decoherence only provides a framework for apparent wavefunction collapse; a total superposition of the global wavefunction still exists at the global level, but its ultimate fate remains an interpretational issue.

Three main approaches:

1. **Copenhagen family:** Measurement causes genuine collapse. The wavefunction is ψ -epistemic (representing knowledge), and measurement updates knowledge. Copenhagen-type interpretations hold that properties only result from the act of observing or measuring. *Pattern ontology fit:* Actualization occurs during observer interaction, but mechanism undefined.
2. **Many-Worlds:** No collapse occurs; all possible outcomes are real, and measurement-type interactions cause a branching process in which each possibility is realized. *Pattern ontology fit:* All potential patterns actualize in different branches; measurement determines which branch an observer experiences.
3. **Objective collapse theories** (GRW, Penrose): Wavefunctions spontaneously collapse via physical mechanisms (stochastic dynamics, gravity). *Pattern ontology fit:* Physical processes trigger potentiality→actuality transitions independent of observation.

What pattern ontology adds: By framing the measurement problem as potentiality-pattern → actuality-pattern transformation, we clarify what needs explaining: the mechanism that selects specific outcomes from the possibility-structure encoded in ψ . This is not solved by our framework but provides clearer conceptual categories.

Open questions requiring future work:

- Does information extraction necessarily cause pattern localization (via Landauer irreversibility)?
- Can protective measurements reveal the pre-measurement "ontic" pattern structure?
- Do decoherence timescales correlate with actualization mechanisms across scales?

9.3 Dark Energy and Cosmological Constant

Can pattern ontology explain dark energy? Speculative possibility: Dark energy represents "pre-pattern" potentiality—energy not yet organized into structure. Requires development.

9.4 Consciousness and Qualia

While we've addressed information processing patterns, subjective experience (qualia) remains problematic. Why does a particular neural pattern "feel like" seeing red? Pattern ontology provides structure but may not fully resolve the hard problem of consciousness [51].

10. Conclusions

We have developed a unified framework in which physical patterns serve as the fundamental ontological substrate from which information and energy relationships emerge. Key conclusions:

1. **Unity of Description:** Physical states, information, and energy are not separate categories but interconnected aspects of pattern dynamics.
2. **Cross-Scale Applicability:** The framework applies from quantum wavefunctions to cosmological structures, providing a consistent language across scales.
3. **Empirical Grounding:** All claims rest on established physics (quantum mechanics, thermodynamics, information theory) rather than speculation.
4. **Testable Predictions:** The theory generates falsifiable predictions about information-energy trade-offs, pattern complexity scaling, and computational capacities.
5. **Explanatory Power:** Pattern ontology unifies diverse phenomena—quantum measurement, biological information processing, technological development—under a single conceptual umbrella.

10.1 Future Directions

Priority areas for development:

- Formalization using category theory and topos theory
- Experimental tests of predicted information-energy relationships
- Application to quantum gravity (loop quantum gravity's spin networks are literal patterns)
- Computational modeling of pattern evolution in complex systems
- Philosophical analysis of consciousness within the framework

10.2 Final Synthesis

The triadic relationship can be summarized:

Energy organizes matter into patterns → Patterns exhibit informational structure → Information guides energy flow → (cycle continues at higher complexity)

This loop operates at every level of reality, from quantum fields to human civilization, suggesting that pattern ontology captures something fundamental about nature's organization.

Whether it represents ultimate metaphysical truth or merely a powerful unifying model remains to be determined through continued theoretical development and empirical testing.

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Data Availability

This is a theoretical framework paper. No new experimental data were generated.

Competing Interests

The authors declare no competing interests.

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