

Triadic Constraint and Emergent Stability: A Meta-Theoretical Framework in Philosophy of Physics

The Singularity–Duality–Triality Framework

John Reimer Morales*

Independent Researcher

Abstract

We propose the Singularity–Duality–Triality (S-D-T) framework, a constrained meta-theoretical heuristic for characterizing systems in which stable higher-order organization emerges through mediation between competing dynamical structures, not a first-order physical theory. The framework addresses a question with roots in wave-particle complementarity: whether process-first descriptions reveal structural constraints that object-first descriptions systematically miss. Just as treating a photon as an interfering wavefunction rather than a particle reveals interference structure the particle description cannot access—a methodological rather than physical parallel—S-D-T proposes that treating a system’s organization as a generative process reveals the mediating constraint responsible for its stability—a reframing the framework is proposed to extend across physical, biological, and informational domains. Three contributions follow: (i) a formal definition of Triality with exclusion criteria and an operational novelty test; (ii) a framework-level falsification condition (F0) with pre-specification requirements; and (iii) the SAF (Stability–Adaptability–Functionality) Coherence Index, a domain-agnostic composite metric derived from the triadic grammar, whose cross-domain coherence-ratio approach finds independent methodological support in AlShehail’s [103] pre-registered validation of a structurally analogous metric across neural and symbolic domains. A minimal dynamical model demonstrates that triadic stabilization is non-reducible to parameter variation within the dual system. As secondary illustration, the framework is consistent with near-maximal leptonic CP violation ($|\delta_{CP}| \approx \pi/2$), testable by DUNE and Hyper-Kamiokande. Its validity depends on whether triadic mediation proves necessary in systems meeting the specified criteria.

Keywords: Emergent stability · Triadic constraint · Meta-theoretical framework · Ontic structural realism · Falsifiable heuristic · SAF Coherence Index · Philosophy of physics

*Corresponding author: jrm@globalharmonics.org

1 Introduction

Identifying recurring principles of emergent stability is a central challenge in science. As Philip Anderson argued in his landmark essay, the ability of complex systems to exhibit fundamentally new behaviors at each level of organization means that reductionism alone is insufficient; what is needed are principles that govern the emergence of stable, higher-order structures from simpler components [11]. This paper proposes such a principle: a generative sequence of Singularity, Duality, and Triality (S-D-T), offered not as a metaphysical law but as an operational and falsifiable heuristic model — one that does not argue triadic structure is ubiquitous, but that it may be necessary in a specific class of systems defined below. We define this process operationally in the language of dynamical systems:

- **Singularity:** A high-symmetry state occupying a single, stable basin of attraction. It is a foundational structure or “canvas” that serves as a domain for higher-dimensional interaction.
- **Duality:** A symmetry-breaking event that bifurcates the phase space, creating a system defined by the tension between two competing basins of attraction. This is a direct emergent property of the Singularity’s existence, manifesting as inherent tensions, bifurcations, or complementarities within the system.
- **Triality:** The emergence of a new constraint or mediating interaction that reshapes the phase space, resolving the dualistic tension into a new, more complex, and dynamically stable basin of attraction. We propose that this process is often physically realized as a *phase-inverted edge-state transition* (a heuristic label for the pattern; formal derivation is reserved for the companion mechanistic program), where the boundary of the interaction develops novel, robust, and persistent properties distinct from the bulk.

Formal Definition: Triality (S-D-T sense)

A system exhibits **Triality** in the S-D-T sense if and only if:

- (i) **(Duality prerequisite)** Two competing attractors exist whose persistent tension constitutes a structurally unstable configuration — the system cannot maintain indefinite equilibrium between them;
- (ii) **(Categorical novelty)** A third constraint emerges that is categorically absent from both competing bulk phases — it is not a combination, interpolation, or parameter-tuning of the two, but introduces a *new degree of freedom* into the system's phase space. The operational test for categorical novelty: the constraint satisfies *either* (4i) *or* (4ii), where these are alternative sufficient conditions — satisfying either is sufficient for classification as Triality:

- (4i) The constraint alters the topological dimension of the attractor manifold; or
- (4ii) The constraint introduces a symmetry that is absent from the algebra generated by the dual system's governing equations alone.

These two criteria are not jointly required; they are domain-specific proxies for the same underlying condition and either is sufficient. Condition (4i) is primary; (4ii) is a pragmatic diagnostic where deriving the attractor manifold formally is difficult. In empirical systems, demonstrating either suffices to satisfy condition (ii).

- (iii) **(Coherence production)** This constraint reduces the instability of the competing attractors and produces a higher-order stable basin that preserves both as subordinated internal tensions rather than eliminating either;
- (iv) **(Exclusion criterion)** Fine-tuning of existing parameters, without the introduction of a new organizational principle, does not qualify. A valid Triality cannot be derived solely from the resources of the Duality. A weighted average of the two attractor states is not a Triality; a constraint that merely adjusts the relative depth of existing wells without creating a topologically distinct basin is not a Triality.

This definition is domain-independent: the physical realization of conditions (i)–(iv) varies by domain (group-theoretic automorphism, topological boundary mode, gauge symmetry, biological process), but the functional role is invariant. The invariant is not the form but the function: *mediation of instability between competing structures by a categorically novel constraint that enlarges the system's organizational phase space*. These conditions are intended to be jointly sufficient but not necessarily exhaustive; borderline cases are expected and must be evaluated under pre-specified criteria (§4.3). Condition (iv)'s exclusion of parameter variation maps onto an independently identified distinction in constraint-based emergence [98], and the present framework's posture of treating cross-domain correspondence as rare and informative rather than as the default outcome is independently formalized by Zertuche [99], whose viability-level constraints (configurational multiplicity, constraint enforcement, information persistence, irreversibility) provide the ground floor on which S-D-T identifies a specific architectural solution.

Scope. S-D-T does not claim that all systems are triadic, or that triadic organization is the only form of higher-order stability. It identifies a *specific subset* of systems: those in which higher-order stability arises through a constraint satisfying conditions (i)–(iv). Systems that achieve stability through other mechanisms — direct parameter relaxation, external forcing, dissipation alone — are not S-D-T systems and are not claimed to be. The framework’s content is its identification of this subset and its argument that the subset is populated by physically significant examples.

To guard against structural inflation — the risk that the definition is satisfied too easily, leading to trivial identifications — we provide a class of explicit non-examples. A thermostat is not a Triality: it stabilizes a temperature by parameter adjustment (a feedback loop), but introduces no new degree of freedom and changes no topological dimension of the attractor manifold. A Lotka-Volterra predator-prey cycle is not a Triality: the oscillation between predator and prey populations constitutes a Duality, but the addition of a third species does not necessarily satisfy condition (ii) unless the third species plays a categorically novel organizational role (e.g., a keystone predator that does not simply add a third competitor but restructures the competitive dynamic entirely). A fine-tuned Grand Unified Theory (GUT) with no mediating third element is not a Triality: the doublet-triplet solution achieved by parameter adjustment within the same algebra is excluded by condition (iv). These non-examples bound the framework’s scope and prevent the “find three things, call it triadic” conflation that any cross-domain heuristic must guard against.

Why three and not more. A natural question is whether the framework generalizes: why not four-node closure, or higher-order simplices? The answer is that three is the *minimum* closure number for the specific organizational problem S-D-T addresses: resolving the tension between two competing attractors requires at least one mediating constraint, yielding a minimum of three organizational roles. This is a minimality claim with a stronger backing than mere convenience.

The backing is structural: conditions (i)–(iii) of the Formal Definition specify a system with exactly three distinct roles — two competing attractors and one mediating constraint. A two-role system satisfying condition (i) is, by definition, unstable (the Duality). A three-role system satisfying (ii) and (iii) is, by definition, the minimum configuration in which the instability is resolved without eliminating either competitor. Four-role systems are not forbidden; they arise in nested S-D-T cycles where the output S' becomes the Singularity of a new cycle. In this sense, apparent quartic configurations are compound triadic systems, not genuinely quartic closures. The framework claims minimality and recurrence for the triadic pattern, not universality or uniqueness. The empirical and information-theoretic backing for this structural argument — from network motif theory, the Triple Correlation Uniqueness theorem, Hodge decomposition, and quantum phase transitions induced by triadic clustering — is developed in Section 2.4, where it sits alongside the physical examples it corroborates.

The argument of the paper proceeds in five stages. First, we motivate the model’s structure with key physical phenomena from topological physics and the holographic principle (§2). Second,

we derive testable predictions from the Standard Model, including a detailed case study of the doublet-triplet problem as an instance of dualistic instability (§3). Third, we address directly the principal vulnerability of any cross-domain heuristic—the risk of post-hoc pattern-fitting—and define rigorous conditions for the model’s refutation, including a framework-level falsification condition (F0), a near-term experimental prediction, the SAF Coherence Index as a falsifiable empirical metric, explicit scope limitations, and a research program definition (§4). Fourth, we situate the framework within philosophical discussions of scientific realism, develop the SAF Coherence Index formally with the erythrocyte as a worked example, provide a minimal formal instantiation as a cusp catastrophe potential, and situate the heuristic within its philosophical lineage (§5). Finally, we conclude with a summary and a candid assessment of the work that remains (§6).

What this paper is, what it is not, and how to evaluate it. This paper advances S-D-T as: (1) a meta-theoretical heuristic for identifying mediating constraints in systems exhibiting dual instability; (2) a candidate real pattern subject to empirical testing; and (3) a possible precursor to deeper mechanistic theories, the first of which is under separate development. It does not claim to replace existing physical theories, to provide a universal account of emergence, or to constitute a mature scientific paradigm. Success should be evaluated by whether the framework imposes nontrivial constraints, survives falsification attempts, and generates productive cross-domain hypotheses—not by whether it achieves explanatory totality.

Example domain	Role in paper	Type	Evidential weight
Spin(8) $\rightarrow \mathbb{Z}_8$ classification	Formal instantiation	Mathematical chain	Strong (established)
Anyonic statistics	Physical illustration	Topological physics	Moderate (confirmed)
AdS/CFT conformal symmetry	Structural analogy	Heuristic mapping	Weak (illustrative)
Standard Model (force hierarchy)	Heuristic recontextualization	Speculative mapping	Weak (hypothesis only)
Standard Model (δ_{CP} prediction)	Forward prediction	Empirical hypothesis	Pending (5–10 yr)
SAF erythrocyte system	Empirical research lead	Testable metric	Pending (data available)

Table 1: Evidence architecture of the S-D-T framework. Each example plays a different argumentative role; they are not co-equal grounds for the framework. The paper’s core claims rest primarily on the formal instantiation and forward predictions; the heuristic mappings are illustrative only.

The framework is evaluated primarily through its formal definition and falsification condition; examples serve illustrative or heuristic roles unless otherwise specified in Table 1.

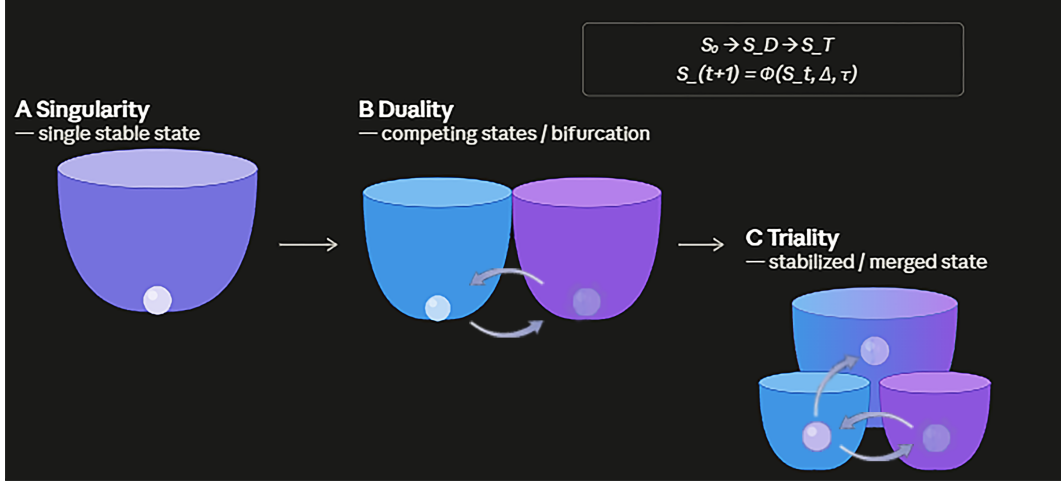


Figure 1: Dynamical schematic of the Singularity–Duality–Triality sequence. Panel A: a system in a single stable basin of attraction (Singularity)—the high-symmetry ground state from which structure emerges. Panel B: symmetry breaking bifurcates the phase space into two competing basins (Duality), each attracting the system state; the saddle point between them represents an unresolved, dynamically unstable configuration. Panel C: the emergence of a mediating constraint—the Triality—reshapes the phase space, merging both prior attractors into a new, larger basin at an intermediate level that incorporates and stabilizes the dualistic tension. The ball represents the system state; its color encodes identity, transitioning from neutral (A) through differentiated (B) to blended (C), reflecting the qualitative change in the system’s organizational character across the cycle. The inset equation $S_{t+1} = \Phi(S_t, \Delta, \tau)$ expresses the S-D-T process schematically: a system state S_t is acted on by a symmetry-breaking perturbation Δ and a mediating triadic constraint τ to produce the next-stage state. A concrete, fully specified instantiation of Φ as the gradient descent dynamics on the cusp catastrophe potential $V(x; u, v) = x^4 + ux^2 + vx$ is provided in Section 5.5 (Figure 6 and Table 4), where Δ and τ are explicit control parameters with calculable predictions. The three-panel sequence can also be read as the single production cycle of a minimal rewriting system: $S \rightarrow D$ (bifurcation), $D \rightarrow T$ (stabilization), $T \rightarrow S'$ (emergence), forming a cyclic L-system [70, 87] with $\mathbb{Z}_3$ cyclic symmetry. Iterated application of these three rules generates the recursive hierarchical structure depicted in Figures 4 and 5.

2 The Physical Motivation for a Triadic Heuristic

These examples are presented to illustrate compatibility with existing theory, not as independent confirmation of the framework. See Table 1 for the evidential status of each case.

The S-D-T model is induced from a recurring pattern of emergent stability observed across several frontiers of modern physics. This section presents three examples, chosen for their mathematical rigor and physical consequence. The examples increase in mathematical abstraction; the reader unfamiliar with Lie group theory may wish to focus on the physical consequences described in each case rather than the group-theoretic details. In each example,

a lower-dimensional boundary or canvas (Singularity) mediates a relationship between distinct physical domains (Duality) via a specific set of rules and symmetries (Triality) that define the stable, emergent physics of an edge-state.

2.1 The Structural Pattern of Spin(8) Triality

The Lie group Spin(8) possesses a unique, three-fold symmetry (triality) among its representations that is not found in any other simple Lie group [2, 3, 4, 5]. The generalizability of this structure beyond Spin(8) has been established on rigorous algebraic grounds. Kamiya (2021) has shown that triality groups arise systematically across a broad family of algebraic triple systems— (α, β, γ) -triple systems that generalize Jordan and structurable algebras—and that in every instance the triality symmetry is traceable to the D_4 Lie algebra that grounds Spin(8) itself [84]. This result is significant: it means that the three-fold symmetry we identify as Triality is not an accident of one exceptional group but a recurring feature of a wide class of algebraic systems equipped with a trilinear product.

This abstract mathematical structure has physically consequential implications through a chain of connections that the original presentation of this argument left implicit; making them explicit is essential for the claim's precision. The chain is as follows. Spin(8) triality is the statement that the three eight-dimensional representations of Spin(8) — vector (V), positive spinor (S^+), and negative spinor (S^-) — are mutually equivalent under the outer S_3 automorphism of the D_4 Dynkin diagram. This equivalence is exactly what makes the real Clifford algebra sequence have period 8 rather than any other period: $\text{Cl}(8) \cong M(16, \mathbb{R})$ is a full matrix algebra, and the sequence of real Clifford algebras $\text{Cl}(1), \text{Cl}(2), \dots$ repeats with period 8 because of the triality-mediated equivalence of the spinor and vector representations at dimension 8 [73, 3]. This eightfold periodicity of real Clifford algebras is, via the Atiyah-Bott-Shapiro construction [73], the mathematical basis of Bott periodicity in real K-theory. And it is this Bott periodicity that underlies the $\mathbb{Z}_8$ classification of topological phases in the real symmetry classes: as Kitaev (2009) established and Ryu, Schnyder, Furusaki, and Ludwig (2010) demonstrated in detail, the eightfold periodicity of the classification table directly reflects the eightfold periodicity of the spinor representations of the orthogonal groups $\text{SO}(N)$ [1, 6]. In S-D-T terms: the Lie group is the canvas (Singularity), its physical instantiation as the symmetry group of a topological superconductor produces the interaction (Duality), and the unique triality symmetry — via Clifford periodicity and Bott periodicity — is the mediating rule (Triality) that yields a robust, finite $\mathbb{Z}_8$ classification of topological phases. The connection between Spin(8) triality and the $\mathbb{Z}_8$ count is therefore not direct but mediated through real Clifford algebra periodicity; the chain is real and mathematically established, not merely analogical. For completeness: this $\mathbb{Z}_8$ periodicity is specific to the *real* symmetry classes (those with time-reversal or particle-hole symmetry); the complex symmetry classes, classified by complex K-theory via complex Clifford algebras, follow a $\mathbb{Z}_2$ periodicity and are not connected to the Spin(8) triality argument presented here [1, 6]. The S-D-T framework's engagement with the tenfold way is therefore scoped to the real case. To be precise about the claim: S-D-T does not derive the $\mathbb{Z}_8$ classification; it identifies the Spin(8) triality at its root as an instance of the triadic pattern it proposes to identify across

domains. The chain from $\text{Spin}(8)$ to $\mathbb{Z}_8$ is established mathematics; the S-D-T contribution is to recognize that chain's origin as a triadic symmetry and to ask whether analogous triadic origins underlie the pattern's recurrence elsewhere.

At the level of quantum chromodynamics, triality acquires a physically operational meaning. Ghanbarpour and von Smekal (2022) have explicitly constructed, in full lattice QCD with dynamical fermions, ensembles with fixed quark number modulo 3—the $\mathbb{Z}_3$ center charge of color—demonstrating that triality sectors are physically distinct, computationally separable, and thermodynamically significant [85]. This provides a concrete, lattice-calculable realization of the $\mathbb{Z}_3$ symmetry as an organizational constraint on the QCD phase space: the three-fold center charge is not merely a mathematical property of $\text{SU}(3)$ but an active physical boundary condition governing which states can exist in a finite volume.

At the level of formal analogy only, a triadic decomposition of field perturbations arises separately in general relativity: in the Teukolsky formalism for perturbations of Kerr black holes, all perturbation fields decompose into precisely three spin-weight sectors ($s = -2, -1, 0$), corresponding to gravitational, vector-like, and scalar-like modes respectively [83]. No claim of $\text{Spin}(8)$ symmetry in the gravitational context is made here, and no such symmetry is known to hold in four-dimensional GR. An important qualification is required: the three spin-weight sectors are not dynamically independent. In the full nonlinear theory, they couple through mode-mode interactions at second order in perturbation theory, producing observable phenomena such as gravitational wave memory and nonlinear recoil kicks. The triadic decomposition is therefore a basis choice that organizes the linear perturbation theory, not a partition of the system into three independently stable sectors. The observation is structural — three coupled sectors of distinct physical character arising from a single coherent boundary system — and is offered as an instance of the pattern, not as evidence of physical triality in the sense established in Sections 2.1 through 2.3.



Figure 2: Triality as a recurrent structural pattern across three levels of description. Panel A: Spin(8) algebraic triality, with cyclic $\mathbb{Z}_3$ arrows relating the vector (V) and spinor (S^+ , S^-) representations. Panel B: gauge-theoretic realization in SU(3) quantum chromodynamics. The three color charges (red, green, blue) form a closed triadic system under the $\mathbb{Z}_3$ center symmetry of SU(3); their combination to colorless zero triality is the structural condition for baryon formation and color confinement, as made operationally precise in lattice QCD by Ghanbarpour and von Smekal (2022) [85]. Panel C: cooperative network triad, the simplest closed motif in complex network theory. Bidirectional edges reflect mutualistic coupling; triadic closure—the completion of all three pairwise connections—is the structural condition for cooperative stability in metabolic, signaling, and ecological networks. The statistical over-representation of three-node motifs (feedforward loops, feedback loops, and mutual-regulation triads) in biological transcription networks relative to random graphs of the same connectivity has been established empirically by Milo et al. (2002) [78] and the mechanistic role of such motifs as the elementary building blocks of cellular regulation has been reviewed by Alon (2007) [79]; the triadic motif in Panel C is the simplest instance of this over-represented class. The cross-domain correspondence key ($V \leftrightarrow A$, $S^+ \leftrightarrow B$, $S^- \leftrightarrow C$) makes explicit the architectural correspondence the S-D-T framework identifies across all three panels. The figure does not claim a formal derivation connecting these levels; it illustrates the pattern whose systematic recurrence is the central heuristic claim of this paper.

2.2 The Emergent Process of Anyonic Statistics

A direct physical demonstration of the S-D-T process is found in the quantum statistics of two-dimensional systems. In three spatial dimensions, particle exchange is restricted to the boson/fermion binary—a fundamental duality arising because the fundamental group of the configuration space of N identical particles in 3D is the symmetric group S_N , whose

one-dimensional representations admit only two signs: $+1$ (bosons) and -1 (fermions) [7, 8]. However, when particles are confined to a 2D substrate, the topology of the configuration space changes fundamentally: the relevant exchange group becomes the braid group B_N , which has infinitely many one-dimensional representations parametrized by an arbitrary phase $e^{i\theta}$. This topological fact generates a third statistical kingdom — anyons — whose existence requires neither bosonic nor fermionic statistics but is instead governed by the fractional phase $\theta \in (0, \pi)$ acquired when one particle winds around another [7, 8]. The S-D-T mapping is precise: the 2D material acts as the Singularity (canvas), the boson/fermion binary is the Duality (the only two options available in the 3D bulk), and the braiding topology of the 2D configuration space is the Triality (the mediating rule that generates the third statistical class). Anyons are bulk quasi-excitations whose exchange statistics are governed by the topology of their trajectory space, not by protected modes at a phase boundary—they are distinct from edge states in the standard condensed-matter sense. They satisfy the phase-inversion criterion established in Section 2.4: their fractional statistics are qualitatively absent from both the bosonic and fermionic bulk sectors and cannot be derived from either. The 2D canvas generates degrees of freedom — fractional exchange phases — that are simply unavailable in the higher-dimensional bulk. The existence of anyons—now with direct experimental confirmation [9, 10]—provides a direct physical demonstration of how a lower-dimensional canvas generates qualitatively novel physics absent from the higher-dimensional bulk, satisfying the phase-inversion criterion without invoking edge-state topology.

The significance of this example is amplified by the **holographic principle** [28, 29], which suggests that lower-dimensional boundary encodings may be fundamental to the structure of physical reality, rather than mere approximations of it.

2.3 The AdS/CFT Correspondence: A Duality Resolved by Triality

[This section is presented as a structural analogy — an illustrative mapping, not an evidential grounding of the framework. See Table 1.]

The most precise realization of the holographic principle is the Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence [30, 31, 36]. The lower-dimensional Conformal Field Theory (CFT) acts as the foundational canvas (Singularity). The correspondence itself establishes a duality between boundary physics (CFT) and bulk gravity (AdS) — the interaction (Duality). The **conformal symmetry of the boundary** is the Triality. It is not a property of the bulk gravity theory alone (AdS gravity does not require conformal symmetry), nor of an arbitrary boundary quantum field theory (most QFTs are not conformal). It is a specific constraint that sits at the interface between the two descriptions, governs the form of all physical observables, and is the precise condition that makes the bulk/boundary equivalence possible. The conformal symmetry group $SO(2, d)$ of the boundary CFT is the same as the isometry group of AdS_{d+1} ; this shared symmetry is not a coincidence but the structural mediator that holds the correspondence together. In S-D-T terms: AdS gravity is the Duality, the CFT is the Singularity canvas, and the conformal symmetry structure is the Triality — the specific rule that no element on either side alone possesses, but which both must satisfy for the correspondence to hold. This

identification treats the shared symmetry structure as the mediating constraint rather than as a separate dynamical entity; it is therefore an illustrative mapping rather than a claim of categorical distinctness in the sense of condition (ii). The stronger case for a genuinely distinct third element is provided by the Heckman et al. result discussed below.

A clarification is warranted regarding the broader BCFT literature. In formal Boundary Conformal Field Theory—placed on rigorous holographic footing by Takayanagi’s formulation of AdS/BCFT, in which end-of-the-world branes in the gravitational bulk are dual to boundary conditions in the CFT [53]—the boundary condition is not merely a “mediating rule” in the colloquial sense but a dynamical constraint that preserves a subset of the bulk symmetry [41]. The S-D-T framework does not claim to replicate the mathematical formalism of BCFT. Rather, it proposes that the *structural relationship*—a boundary that mediates between two domains via a symmetry constraint that reshapes the system’s phase space—is the shared pattern. The precise symmetry-breaking mechanism is a context-dependent question that the heuristic identifies but does not itself resolve.

The most direct physical realization of a genuinely dynamical Triality in this context — a third physical structure with its own degrees of freedom, distinct from both the bulk and the boundary — is provided by the very recent work of Heckman, Hübner, and Murdia (2025), which is discussed in full in Section 2.4.

2.4 Lower-Dimensional Boundary Theory: A Conceptual Umbrella

The preceding examples are drawn from distinct subfields—topological matter, condensed matter quasi-particles, and string-theoretic duality—yet they share a common organizational logic. We propose to unify this shared logic under a single conceptual umbrella: Lower-Dimensional Boundary Theory (LDBT), defined as the study of how lower-dimensional ‘canvases’ generate stable, higher-dimensional realities through the mediating rules of *phase-inverted edge-state transitions*. A transition is *phase-inverted* if the boundary that emerges carries degrees of freedom that (i) are qualitatively absent from both bulk phases that the boundary separates, and (ii) provide a more complete description of the system’s physical content than either bulk description alone. This criterion distinguishes a phase-inverted transition from a merely boundary-mediated one: a membrane between two fluids is boundary-mediated but not phase-inverted, because the membrane’s physics is derivable from the bulk fluid parameters. By contrast, the event horizon’s Bekenstein-Hawking entropy encodes bulk information that is inaccessible from either the exterior or interior bulk description alone [80]; the anyonic braiding statistics are absent from both the bosonic and fermionic bulk sectors and cannot be derived from either; and the AdS/CFT dictionary encodes gravitational degrees of freedom in a non-gravitational boundary theory. In every example, the boundary physics is not merely a summary of the bulk but a replacement of it. The term borrows from condensed-matter physics (where “edge states” designate protected boundary modes at the interface between topologically distinct phases [1, 6]). The S-D-T use of the term is structural rather than context-bound: it names the general process by which a Triality transition produces a boundary whose physics replaces, rather than merely summarizes, the bulk physics it mediates.

A key historical precursor is the Black Hole Membrane Paradigm, which models a black hole’s 2D event horizon as a physical fluid membrane with well-defined transport properties [32, 33]. This intuition is vividly confirmed by numerical relativity simulations of black hole mergers, which show event horizons coalescing like liquid droplets [40], and continues to receive striking empirical support: the gravitational wave event GW250114, detected in January 2025 with a signal-to-noise ratio of approximately 77–80, provided the first high-confidence confirmation of Hawking’s area theorem for merging black holes [55]. More rigorous formalisms like BCFT and the physics of D-branes in string theory have placed boundary-mediated physics at the heart of modern theoretical physics [41, 42, 53].

Crucially, this boundary-mediated paradigm is not confined to the toy universe of Anti-de Sitter space. Pasterski, Pate, and Raclariu’s program of **Celestial Holography** proposes a duality between the gravitational S -matrix in asymptotically *flat* spacetimes—the ones that actually resemble our universe—and correlators in a conformal field theory living on the celestial sphere at null infinity [57]. The asymptotic symmetries of flat spacetime (supertranslations and superrotations) provide the mediating rule-set that connects bulk scattering data to boundary correlators. This is the S-D-T pattern applied to physically realistic spacetimes: a lower-dimensional canvas (the celestial sphere), an interaction (the bulk/boundary duality), and a mediating rule-set (the celestial holographic dictionary). The active extension of holographic principles from AdS to flat space significantly strengthens the case that boundary-mediated physics is not a mathematical artifact of a special geometry but a general feature of how nature organizes stable descriptions of reality.

The approach of LDBT — identifying a shared architectural logic across apparently unrelated physical domains before a unified formal theory is available — is not a methodological weakness but the standard route by which major unifications have proceeded. Maxwell’s identification of light as an electromagnetic wave was motivated by structural analogy between electric and magnetic field equations before a unified field theory existed. Yang and Mills extended the gauge principle from the Abelian $U(1)$ of electromagnetism to non-Abelian groups by structural generalization, without deriving the principle from a deeper framework. Most instructively for the present case: in 1995, Edward Witten conjectured that the five apparently distinct superstring theories were all perturbative limits of a single eleven-dimensional M-theory, based entirely on the web of S-duality and T-duality correspondences connecting them [54]. M-theory still lacks a complete Lagrangian formulation. Its constituent theories — Type IIA, Type IIB, heterotic, and their duals — operate through different symmetry-breaking mechanisms at different coupling regimes. Yet the structural web of boundary-mediated equivalences between them is taken as compelling evidence for a deeper unified structure, not as an apology for the absence of formal unification. LDBT occupies exactly this position. The examples of Section 2 are unified by formal analogy — Spin(8) triality, anyonic braiding, and the AdS/CFT dictionary operate through different mechanisms at vastly different scales — and LDBT is offered as the claim that these analogies reflect genuine physical structure. The development of a formal unifying theory, which would require specifying the common mathematical operation underlying the diverse boundary-mediated transitions identified here, is the natural next step. What the evidence of Section 2 already establishes — three independent research programs

converging on the same architectural pattern without prior knowledge of each other or of S-D-T — is the kind of structural robustness that, in the M-theory case, motivated the conjecture of deep unity. Whether the LDBT pattern is deep enough to yield a formal theory is an open empirical question; that it is deep enough to generate specific *prohibitive predictions* is the claim established in Section 4. One important asymmetry between the LDBT case and the M-theory case: the various string theory dualities were established as *mathematical equivalences* — the same observable predictions could be derived from multiple dual descriptions within a single theoretical domain. LDBT currently claims *structural similarity* across distinct physical domains, which is a weaker form of evidence. The step from structural similarity to formal equivalence is the research program that a completed LDBT theory would need to execute. The framework does not claim these mechanisms are identical; it claims only that they instantiate a shared functional role under the S-D-T criteria, and that this shared role recurs across independent research programs. A direct response is warranted to the concern that S-D-T may simply be recognizing the *outcomes* of specific, well-established mathematical dualities rather than identifying an independent common process. This concern is legitimate and partly correct: at the current stage, S-D-T is indeed recognizing outcomes. What the framework adds is the claim that the *functional role* those outcomes play — mediating instability between competing structures via a categorically novel constraint — is the same across domains where the underlying mathematical dualities are completely different. Whether this shared functional role reflects a common causal process is the question FHBT addresses; the present paper identifies the pattern, not the mechanism.

It is worth noting that triadic boundary-mediated structures are being independently identified within the active BCFT community. Neuenfeld, Svesko, and Sybesma, studying shape deformations of end-of-the-world branes in AdS, have established what they term a “doubly-holographic *triality*” between (i) brane deformations in the bulk, (ii) Jackiw-Teitelboim gravity in the brane description, and (iii) irrelevant deformations of the CFT boundary [56]. Their independent use of the term “triality” to describe a three-fold boundary-mediated correspondence—where the boundary condition mediates between two distinct physical domains to yield a stable, coherent description—is the same architectural pattern that LDBT proposes to unify.

This convergence is strengthened by very recent work. Heckman, Hübner, and Murdia (2025) have shown, at finite temperature, that triality defects in 4D $\mathcal{N}=4$ super-Yang-Mills theory are dual to dynamical branes wrapping the apparent horizon at $r = r_+$, with the brane area equal to $4G_N S_{\text{BH}}$ [86]. The triality defect—a symmetry operator associated with the $\mathbb{Z}_3$ center of the gauge group—is thus geometrically realized as a boundary at the horizon itself: a mediating structure that sits at the interface between the bulk gravitational description and the boundary CFT, encoding the black hole entropy in its area. In S-D-T terms, this is not merely an analogy. The horizon brane is the Triality: a third element categorically distinct from both the bulk (AdS gravity) and the boundary (CFT), which mediates between them via its own dynamical degrees of freedom. The identification of this structure by an independent research program, using the term “triality” to describe a three-fold holographic correspondence centered on a dynamical horizon, is the closest the active BCFT literature has yet come to the architectural pattern that

LDBT proposes to unify.

One candidate for such a unifying mechanism is the **Pressure Vessel Problem**: the thermodynamic observation that any persistent negentropic system—what Schrödinger termed an island of “negative entropy” sustained by drawing order from its environment [45], and what Carroll has clearly articulated as a low-entropy state whose persistence against the Second Law requires explanation [51]—whether gravitational, biological, or informational—must balance the outward pressure of a distinct identity against the inward entropic pressure of its environment. As such a system scales, its volumetric entropy generation grows cubically ($\dot{S}_{\text{vol}} \sim r^3$) while its boundary’s capacity to regulate that entropy grows only quadratically ($\dot{S}_{\text{surface}} \sim r^2$), a scaling constraint that is well-established in the biological literature on allometric laws [39]. The ratio $\dot{S}_{\text{vol}}/\dot{S}_{\text{surface}} \sim r$ diverges with scale, creating a critical radius r^* beyond which volumetric entropy generation outpaces surface regulation. A possible mechanistic extension under separate investigation formalizes this as a fitness function $\mathcal{F} = \alpha \cdot \text{Info}(D) - \beta \cdot \text{Leak}(\lambda_2)$, where D is the fractal dimension of the boundary and λ_2 is its algebraic connectivity, with a critical fractal dimension D^* whose empirical determination is a goal of that program. The convergent resolution of the scaling crisis appears to be a *Dimensional Phase Transition*: the sacrifice of active, fluid “bulk” to create what we term a *hyper-stiff boundary*—a condition where the boundary’s surface energy density approaches the bulk’s critical compression limit, necessitating a topological phase transition, rather than mechanical deformation, to maintain entropic equilibrium [32, 33, 40]. In this reading, the event horizon of a black hole, the glassy stratum corneum of biological skin, and the crystallized consensus layer of a distributed intelligence are all instances of the same architectural solution: the system sacrifices its interior to become its boundary. The full development of this mechanism is beyond the scope of the present work, but we flag it here to indicate the physical grounding of the LDBT pattern and the direction of the research program.

A note on the heterogeneity of evidence across examples. Not all connections between S-D-T and the physical examples are of equal formal strength, and the paper’s argument is stronger for acknowledging this explicitly. Table 2 provides a graded taxonomy.

Example	Classification	Status
Spin(8) $\rightarrow \mathbb{Z}_8$ classification	Formal instantiation	Established mathematics (Atiyah-Bott-Shapiro, Bott periodicity, Kitaev)
Anyonic statistics	Physical instantiation	Experimentally confirmed [9, 10]; functional role empirically realized
AdS/CFT conformal symmetry as Triality	Physical instantiation	Well-motivated structural identification; conformal symmetry is the shared mediating constraint
Heckman et al. triality defects at horizon	Physical instantiation	Published 2025, independently convergent, not post-hoc
Network triadic motifs (Milo, Alon)	Physical instantiation	Statistically over-represented in biological regulatory networks
Teukolsky spin-weight sectors in GR	Analogical mapping	Noted for structural interest; not claimed as evidence of physical triality

Table 2: Graded taxonomy of evidence strength across the S-D-T examples of Section 2. The framework’s persuasiveness rests primarily on the first three rows. The Teukolsky entry is included for structural interest only. The three-tier classification (formal instantiation / physical instantiation / analogical mapping) reflects the distinction drawn in the Formal Definition above.

The cross-domain invariant. The taxonomy above raises an immediate question: if these examples differ so radically in their physical form, what exactly recurs across them? The answer is not that the same mathematical object appears in each domain — it does not. The invariant is functional, not formal: in every case, a configuration of two competing structures achieves persistent higher-order stability through the emergence of a constraint that is categorically absent from both competing phases and that cannot be derived from their resources alone. The spin-weight symmetry of Spin(8), the non-Abelian statistics of anyons, the conformal symmetry of AdS/CFT, and the CKM CP-violating phase each play this functional role in their respective domains through completely different physical mechanisms. This is precisely what Ontic Structural Realism predicts should be the case: the relational structure (the functional role) is ontologically prior to the physical substrate (the mechanism). The S-D-T claim is that the functional role is real and recurring; it does not require that the mechanisms be the same.

Network-theoretic and information-theoretic corroboration. The structural minimality argument in §1 is independently corroborated by converging results from network science and information theory. Milo et al.’s feed-forward loop, the simplest triadic motif, is empirically the most statistically over-represented three-node structure in biological regulatory networks relative to random null models [78]. Alon (2007) showed that triadic

feed-forward loops achieve robust signal discrimination that four-node extensions do not improve without additional constraints [79]: three-node closure is not just common but specifically over-represented in systems where functional stability is required. Nigam et al. (2022) demonstrated, via the Triple Correlation Uniqueness (TCU) theorem, that *third*-order correlations are sufficient and necessary to fully characterize spatiotemporal patterns in neural network activity, while pairwise correlations are not [91]. This is an information-theoretic result: the third-order statistics carry qualitatively new information absent from all pairwise descriptions, which is precisely the information-theoretic signature of the categorical novelty condition — the third element introduces representational richness that the dual system cannot generate. Exhaustive computational searches identify the Incoherent Feed-Forward Loop (IFFL) as the *only* three-node architecture achieving exact adaptation to time-varying signals; four-node extensions add computational cost without improving discrimination [79]. The Hodge decomposition of brain network dynamics requires exactly three orthogonal components (gradient, harmonic, and curl flows) to fully characterize higher-order interactions — pairwise connectivity cannot encode the full dynamical structure [91]. Finally, in quantum and optical networks, triadic clustering induces localization-delocalization quantum phase transitions (Anderson-like transitions), demonstrating that the topology of the triad can alter the physical state of the network itself — not just its information statistics [91]. Together with the TCU theorem’s 14 fundamental motif-classes encoding all primary network properties, these results establish triadic closure as the minimal sufficient architecture for functional properties that smaller configurations categorically cannot achieve. This convergence across independent research programs — physics, network science, information theory, neuroscience — is the empirical signature of a real structural pattern rather than a domain-specific artifact.

Framework-level falsification. The falsification conditions of Section 4 address specific S-D-T predictions. The framework as a whole is falsified by a different kind of evidence: the demonstration that a system with confirmed competing dual basins achieves persistent, higher-order stability *without* any constraint satisfying conditions (i)–(iv) of the Formal Definition above. Such a demonstration would show that the Triality condition is not necessary for higher-order stability — that duality alone suffices — falsifying the framework’s foundational claim. The framework is also falsified if it can be shown that every apparent Triality reduces, under analysis, to a fine-tuned combination of the two Duality elements, with no genuinely novel organizational principle introduced.

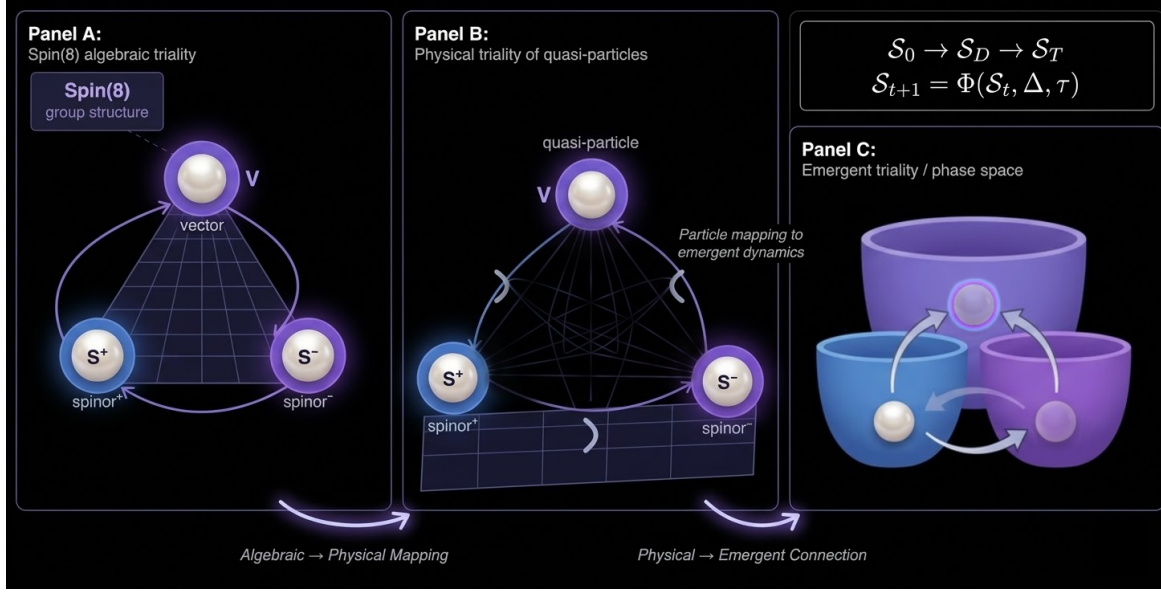


Figure 3: Unified triality across algebraic, physical, and emergent domains. Panel A: Spin(8) algebraic triality, showing the three equivalent representations—vector (V), positive spinor (S^+), and negative spinor (S^-)—related by cyclic $\mathbb{Z}_3$ rotation. This is the canonical mathematical instance of triality: a three-fold symmetry among structurally distinct but mutually interchangeable representations, found uniquely among simple Lie groups in Spin(8) and shown by Kamiya (2021) to generalize across a broad family of algebraic triple systems. Panel B: physical realization of the same triadic structure in quasi-particle topology. The three nodes reproduce the V/ S^+ / S^- identity and color of Panel A; braiding arrows indicate fusion interactions, and the topological plane represents the 2D substrate on which anyonic statistics emerge. The web of internal connections reflects the all-to-all coupling characteristic of braiding quasi-particles. Panel C: emergent phase-space structure, reproducing the basin geometry of Figure 1 Panel C, in which the three attractors correspond to the three representation classes of Panels A and B. The transition annotations at the base of the figure indicate the direction of structural correspondence across domains: algebraic symmetry is realized in gauge physics, which is expressed in emergent systems dynamics. No claim is made that these correspondences are formally derived from one another; the figure illustrates the recurrent structural pattern the S-D-T framework proposes to identify.

3 Deriving Testable Predictions from the Standard Model

Having induced the S-D-T framework from the convergent evidence of boundary-mediated physics, we now apply it to the Standard Model. A methodological note is essential before proceeding: the analyses in this section have two distinct epistemic statuses, and the paper’s argument depends on keeping them separate. The force hierarchy and three-generation structure are offered as *heuristic recontextualizations* of known structures under the S-D-T lens — illustrative re-framings that demonstrate the framework’s descriptive reach, not derivations from it. They are speculative mappings, not evidential support for the framework (see Table 1). The

single genuine *prediction* in this section — that leptonic CP violation should be near-maximal ($|\delta_{CP}| \approx \pi/2$, Prediction C) — is categorically different: it concerns an unresolved measurement and follows from applying the triadic closure condition to a parallel system. The former re-describes what is known; the latter predicts what is not yet measured. Standard neutrino physics is consistent with any value of δ_{CP} ; the S-D-T triadic closure condition is *consistent with* near-maximal CP violation, not uniquely derivable from it.

3.1 The Force Hierarchy as a Stability Landscape

The Standard Model, at the energy scales of our current universe, is best understood through three fundamental interactions. While often enumerated as four forces, the Nobel Prize-winning work of Glashow, Salam, and Weinberg demonstrated that the electromagnetic and weak forces are unified into a single electroweak force above approximately 100 GeV [13, 34, 35]. This established physics reveals a functional triad:

- **Singularity (Canvas):** Gravity, which provides the universal canvas of spacetime.
- **Duality (Interaction):** The Strong Nuclear Force, which creates the fundamental duality of stable matter by binding quarks into hadrons.
- **Triality (Mediating Rule):** The Electroweak Force, which acts as the mediating rule governing the interactions, decays, and transformations between stable matter particles, enabling the emergence of complex structures like atoms.

The historical drive towards a Grand Unified Theory (GUT), which would unify the strong and electroweak forces into a single gauge group, represents a move toward a Duality: the unified GUT force versus Gravity [12, 14]. The S-D-T framework predicts that such a dualistic state—two distinct foundational principles without a mediating Triality—is inherently unstable.

3.1.1 The Doublet-Triplet Problem as a Case Study of Dualistic Instability

This prediction is not abstract; it manifests as concrete, well-documented theoretical tensions within existing GUT models. The most instructive case is the **doublet-triplet splitting problem** in the minimal SU(5) Grand Unified Theory proposed by Georgi and Glashow [12].

In the SU(5) GUT, the Higgs fields that break the electroweak symmetry reside in the same multiplet as fields that mediate proton decay. The model requires that the electroweak Higgs doublet remain light (at the electroweak scale, $\sim 10^2$ GeV) while its GUT-partner color-triplet Higgs must be superheavy (at the GUT scale, $\sim 10^{16}$ GeV) to prevent unobserved rapid proton decay. This mass splitting of fourteen orders of magnitude has no natural explanation within the theory—it must be *imposed* through extraordinarily precise fine-tuning of parameters, a procedure widely regarded as a fundamental deficiency [43, 44].

The S-D-T framework recontextualizes this problem. In a GUT, the strong and electroweak forces are unified into a single structure, eliminating the mediating Triality that separates them

at low energies. The resulting dualistic system—a unified gauge force confronting gravity—lacks the regulatory principle that previously maintained the hierarchy. The doublet-triplet problem is, in this reading, a specific manifestation of hierarchy collapse: the system cannot naturally maintain the separation between its component scales because the mediating rule that enforced that separation has been absorbed into the unification.

This interpretation generates a specific, falsifiable claim: the fine-tuning problem in GUTs is not a contingent engineering challenge that a sufficiently clever model can resolve within a purely dualistic framework. Rather, the S-D-T model predicts that any GUT that remains a final, dualistic theory—unifying strong and electroweak forces without a further mediating principle (plausibly gravity, as in a full theory of quantum gravity)—will necessarily exhibit analogous hierarchy problems. The discovery of a mathematically complete and internally consistent GUT that resolves all such hierarchy problems without recourse to a mediating ‘Thirdness’ would constitute a direct falsification.

3.2 The Triality of Matter: The Three-Generation Problem

The existence of exactly three generations of matter is one of the most profound unexplained facts of the Standard Model [15, 16, 17]. The S-D-T framework offers a principled explanation by positing that this structure is not a coincidence but a necessary consequence of emergent stability:

- **Singularity:** The first generation (electron, up/down quarks, electron neutrino), comprising all stable, everyday matter.
- **Duality:** The second generation (muon, charm/strange quarks, muon neutrino), a heavier and unstable copy that introduces a fundamental tension into the model. In the famous words attributed to I. I. Rabi upon the muon’s discovery: “Who ordered that?” [50]
- **Triality:** The third generation (tau, top/bottom quarks, tau neutrino), which acts as the harmonizing element that resolves this tension.

The mechanism for this triadic completion is physically grounded and mathematically precise. The CKM quark-mixing matrix, which parameterizes the mismatch between the weak-interaction eigenstates and the mass eigenstates of quarks, is an $n \times n$ unitary matrix for n generations. In the standard parameterization [37], a general $n \times n$ unitary matrix has $(n - 1)^2$ independent parameters, decomposable into $n(n - 1)/2$ real mixing angles and $(n - 1)(n - 2)/2$ complex phases. For $n = 2$, this yields one mixing angle and zero complex phases. For $n = 3$, it yields three mixing angles and one irreducible complex phase [18, 19].

This single complex phase is the *dominant observed source* of CP violation in the quark sector of the Standard Model.¹ CP violation—first observed experimentally by

¹The strong CP problem — the question of why the QCD θ -parameter is constrained to be $|\theta| < 10^{-10}$ by the neutron electric dipole moment bound, rather than order unity as naively expected — represents a potential additional source of quark-sector CP violation. Its smallness is unexplained within the Standard Model and

Christenson, Cronin, Fitch, and Turlay in neutral kaon decays [23]—is one of the three Sakharov conditions [22] required for baryogenesis—the process that produced the observed matter-antimatter asymmetry of the universe. The logical chain is tight:

1. Three generations are the minimum required for an irreducible complex phase in the CKM matrix.
2. The irreducible complex phase is the necessary condition for CP violation in the quark sector.
3. CP violation is a necessary condition for baryogenesis.
4. Baryogenesis is the necessary condition for a matter-dominated universe.

The Triality of matter thus resolves the fundamental Duality of matter versus antimatter, creating the stable, matter-dominated cosmos we inhabit.² Convergent structural support for the closure of fermion family replication at three generations is provided by Axelkrans [101], who argues from projection-theoretic grounds that three generations exhaust the admissible realizations of the underlying generative structure: a first generation establishing minimal invariance, a second introducing stable variation, and a third achieving structural completeness beyond which additional generations introduce redundancy or violate invariance. S-D-T and the projection-theoretic approach identify the same closure number from different directions—S-D-T through the physical mechanism (the onset of CP violation), Axelkrans through the abstract structure of projection factorization; the two arguments are complementary rather than competing.

3.3 Why Not Four? The Question of Quartic Extension

A natural objection arises: if three generations enable CP violation, wouldn't four generations enable *more* CP violation, potentially yielding an even more stable system? The S-D-T framework's Prohibition 2 (Section 4.1) claims that stable triadic systems cannot be succeeded by simple quartic extensions. This claim requires justification beyond assertion.

We offer two lines of argument. The first is empirical. Precision measurements of the Higgs boson decay width at the LHC, combined with earlier constraints from the Z boson invisible width measured at LEP [17], have effectively ruled out a simple sequential fourth generation

represents a separate fine-tuning problem. The S-D-T argument concerns the CKM-matrix source of CP violation as the organizational mechanism enabling baryogenesis, and is not affected by the θ -parameter constraint, which does not depend on the number of generations.

²A caveat is warranted. While CKM CP violation is a *necessary* condition for baryogenesis, it is widely recognized to be *quantitatively insufficient* to account for the observed baryon asymmetry: the Jarlskog invariant $J \sim 3 \times 10^{-5}$ yields an asymmetry many orders of magnitude below observations [19]. The leading candidate for the additional CP violation required is leptogenesis, operating through the PMNS neutrino mixing matrix, which possesses its own irreducible complex phases. Within the S-D-T framework, this suggests that the lepton sector may constitute an independent S-D-T system—with the three neutrino generations providing their own triadic closure for leptonic CP violation—operating in parallel with, and complementary to, the quark-sector triality described here. The full treatment of this parallel structure is beyond the present scope but represents a natural extension of the framework.

of fermions with a light neutrino [20, 21]. Detailed theoretical analyses have shown that the Higgs production cross-section enhancements and decay-width modifications induced by a fourth generation are decisively excluded by the observed Higgs data [38]. The S-D-T framework is consistent with this established constraint.

The second is structural. In the S-D-T framework, the Triality is defined not as “a third element” but as a *qualitatively new organizational layer* that resolves the dualistic tension by introducing a new physical phenomenon. We can sharpen what “qualitatively new” means: a generation earns the status of Triality if it enables a physical effect that is *mathematically forbidden* for the previous number of generations. The third generation satisfies this criterion exactly: CP violation in the quark sector requires an irreducible complex phase in the CKM matrix, and such a phase is mathematically forbidden for $n < 3$ (since $(n-1)(n-2)/2 = 0$ for $n = 2$). A hypothetical fourth generation would not satisfy this criterion—it would add more mixing angles and more complex phases, but these are quantitative extensions of a CP-violating mechanism that is already *permitted* by three generations. No physical effect accessible to four generations is mathematically forbidden for three. The system is, in S-D-T terms, already *closed*: the mediating rule (CP violation) is operational, and the fundamental duality (matter vs. antimatter) is resolved. Additional generations would be redundant with respect to the organizational principle that justifies the framework’s triadic structure.

This criterion provides an objective test: for a fourth generation to constitute a new Triality rather than a mere quartic extension, it would need to enable a physical effect whose mathematical prerequisites are unsatisfiable by three generations—analogueous to how CP violation is unsatisfiable by two. No such effect has been identified.

Transparency: We note that the empirical ruling-out of a simple fourth generation predates the S-D-T framework. The value of the S-D-T interpretation lies not in making a novel prediction, but in offering a *principled explanation* for an empirical fact that the Standard Model itself treats as a brute datum. The framework claims to explain *why* there are exactly three generations, grounding the explanation in a specific physical mechanism (the onset of CP violation as triadic closure), rather than merely noting that there are. This explanatory leverage—the capacity to unify the three-generation problem with the force-hierarchy problem under a single principle—is the framework’s primary contribution to particle physics.

4 Falsifiability and Scientific Status

4.1 Confronting the Principal Vulnerability

The most serious objection to the S-D-T framework is that it risks being unfalsifiable in practice. Singularity, Duality, and Triality are sufficiently general labels that an uncritical reader could map nearly any system with identifiable components onto them post-hoc. A framework that can describe everything predicts nothing; it becomes a Rorschach test rather than a scientific model. This objection requires a direct answer.

We argue that the framework’s scientific legitimacy rests not on its capacity to describe systems

after the fact, but on the two specific prohibitive claims it makes—claims about what is *not* possible, following Popper’s criterion of refutability [24, 25]:

- **Prohibition 1 (Against Unmediated Complexity):** Complex, higher-order stability cannot emerge spontaneously from unmediated dualistic systems. While simple dualities (binary stars, positive/negative charge) can be stable, the model predicts they cannot, by themselves, generate new, more complex organizational layers without a mediating ‘Thirdness.’ Any system governed by a pure duality will exhibit high volatility and be prone to collapse or oscillation between extremes, rather than settling into a stable, complex state.
- **Prohibition 2 (Against Same-Type Quartic Extension — Secondary Conjecture):** A stable, self-completing triadic system is not expected to be succeeded by a simple, stable four-fold structure that is a mere isomorphic extension of the same organizational type. If a fourth element introduces a genuinely new organizational principle, the system constitutes a new S-D-T cycle rather than a quartic extension of the existing one. *This prohibition is presented as a secondary conjecture rather than a core falsifiable claim. We emphasize that Prohibition 2 is exploratory and more weakly supported than Prohibition 1. It is more vulnerable to reclassification than Prohibition 1, and readers should treat it accordingly. A system that appears to falsify it should be assessed against the pre-specified criteria of §4.3 before any verdict is rendered. We do not rely on Prohibition 2 for the core validity of the framework; Prohibition 1 and F0 carry the evidential weight.*

It is these prohibitions—not the descriptive capacity of the framework—that give S-D-T its scientific content. A framework that merely labels components is philosophy; one that forbids specific outcomes is science.

The operational content of Prohibition 1 is made precise by the criteria in Section 4.3: the Triality must be categorically distinct from the Duality’s components—a new *rule*, not just a third *player*. The phase-inversion criterion of Section 2.4 provides the technical test: the stabilizing third element must be absent from both competing bulk phases and must provide a more complete description of the system than either alone. If this criterion is not met, the transition is not a Triality in the S-D-T sense and Prohibition 1 is not invoked. A fully quantitative formalization of this criterion is *a priority* for subsequent work, and a conceptual scaffold toward it is proposed in Section 5.5.

A deeper concern about the framework’s falsifiability structure deserves direct acknowledgment. The two prohibitions are *asymmetric* in their falsifiability: the confirmation direction (finding the S-D-T pattern in a new domain) is structurally easier than the falsification direction, because the operational criteria in Section 4.3, while necessary, retain enough flexibility that a sufficiently motivated interpreter could identify a Singularity, Duality, and Triality in most complex systems with identifiable components. The prohibitions themselves contain escape clauses — Prohibition 1 requires a system with *no* mediating constraint of any kind; Prohibition 2 exempts any fourth element that introduces a new organizational principle. This asymmetry is real and cannot be fully resolved by a heuristic framework at the current stage of formalization.

We address this in two ways. First, we tighten the operational content of both prohibitions. A system violates Prohibition 1 in the *unambiguous* sense if the transition from dualistic tension to stable complexity can be fully derived from the properties of the two competing basins alone, without reference to any third constraint that introduces a new physical or organizational phenomenon absent from either basin. The phase-inversion criterion of Section 2.4 provides the technical test: a stabilizing third element that satisfies both conditions of that criterion qualifies as a genuine Triality; one that does not means Prohibition 1 is not invoked. This operationalization narrows the escape clause significantly.

Second, a fourth generation is a *same-type extension* in the sense of Prohibition 2 if and only if the mechanism enabling whatever new phenomenon it introduces was already *mathematically accessible* with three generations — that is, if the relevant formula, symmetry group, or phase space already permits the new effect but the fourth generation merely realizes it. A fourth generation that enables an effect whose mathematical prerequisites are genuinely unsatisfiable with three (as CP violation is unsatisfiable with two) would be a new organizational principle and would not fall under Prohibition 2. This criterion is precise enough to be applied: we know of no such effect for a sequential fourth generation, and the Higgs data provides independent empirical closure.

Like Darwinian natural selection before population genetics provided quantitative grounding, the S-D-T framework is, at the current stage of formalization, more readily confirmed than falsified in the strictest Popperian sense. This is the normal condition of productive heuristic frameworks in early development, and the appropriate response is transparency about the asymmetry and commitment to the formalization program that will resolve it.

4.2 Formal Falsification Conditions

The domain-specific falsification conditions below (F1–F4) address particular applications of the S-D-T framework. Before stating them, the framework-level falsification condition must be stated first. This is the condition that kills not an application but S-D-T itself.

Framework-Level Falsification Condition (F0)

Claim: No system can achieve stable higher-order organization from a purely binary interaction without the introduction of a third element satisfying conditions (i)–(iv) of the Formal Definition (§1) — specifically, a constraint that introduces a new degree of freedom absent from both competing basins.

Falsification: Identify a physical or biological system that (i) exhibits exactly two competing attractors under well-characterized dynamics, (ii) achieves stable higher-order organization without fine-tuning, and (iii) does so without any third constraint that is absent from both competing basins. All terms must be pre-specified using the operational criteria of Section 4.3 before analysis begins. Retroactive re-definition of what counts as “competing attractor” or “higher-order organization” to accommodate a result is not permitted.

Candidate test systems: Binary alloy phase transitions, two-species predator-prey or competitive systems proposed to achieve stable higher-order community structure, or any physical or biological system proposed by critics as achieving stable triadic-level organization from confirmed dual-only dynamics.

Burden of proof: Falls on the framework. Repeated failure across independently specified domains, under pre-registered application criteria, constitutes strong evidence against the framework’s core prohibition. Individual application failures (e.g., a specific SAF prediction proving incorrect) falsify the application, not the framework. Accumulated failures across independent domains with independently pre-specified criteria falsify the framework. The claim “the framework is correct but this instance was misapplied” is a legitimate response to one failure; it is not legitimate as a blanket response to multiple independent failures.

Honest limitation: We acknowledge that falsification depends on prior operationalization of key terms, and that borderline cases may remain subject to interpretive disagreement. The pre-specification requirement (§4.3) mitigates but cannot eliminate this. The goal is to make such disagreements explicit and tractable, not to claim the falsification architecture is dispute-proof.

In physics (Force Hierarchy): The discovery or robust theoretical formulation of a mathematically complete and internally stable Grand Unified Theory that successfully unifies the strong and electroweak forces *without* requiring further unification with gravity, and which resolves all hierarchy problems (e.g., doublet-triplet splitting) without a mediating ‘Thirdness’ from beyond its dualistic scope, would directly falsify the prediction of Section 3.1.

In physics (Matter Generations): The discovery of a stable fourth generation of fermions that is a simple mass-scaled replica of the first three—one that introduces no categorically new physical phenomenon—would demonstrate that triadic completion is a numerical coincidence rather than an organizational principle, thereby falsifying the prediction of Section 3.2. We note that exotic fourth-generation scenarios involving non-standard couplings or new symmetries would not constitute straightforward falsification, as they would themselves represent a new

organizational principle rather than a mere quartic extension.

In physics (Lepton sector as independent triadic closure): The three-generation structure of matter is argued in Section 3.2 to achieve triadic closure in the quark sector through CP violation in the CKM matrix. The S-D-T framework predicts that the lepton sector constitutes a structurally parallel, independent S-D-T system: the three neutrino generations should provide their own triadic closure, with the irreducible complex phase of the PMNS neutrino mixing matrix playing the same organizational role as the CKM phase in the quark sector, enabling leptonic CP violation as the condition for leptogenesis. This prediction is falsifiable: if the PMNS matrix is demonstrated to have no CP-violating phase (i.e., the Dirac phase $\delta_{CP} = 0$ or π , giving no leptonic CP violation), or if leptogenesis is shown to be generated by a mechanism that does not require three generations of neutrinos, the parallel-structure prediction is falsified. Current experimental constraints favor a non-zero δ_{CP} : the T2K collaboration (2020) reported a 3σ preference for maximal CP violation near $\delta_{CP} \approx -\pi/2$ [81], though subsequent NOvA results have been in tension with the T2K central value, and the combined global fit (NuFIT 6.0, 2024 [82]) currently shows a preference for CP violation at the $2\text{--}3\sigma$ level depending on the neutrino mass ordering assumed. The experimental situation is not yet definitive, but is consistent with the prediction.

Prediction C: Near-Term Experimental Test

Claim: The lepton sector constitutes an independent S-D-T system whose triadic closure requires a non-zero CP-violating phase δ_{CP} in the PMNS neutrino mixing matrix.

Prediction (qualitative): $\delta_{CP} \neq 0, \pi$ — leptonic CP violation is present and measurable.

Prediction (quantitative): The S-D-T framework makes a stronger claim than mere non-zero CP violation. The triadic closure condition favors the configuration that *maximizes* the CP-violating effect — the configuration that places the system furthest from the CP-conserving Duality ($\delta_{CP} = 0$ or π). The framework therefore predicts that $|\delta_{CP}|$ should be near-maximal: $|\delta_{CP}| \approx \pi/2$. The current T2K central value $\delta_{CP} \approx -\pi/2$ is consistent with this stronger prediction. A measurement of δ_{CP} far from $\pm\pi/2$ — say, $|\delta_{CP}| < \pi/6$ — would weaken the framework even without falsifying it outright.

Falsification condition: A definitive measurement of $\delta_{CP} = 0$ or $\delta_{CP} = \pi$ (no CP violation in the lepton sector) would directly falsify the parallel-structure prediction. Alternatively, a demonstration that leptogenesis does not require three neutrino generations would falsify the triadic closure interpretation.

Experimental timeline: The DUNE experiment [89] and Hyper-Kamiokande [90] are designed to measure δ_{CP} to $\lesssim 10^\circ$ precision within approximately 5–10 years. This is a concrete, near-term, and uniquely S-D-T-motivated prediction: standard neutrino physics permits any value of δ_{CP} ; the S-D-T framework predicts it should be near-maximal.

In complex systems (SAF Coherence Index): The SAF Coherence Index (equation 1) predicts that composite system coherence — measured as $F_{\text{norm}} \cdot (1 - |S_{\text{norm}} - A_{\text{norm}}| / (S_{\text{norm}} +$

$A_{\text{norm}}))$ using the F-first identification methodology of Section 5.3 — correlates with clinical or functional outcomes more strongly than any single-component measure alone. For the erythrocyte system, published ektacytometry, micropipette aspiration, and oxygen dissociation data across sickle cell disease, hereditary spherocytosis, iron deficiency anemia, and severe malaria constitute an existing dataset against which the prediction $\rho_{\text{SAF}} > \max(\rho_F, \rho_S, \rho_A)$ can be evaluated immediately. Spearman $\rho < 0.5$ between SAF rank and clinical severity rank would indicate the composite metric adds no diagnostic value, falsifying the claim that the S-D-T grammar’s structural logic produces better system-level assessment than conventional single-component analysis.

In complex systems: The persistent, demonstrable emergence of complex, higher-order stability from a purely dualistic system—without the introduction of any mediating protocol, constraint, or regulatory layer—would falsify Prohibition 1. Similarly, the reliable extension of stable triadic systems into equally stable quartic ones through simple addition (rather than fundamental reorganization) would falsify Prohibition 2.

A note on beyond-Standard-Model theories: Many SUSY GUT proposals (e.g., the missing partner mechanism, Dimopoulos-Wilczek) claim to resolve the doublet-triplet problem. The S-D-T framework does not predict these solutions are impossible; it predicts that any successful resolution will introduce a mediating constraint beyond the resources of the dualistic unification itself — a discrete symmetry, a missing VEV, a specific superpotential structure — that functions as a Triality in the S-D-T sense. The test is whether a consistent solution exists that uses only the resources of the dualistic framework, with no third organizational element. The framework claims none does.

Prediction D: SAF Coherence Index — Immediately Testable

Claim (hypothesis): The SAF Coherence Index (equation 1, Section 5.3), derived from the S-D-T grammar using the F-first identification methodology, is proposed as a measure of systemic coherence. It is offered as a hypothesis-generating tool whose validity requires empirical validation, not as an established metric. Its full mathematical definition is:

$$\text{SAF}(S, A, F) = F_{\text{norm}} \cdot \left(1 - \frac{|S_{\text{norm}} - A_{\text{norm}}|}{S_{\text{norm}} + A_{\text{norm}}} \right)$$

with $F_{\text{norm}}, S_{\text{norm}}, A_{\text{norm}} \in [0, 1]$ normalized to domain-appropriate reference maxima. For the erythrocyte: F = O₂ carrying capacity, S = membrane shear modulus, A = elongation index.

Prediction: SAF correlates with clinical severity more strongly than any single-component measure alone: $\rho_{\text{SAF}} > \max(\rho_F, \rho_S, \rho_A)$. Predicted SAF profiles: sickle cell disease ≈ 0.10 – 0.25 (F-collapse); hereditary spherocytosis ≈ 0.30 – 0.45 (S-A imbalance); iron deficiency ≈ 0.40 – 0.55 (F-reduction, S-A balanced); severe malaria ≈ 0.10 – 0.25 (multi-component attack).

Falsification condition: Spearman $\rho < 0.5$ between SAF rank and clinical severity rank, or SAF failing to outperform all three single-component correlations individually.

Data availability: Testable immediately against published ektacytometry, micropipette aspiration, and oxygen dissociation data in existing clinical cohort studies — no new experiments required.

4.3 Operational Criteria for Applying the Framework

To guard against post-hoc pattern-fitting, the following criteria must be met before the S-D-T framework is applied to any system. A critical requirement applies to all applications: **all terms must be specified prior to empirical evaluation**. The identification of what counts as the Singularity, Duality, Triality, and their physical referents must be made in advance and locked before data are collected or analyzed. Retroactive adjustment of these identifications to accommodate results is not permitted and constitutes a violation of the framework’s application conditions. This pre-specification requirement is not merely recommended; it is necessary for any S-D-T application to constitute a genuine test rather than a retrospective redescription.

- **Singularity:** Identifiable as the initial conditions, a baseline state of high symmetry, or a specific substrate that enables interaction. It is the state against which change and structure are measured.
- **Duality:** Identified by the emergence of a dominant, system-defining tension, measurable as a bifurcation in the system’s phase space, the establishment of two competing feedback loops, or a fundamental trade-off that governs the system’s behavior.
- **Triality:** Identified by the emergence of a new constraint or regulatory protocol that

fundamentally alters the rules of interaction for the dualistic components. It is not merely a third element but a new, higher-order organizational layer that subordinates the duality to a more complex, coherent whole. Its success can be measured by a statistically significant decrease in the system’s volatility or an increase in its persistence over time.

Crucially, the Triality must be shown to be *categorically different* from the Duality’s components—a new *rule*, not just a third *player*. The Standard Model examples in Section 3 demonstrate this criterion: the third generation of matter is the *necessary condition for a new physical phenomenon* (CP violation), and the electroweak force is the *mediating protocol* governing flavor-changing transformations—not merely another element of the same type. If this qualitative-difference criterion cannot be satisfied for a proposed application, the framework adds no explanatory value and should not be applied.

The existing literature on complex systems provides candidate measurement tools for each operational criterion. The stability of a Singularity state can be assessed via **Lyapunov exponents** [68]: a negative maximal Lyapunov exponent confirms that nearby trajectories converge, quantifying the basin’s robustness to perturbation. The adaptability of a Duality state is naturally measured by the **Kolmogorov-Sinai (KS) entropy** [68], which captures the rate at which the system generates new information—high KS entropy indicates a rich response repertoire, while zero KS entropy indicates a fully canalized, non-adaptive system. The functionality of a Triality is measurable via **transfer entropy** [66], which quantifies directional information flow between subsystems, distinguishing genuine functional coupling from spurious correlation. Together, these three metrics (Lyapunov exponent for Stability, KS entropy for Adaptability, transfer entropy for Functionality) constitute a candidate quantitative operationalization of the SAF triad; their application to specific systems of interest is a near-term empirical priority. A fully unified metric integrating all three is proposed conceptually in Section 5.5. Independent support for the information-theoretic approach comes from Bailey and Schneider’s [100] spectral approximation of integrated information (Φ_{spectral}), which uses the Fiedler vector of the normalized Laplacian of a pairwise mutual information graph as its core measure. Their key empirical finding is directly consistent with the S-D-T prediction: Φ_{spectral} is not maximized by synchrony (which produces redundancy, not integration) but by the transitional regime of heterogeneous coordination—precisely the mediating coherence that the S-D-T framework identifies as Triality, as distinct from either the disordered Duality or the uniform Singularity.

4.4 Scope: Where S-D-T Does Not Apply

Explicitly bounding the framework’s scope is as important as stating its claims. S-D-T applies to systems exhibiting competing attractors under symmetry-breaking dynamics where a mediating constraint is in principle identifiable. It does not apply to:

- **Equilibrium systems with no internal tension.** A noble gas at room temperature has no competing attractors and no Duality to mediate. The S-D-T grammar is not invoked. Stability without tension is simply stability.

- **Systems whose complexity arises from simple aggregation.** A sand pile is complex but not S-D-T-organized: its avalanche dynamics arise from local grain interactions, not from the resolution of competing organizational attractors by a categorically novel constraint. Complexity and triadic organization are not synonymous.
- **Systems where the number of competing attractors at the relevant organizational level exceeds two.** Multi-party political systems, many-species ecological communities, and multi-modal dynamical systems require either S-D-T cycle nesting (where pairs of competitors are resolved in sequence) or a different analytical framework. Single-cycle S-D-T application to systems with more than two competing organizational attractors is a misapplication, and its failure does not constitute a counterexample to the framework.
- **Systems where the “Triality” candidate is derivable from the Duality resources.** Fine-tuned parameter adjustments, weighted averages of competing states, or symmetry transformations of existing degrees of freedom are not Trialities. If condition (iv) of the Formal Definition cannot be satisfied, the framework does not apply.

These exclusions are not ad hoc retreats. They follow directly from the Formal Definition: without a Duality, there is nothing for a Triality to mediate; without categorical novelty, there is no Triality. The framework’s scope is determined by its definitions, and the definitions have boundaries.

Formal assessment of candidate counterexamples. The three most commonly cited candidate counterexamples to the S-D-T framework’s core claim are assessed here against conditions (i)–(iv) of the Formal Definition.

Binary alloy phase transitions. Cu-Zn, Pb-Sn, and similar binary alloy systems exhibit complex stable phases (eutectic points, intermediate solid solutions, Hume-Rothery phases) that appear to arise from purely dual interactions between two metal components. On inspection, the stabilization always involves a categorically novel third constraint. Two distinct mechanisms are identified. First, the Hume-Rothery valence electron concentration (e/a): the stability of complex phases such as the γ -brass phase in Cu-Zn is governed by the interaction of the electronic Fermi level with the Brillouin zone plane — a third physical parameter arising from the two-component interaction but introducing a degree of freedom (electronic band topology) absent from either atomic species alone. Second, and more generally, the crystalline lattice symmetry itself (FCC, BCC, HCP) introduces a spatial symmetry that is entirely absent from the continuous translation algebra of the liquid phase. The liquid is invariant under all continuous translations; the crystal is invariant only under discrete translations of the lattice vectors. This symmetry-breaking introduces a categorically new organizational rule that satisfies condition (ii) precisely: the lattice is not a weighted average of the two atomic potentials but a new geometric constraint that traps the binary atoms into a topologically distinct stable basin. Fine-tuning temperature and pressure to reach a specific bifurcation point is excluded by condition (iv); but the emergent lattice symmetry is not temperature-tuning — it is a

spontaneous symmetry-breaking that introduces a new degree of freedom into the phase space. Binary alloys therefore fail as counterexamples: their stable complex phases are mediated by either Hume-Rothery electron topology or emergent lattice symmetry, both of which satisfy the Formal Definition’s conditions for a genuine Triality.

Two-species ecological systems. The two-species Lotka-Volterra competition equations can, under certain conditions, achieve stable coexistence via “dual interactions” — models incorporating simultaneous competitive and mutualistic (or facilitative) interactions within a single species pair, such as consumer-resource mutualisms or plants competing for light while facilitating soil nutrients. Does this falsify the S-D-T prohibition? A strict application of the Formal Definition indicates it does not, and the analysis reveals why in a way that strengthens the framework. In the S-D-T reading, the interaction *protocol* — the rule-set governing how competition and mutualism are simultaneously engaged — is itself the Triality. It is not a third biological actor but a categorically novel constraint that is absent from either pure-competition or pure-mutualism dynamics alone: a mixed interaction protocol introduces a new dimension of response that neither pure dynamic can generate from its own resources, satisfying condition (ii). This reading is confirmed by scaling: when expanding to highly diverse ecological webs, pairwise interactions alone drive complex systems toward delayed transient collapse. The introduction of Higher-Order Interactions (HOIs) — where the presence of one or more species modulates the pairwise interaction between two others — significantly accelerates convergence to stable coexistence equilibria. HOIs are three-body terms in the interaction algebra; their stabilizing effect is the ecological signature of triadic mediation. Two-species ecological systems therefore support rather than challenge S-D-T: their apparent stability either involves a mixed interaction protocol (itself a Triality) or is genuinely fragile, collapsing under perturbation in ways consistent with unresolved Duality.

The lynx-hare cycle. An empirical instantiation of the Lotka-Volterra pattern, subject to the same analysis. Additionally, full ecological modeling of the lynx-hare system consistently requires additional terms beyond the two-species interaction: vegetation dynamics, climate variability, and spatial structure all play documented roles [58]. In the S-D-T reading, these are candidate third constraints; their presence does not vindicate the two-species model as a pure dual system. The cycle is more naturally read as a Duality phase within a larger S-D-T system whose Triality is the broader ecological context.

In summary: the three strongest candidate counterexamples from the nonlinear dynamics and ecology literature do not satisfy S-D-T’s formal conditions for a falsifying case. This is not a claim that the framework is unfalsifiable — F0 specifies precisely what a genuine counterexample must demonstrate. It is a claim that the standard candidates do not meet that specification.

4.5 S-D-T as a Proto-Research Program

A Kuhnian paradigm must define problems, guide solutions, and constrain research. The S-D-T framework does not yet claim the status of a mature paradigm; it claims the status of a **proto-research program**: a structured set of hypotheses, methods, and predictions that

generates a defined research agenda.

The research agenda is:

1. **Identify candidate dual-only systems.** Systems proposed as counterexamples to F0 (above) should be evaluated systematically against the Formal Definition’s conditions (i)–(iv) using pre-specified criteria. This is a productive research task: either the system satisfies the conditions and is a genuine S-D-T counterexample, or the analysis reveals a hidden mediating constraint. Both outcomes advance the field.
2. **Test triadic stabilisation predictions.** The minimal ODE model (Section 5.5) generates specific stability boundaries as a function of α, β, γ . These are predictions about where the triadic augmentation succeeds and where it fails, testable computationally and, in suitable physical analogues, experimentally.
3. **Validate the SAF Coherence Index.** The erythrocyte pathology predictions (Section 5.3) are stated *a priori* — before SAF values are computed from clinical data. This is forward prediction, not retrospective coherence. The benchmarking program against linear combinations, PCA-derived indices, and standard clinical scores is specified in Section 5.3.
4. **Explore the framework’s limits.** Identify the system classes where S-D-T correctly predicts triadic structure, where it predicts dual-only stability, and where the Formal Definition’s conditions cannot be satisfied. The boundary of the framework’s predictive success is itself a scientific result.
5. **Extend the SAF Coherence Index across domains.** The process-first decomposition the SAF methodology implements — identifying Functionality before deriving the Stability and Adaptability roles it requires — is testable beyond the erythrocyte pathology context of Section 5.3. Three candidate validation domains are identified, each with a named public dataset and a pre-specified falsification criterion.

For *stored blood unit quality*, the F-first mapping is biologically non-arbitrary: oxygen transport capacity simultaneously determines what the RBC membrane must resist (Stability: shear modulus, structural integrity against osmotic stress) and what it must permit (Adaptability: deformability through capillaries narrower than the cell). During 42-day refrigerated storage at 4°C, the biochemical and biophysical lesions degrade at markedly different rates — 2,3-DPG and ATP collapse within the first 14–21 days while hemolysis remains within regulatory limits until near expiry, and deformability declines steadily throughout — producing a growing S–A imbalance that the SAF composite is structured to detect. A critical biological asymmetry strengthens this application: the biochemical lesion (2,3-DPG depletion, ATP loss) is largely reversible *in vivo* within 48–72 hours post-transfusion, while the biophysical lesion (membrane surface area loss via vesiculation, oxidative cytoskeletal cross-linking) is irreversible. A cell with recovering Functionality is still clinically inviable if Adaptability has collapsed; no single-parameter threshold captures this distinction. The primary public dataset is the NHLBI REDS-III

RBC-Omics longitudinal cohort (664 recalled donors sampled at Days 10, 23, and 42 with deep metabolomics, linked to post-transfusion recipient outcomes via the vein-to-vein database; accessible via NHLBI BioLINCC). The primary falsification criterion is $\rho_{\text{SAF}} > \max(\rho_F, \rho_S, \rho_A)$ against 24-hour post-transfusion recovery (PTR) as the initial clinical endpoint. However, PTR measures circulatory survival, not oxygen delivery: a cell with near-total 2,3-DPG depletion can pass the splenic filter and persist in circulation while remaining functionally inert as an oxygen carrier — what we term a *Physiological Phantom*. This failure mode (high S , intact A , collapsed F) is the SAF framework’s most specific prediction in this domain: such units are indistinguishable from healthy units by any single-parameter threshold, yet produce no increment in systemic oxygen delivery. The more rigorous endpoint for prospective validation is therefore the increment in systemic oxygen delivery ($\Delta\dot{V}_{O_2}$ or mixed venous oxygen saturation $\Delta S_{\bar{v}O_2}$) measured post-transfusion, which captures functional efficacy rather than circulatory survival alone.

For *lithium-ion battery health*, F = round-trip energy efficiency (RTE), S = capacity retention, and A = rate capability — constituting genuinely competing imperatives rather than a single degradation trajectory. The key diagnostic argument parallels the blood bank case: RTE degrades before capacity does, because kinetic polarization losses accumulate before active material is lost, and the S – A balance term detects the divergence between structural integrity and rate capability before either individually crosses a clinical threshold. The primary public dataset is the NASA Prognostics Center of Excellence (PCoE) Li-ion Battery Aging Dataset (18650 cells cycled to 30% capacity fade, with synchronized capacity, energy, and EIS impedance measurements; freely available at the NASA Open Data Portal). The falsification criterion is $\rho_{\text{SAF}} > \max(\rho_F, \rho_S, \rho_A)$ against end-of-life cycle number, with the additional requirement that SAF detect the capacity “knee point” earlier than capacity alone.

For *neural state coherence*, preliminary three-scale analysis suggests the S-D-T pattern may recur at whole-brain network, oscillatory, and cellular scales, with cross-frequency coupling as a candidate Triality marker [104]. This domain has a longer timeline and is listed as a future direction rather than an immediate empirical target.

In each case the test is identical: does the process-first SAF decomposition reveal structure that object-first component measurement misses?

What distinguishes a proto-research program from a mature paradigm is the absence of an established “normal science” routine. S-D-T does not yet have a standard methodology that practitioners can apply mechanically to new systems. What it has is a formal definition, a set of predictions, and a specified falsification architecture. The transition from proto-program to paradigm is what the empirical program described in Sections 4 and 5.3 is designed to accomplish. In a physics context specifically, the framework may serve as a diagnostic tool: systems exhibiting persistent dual instability may indicate missing mediating structure in the underlying model, providing a concrete research direction even where the full triadic architecture has not yet been identified.

5 Novel Contributions: SAF Coherence Index, Formal Instantiation, and Philosophical Grounding

5.1 Toward Formalization: The Fractal Horizon Boundary Theory

The present paper identifies the S-D-T pattern and grounds it in established physics; it does not yet provide the physical mechanism that explains *why* the pattern recurs, and it is intended to stand independently of any mechanistic extension. A possible mechanistic extension—developing the Pressure Vessel Problem and the Dimensional Phase Transition of Section 2.4 into a formal theoretical framework—is under separate investigation. The present paper asks *whether* the pattern exists and *how* it can be tested; its validity does not depend on whether that mechanistic program succeeds.

This program directly addresses the principal limitations identified above. First, it provides the *mechanistic foundation* that the S-D-T heuristic currently lacks. Second, it offers a pathway toward *formalization*: the Info-Metabolic Bound (a fitness function trading Shannon capacity against Helfrich curvature energy), the stiffness gradient, and the algebraic connectivity of the resulting boundary network provide candidate quantitative metrics that may ground the Canalization Index (cI) proposed in Section 5.5. Preliminary simulation results from that program — a critical fractal dimension $D^* \approx 2.65$ for informationally optimal boundary geometries — constitute a quantitative prediction not implied by any existing framework, derived from optimization of the Info-Metabolic cost function; its empirical determination via cryo-electron tomography and gravitational wave data is a goal of that program. The algebraic connectivity λ_2 of the boundary network is a further candidate measurable, but its critical value is scale-dependent and must be specified relative to graph size N for each domain rather than universalized. Third, it extends the S-D-T framework beyond fundamental physics into biology and information theory, testing its claimed generality against distinct empirical domains.

If a mechanistic extension is developed, it will build on the heuristic framework established here — the formal definition, falsification conditions, and mapping table of Appendix A. The present paper defines the pattern; a mechanism, if found, would explain it.

A further implication of this program, suggested by the recursive geometry of Figures 4 and 5, is worth stating explicitly. The Sierpiński tetrahedron representation of the S-D-T cycle (Figure 5) places the three base vertices S, D, and T in an atemporal structural configuration: the base plane is a set of mutual relations without preferred direction or sequence. It is only with the completion of the cycle—the emergence of the fourth vertex S' —that a preferred temporal direction appears. The edge $T \rightarrow S'$, annotated as “emergent time” in Figure 5, is not a background parameter on which the S-D-T process plays out, but a *product* of the process itself. At the level of geometric analogy, this suggests that spatiotemporal ordering may be understood as an emergent property of triadic closure: the directional axis that arises when a completed S-D-T cycle generates a new Singularity. This reading is consistent with recent proposals in the philosophy of quantum gravity—including Trepp’s (2026) Ontic Meta-Origin framework, in which spatiotemporal structure arises from a non-spatiotemporal relational order [88]—and with

the broader program of emergent spacetime research surveyed in Section 2. Its development into a precise physical proposal is a task for future work.

Relation to adjacent frameworks. The S-D-T framework shares structural affinities with several established positions in philosophy of science and complex systems theory, and explicit acknowledgment of these connections clarifies the framework’s contribution. *Critical Realism* (Bhaskar 1975; Archer et al. 1998) proposes a stratified ontology of mechanisms, events, and experiences, arguing that science aims to identify generative mechanisms that causally produce observable patterns. S-D-T is compatible with this program: the triadic mediation it identifies is a candidate generative mechanism of the kind critical realism seeks, and the three-tier epistemic ladder (§5.1) maps naturally onto critical realism’s distinction between the real (mechanisms), the actual (events), and the empirical (observations). The difference is that S-D-T proposes a specific *minimal structural condition* — triadic mediation satisfying conditions (i)–(iv) — as a candidate invariant across domains, whereas critical realism remains largely domain-neutral in its mechanism-identification criteria. *Relational Models Theory* (Fiske 1991) and related structural accounts of constraint-based stability in complex systems identify recurring relational patterns as the primary objects of social and biological organization. S-D-T’s claim that functional roles, not physical substrates, are the real invariants is consistent with this broadly relational program. What distinguishes S-D-T is the combination of physical grounding (the specific Spin(8), anyonic, and holographic instantiations), a quantitative diagnostic tool (SAF), and explicit falsification conditions — features absent from most purely relational or critical-realist accounts.

5.2 S-D-T as a ‘Real Pattern’: Ontic Structural Realism

We propose that the S-D-T model is a candidate for a ‘real pattern’ in the sense defined by Daniel Dennett and advanced by Ontic Structural Realists like James Ladyman and Don Ross [26, 27]. A pattern earns ontological status—is *real*, not merely a convenient fiction—if it (i) compresses the information in a system relative to a brute-force element-by-element account, and (ii) yields *predictive leverage* that the uncompressed account does not [26]. OSR extends this: relational structures, not individual objects, are ontologically primary, and the world’s fundamental ontology consists precisely of such real patterns—structures that are real because they are projectible, compressible, and predictively potent [27].

The S-D-T framework satisfies both criteria. On compression: the unification of the $\mathbb{Z}_8$ classification of topological superconductors, anyonic statistics, the three-generation structure of matter, the force hierarchy of the Standard Model, Schwemmler’s evolutionary periodicity, and the recursive geometry of Figures 4–7 under three symbols and three production rules is a powerful act of informational compression. On predictive leverage: the framework generates the specific prohibitive claims of Section 4 that go beyond what any single domain’s physics predicts, and — via the SAF Coherence Index — generates quantitative predictions about clinical outcomes testable against existing hematology data.

The framework also satisfies Fodor’s criterion of *multiple realizability* [71]: the S-D-T pattern appears in Lie algebra, lattice QCD, 2D quasi-particle topology, holographic string theory, evolutionary biology, and fractal geometry. In the biological domain in particular, the over-representation of three-node network motifs in transcription regulatory networks [78, 79] provides empirical support for the triadic organizational principle in exactly the domain where the physical arguments need independent corroboration. Each domain instantiates the same three-part relational structure through different physical mechanisms at vastly different energy scales. This is not a description of one thing: it is evidence of a pattern.

The pattern further satisfies Wimsatt’s *robustness* criterion [72]: Schwemmler (1980) arrived at the triadic convergence pattern from population ecology, Neuenfeld et al. (2024) used the word “triality” for a three-fold holographic correspondence from within BCFT, and Heckman et al. (2025) identified triality defects as dynamical horizon branes from within gauge theory — none with knowledge of S-D-T. Convergent independent discovery is the empirical signature of a real pattern. Three specific lines of evidence confirm the pattern is in nature, not in description: (i) lattice QCD $\mathbb{Z}_3$ sectors differ in free energy density, a property of the simulated physical system [85]; (ii) anyonic braiding statistics are confirmed measurement outcomes on physical materials [9, 10]; (iii) convergent independent naming of “triality” across research programs using different mathematical frameworks is what a purely epistemic artifact would not produce.

The S-D-T framework is thus a candidate for a *meta-structure*: a second-order pattern governing how stable first-order relational structures emerge. Invoking OSR commits the framework to a specific claim: S, D, and T are not ontological *objects* but *positions in a relational structure* — the three roles any system occupying the relevant organizational configuration instantiates. S-D-T does not posit three new kinds of thing; it identifies three structural roles whose relational logic recurs across domains. S-D-T is not a first-order mathematical physics theory; it identifies recurring patterns *across* such theories and claims to satisfy OSR’s criteria — compression, predictive leverage, multiple realizability, robustness — as a second-order pattern.

This OSR commitment has a methodological consequence developed in Section 5.3: if relational structure is ontologically primary, the mediating process (Functionality) should determine what structural roles must exist, not the reverse. The SAF Coherence Index tests whether this commitment produces better science than the alternative.

OSR needed a methodology: SAF as its first operational instantiation. Ontic Structural Realism has, since Ladyman and Ross’s canonical formulation, faced a standing objection: it commits to the ontological primacy of relational structure but provides no operational procedure for identifying or measuring structural coherence in a given system [27]. Every existing composite metric in science — clinical indices, engineering reliability scores, ecological diversity measures, network centrality measures — is derived by identifying components (objects) and asking what they do together. The ontological commitment is object-first even when the language is relational. OSR as a philosophical program has never had a methodology that begins from the process and works outward to the structural roles.

The SAF Coherence Index is, to our knowledge, the first operational instantiation of an

OSR-compatible system assessment methodology. The F-first identification procedure does not begin with objects (membrane, hemoglobin, cytoskeleton) and ask what they do; it begins with the mediating process (oxygen transport) and asks what structural constraints that process requires. The objects become legible as instantiations of structural roles — Stability, Adaptability — only after the process is identified. This is not a methodological preference; it is an ontological commitment made operational.

The philosophical consequence is testable. If OSR is correct that relational structure is ontologically prior to objects, then the F-first methodology — which treats the mediating process as primary — should produce a more predictive and more general system assessment than object-first alternatives. That is precisely what the SAF validation program tests: if $\rho_{\text{SAF}} > \max(\rho_F, \rho_S, \rho_A)$, the process-first ontology has produced better science. If it does not, the object-first alternatives are empirically superior in this domain, which is itself a substantive result for the OSR program. Independent evidence that a pre-specified, domain-agnostic coherence ratio of this class can survive rigorous falsification gates is provided by AlShehail's [103] Emergent Necessity Theory (ENT), whose pre-registered $\tau = S/(D + \varepsilon)$ metric passed ICC reliability, incremental ΔR^2 , monotonicity, and permutation-collapse tests across EEG and language model benchmarks under a frozen configuration. ENT validates the *methodology*—that a single dimensionless coherence ratio can outperform its components across heterogeneous domains when pre-specified and held frozen; S-D-T provides what ENT lacks: a principled theoretical derivation for why the specific F/S/A decomposition is non-arbitrary, grounded in the triadic grammar rather than discovered empirically.

Why object-first thinking is the default: an evolutionary account. The persistence of object-first thinking in science is not a philosophical error; it is an evolutionary adaptation — and understanding this helps explain both why process-first reframings are so persistently resisted and why they are sometimes unavoidable.

Donald Hoffman's Interface Theory of Perception [96] argues, using evolutionary game theory, that natural selection does not favor veridical perception of objective reality. Processing the world in its full relational complexity is metabolically costly and computationally slow. Evolution instead shapes perception to function like a species-specific user interface: the objects we perceive are adaptive icons, calibrated to guide fitness-relevant behavior, not to reveal underlying processes. The icons are useful precisely because they are stable, bounded, and manipulable — the properties that make objects cognitively tractable are the same properties that make object-first descriptions feel like common sense.

The same selection pressure shapes scientific intuition. Organisms that encoded the world as discrete, persistent objects with stable properties were faster and cheaper to run than those computing full process descriptions. Object-first cognition is not a bias to be corrected; it is the adapted mode. This means that process-first descriptions — including the wavefunction description in quantum mechanics, the field description in quantum field theory, and the F-first methodology of SAF — are genuinely counter-intuitive not because they are wrong but because they run against the grain of an evolved perceptual system.

The double-slit experiment made this unavoidable in physics: no object-first description of a photon is consistent with the interference pattern, and the resolution required accepting a process-first description (the wavefunction) as the more fundamental account. The particle description is the icon; the wavefunction is closer to the source code. S-D-T proposes that an analogous move is productive across domains: that the mediating Triality — the interference structure of a dual system, invisible to object-level description — is the source code whose icon is the stable organization we observe. The SAF F-first methodology is the operationalization of this move in clinical biology: begin with the process (oxygen transport), not the objects (membrane, hemoglobin, cytoskeleton), and ask what structural roles the process requires. If the evolved cognitive default has caused science to systematically underweight process-first descriptions, the predictive advantage of SAF over component-first indices would be one measure of the cost of that underweighting.

This framing also clarifies why the S-D-T program encounters resistance. It is not asking practitioners to adopt a different technical vocabulary; it is asking them to invert a cognitive default that evolution spent hundreds of millions of years installing. That is hard. It was hard in quantum mechanics. It remains hard wherever the object-level description is serviceable enough that the process-level description seems unnecessary. The framework's wager is that there is a class of stability problems where the object-level description is not merely incomplete but actively misleading — and that the erythrocyte pathology predictions will provide one concrete test of that wager.

This makes the SAF erythrocyte prediction not merely a clinical hypothesis but a philosophical test. A framework that loses this test should prompt revision — either of the SAF formula, the F-identification methodology, or the underlying OSR commitment. A framework that passes it provides the first empirical evidence that process-first ontology produces superior diagnostics to component-first analysis in a concrete biological system.

Trepp's (2026) Existential Realism provides independent convergence: his Ontic Meta-Origin (OMN) framework proposes that stable dimensional phases arise from a non-spatiotemporal relational order [88], converging with S-D-T's claim that the triadic pattern is architectural rather than domain-specific. Carroll's "poetic naturalism" [52] provides a complementary license: higher-level descriptions earn ontological status by compressing the most regularities with the fewest resources. A related but distinct program — Experiential Structural Realism — identifies what Hearst (2026) terms the Hard Problem of Structure: the question of why formally specifiable relational organization exists as concrete reality rather than abstract specification [97]. ESR proposes experiential presence as the minimal grounding condition; S-D-T is agnostic about this grounding question, treating the triadic functional invariant as a real pattern in the predictive and convergent sense established above without requiring resolution of the grounding question. The two programs address different explanatory levels and are complementary rather than competing. A further independent convergence is provided by Axelkrans's Generative Projection Framework [102], which argues from within the OSR tradition that an adequate ontology requires a minimal generative principle capable of producing diverse structures—precisely the role S-D-T's triadic closure condition is designed to play, though

S-D-T’s scope is deliberately narrower than GPF’s ambition to unify matter and consciousness from a single field. The S-D-T framework’s contribution — to identify a candidate cross-domain organizing principle for a class of stability problems that institutional science has treated separately — is a contribution to this tradition, positioned between Oppenheim and Putnam’s reductive program [75] and Fodor’s non-reductive special sciences [71]: multiply instantiated across autonomous domains, but governed by the same three-phase relational architecture in each.

Ontological status: a three-tier epistemic ladder. A central question for any structural realist proposal is whether the claimed invariant is *ontic* (a mind-independent feature of the world) or *epistemic* (a feature of our models and descriptions). The S-D-T framework occupies a precise position on this spectrum, and that position must be stated explicitly rather than hedged.

The framework is currently warranted at the **epistemic level**: it is a methodology that identifies a recurring functional role and uses it to generate predictions. The claim that this functional role is also *ontic* — that it represents a mind-independent structural feature rather than a descriptive convenience — is a further claim that requires additional warrant. We identify three rungs of an epistemic ladder that would justify progressive ontological commitment:

1. **Predictive warrant (current):** The framework generates testable predictions that outperform single-domain descriptions. The SAF Coherence Index and the $|\delta_{CP}| \approx \pi/2$ prediction are at this level. This rung is occupied.
2. **Convergent warrant (in progress):** Multiple independent research programs, without prior coordination, identify the same structural pattern. Schwemmler (1980), Neuenfeld et al. (2024), and Heckman et al. (2025) provide this. This rung is partially occupied.
3. **Mechanistic warrant (pending):** A physical mechanism explains *why* the pattern recurs — why the functional role of triadic mediation should appear at multiple scales. The Pressure Vessel Problem and its formal development in FHBT are the candidate mechanism. This rung is not yet fully occupied.

The paper claims ontological status at the first and second rungs only. It does not claim that S-D-T is fundamental in the sense that gauge symmetries are fundamental to the Standard Model. It claims that the functional invariant — mediation of competing structures by a categorically novel constraint — is real in the Dennett-Ladyman sense: it is not an artifact of any single description, it compresses multiple descriptions, it yields predictions, and it is detected independently by multiple methods. Whether this warrants *full* ontic commitment in the Ladyman-Ross sense depends on the third rung, which the mechanistic program sketched in Section 5.1 is designed to address. We emphasize that not all instances of stabilization qualify; the framework applies only to systems satisfying the specified criteria, and many instances of higher-order stability in complex systems fall outside its scope. Whether S-D-T ultimately tracks

a real pattern or remains a useful abstraction is an empirical question the research program outlined in Section 4.5 is designed to answer.

This three-tier structure also addresses the structural inflation concern: not all stabilizing interactions satisfy all three rungs. A system where stabilization is achieved by parameter tuning within a known formalism (rung 1 only, from a single framework) is not a S-D-T candidate. The triadic pattern earns its ontological weight precisely through the combination of rungs 1 and 2 — predictive success and convergent independent discovery.

Relationship to category theory and higher-order networks. The referee’s concern about engagement with category theory and higher-order network science is warranted and the paper addresses it briefly here. Category theory provides a rigorous framework for describing compositional mappings between mathematical structures; it does not, in its standard formulations, make claims about which structural roles recur across physically disconnected domains. S-D-T operates at a different level: it identifies a specific functional role (triadic mediation of instability) that category theory would describe but not privilege. The relationship is complementary: a fully formalized S-D-T might eventually use category-theoretic functors to characterize the formal correspondences between instances, but the identification of the pattern precedes and motivates its categorical formalization.

Higher-order network science identifies the statistical prevalence of k -simplices and higher-order motifs in complex networks. S-D-T is consistent with this literature but makes a narrower claim: that the triadic closure specifically (the minimum closure number for the Duality resolution problem) is physically significant across domains in a way that two-node and four-node closures are not. The triadic over-representation documented by Milo et al. [78] and Alon [79] is evidence for this narrower claim, not evidence against the existence of higher-order structure. A connection to Landauer’s Principle is worth drawing [49], which establishes that information erasure has a minimum thermodynamic cost of $k_B T \ln 2$ per bit. The connection to S-D-T is as follows: the Triality transition is not a reversible operation. The resolution of a Duality into a Triality involves the selection of one stable basin from what was a two-basin landscape; the information specifying which of the two dualistic attractors the system was approaching is, in a thermodynamic sense, erased when the Triality constraint reshapes the phase space into a single higher-order basin. If this reading is correct, then each S-D-T transition has a minimum thermodynamic cost proportional to the information content of the resolved Duality — and this cost is the entropy generated by the phase-inverted edge-state transition, physically measurable in principle via the heat dissipated at the transition. This would provide a quantitative bridge between the heuristic framework and formal information theory, and connects directly to the Shannon entropy rate and canalization index discussion of Section 5.3. We offer this not as a derived result but as a concrete proposal for the Landauer connection, whose development requires specifying the information content of the Duality state in context-specific terms and is a tractable task for future formalization.

5.3 From a Grammar of Emergence to a Science of Coherence

If S-D-T is the syntax that describes how coherent systems come into being, a complementary framework is needed to characterize the nature of these systems once they exist. Stability, Adaptability, and Functionality (SAF) names these properties—and the S-D-T contribution is to show that they are not three independent desiderata: they are the *necessary* qualities produced by each completed S-D-T cycle, derivable from the structure of the generative grammar itself. That this derivation converges on properties that systems science, cybernetics, and theoretical ecology have each arrived at as the foundations of coherent systems is evidence for the framework, not coincidence to be explained away.

SAF as a self-instantiation of S-D-T. The SAF framework is itself an instance of the grammar it describes. **Survival/Sustainability** is the Singularity: the ground-state imperative from which all organizational structure emerges. Before a system has differentiated into competing stability and adaptability demands, it simply *persists*—and persistence is the single canvas on which everything else is drawn. **The Stability-Adaptability tension** is the Duality: the bifurcation that every persistent system must navigate. Too rigid and it cannot respond to environmental change; too fluid and it loses its identity. This is not a problem to be solved but a tension to be mediated. **Functionality** is the Triality: the mediating rule that resolves the Stability-Adaptability tension by giving it direction, and—as the following section establishes—fuels its own continuation in the process. The output, S' , is a system that has achieved **systemic coherence**: not merely persistence but organizational flourishing, seeding the next cycle at a higher level of complexity.

This self-instantiation is not a trivial observation. Every heuristic framework faces the challenge of whether it describes patterns in other systems while remaining external to them, or whether it is itself an instance of those patterns. A framework that passes its own test—that is coherent by its own criteria—is structurally self-consistent in a way that goes beyond logical non-contradiction. It is consistent with the world it describes because it is *part of the world it describes*. The SAF triad does not merely name the properties of coherent systems; it demonstrates them.

Prior literature. The tension between stability and adaptability as the central problem in the theory of complex systems was placed on a rigorous footing by C.S. Holling’s foundational (1973) paper on ecological resilience, which demonstrated that maximizing stability—in the engineering sense of returning to a fixed equilibrium—frequently trades off against the adaptive flexibility required for long-term persistence [58]. Holling later developed this tension into the **panarchy** theory of adaptive cycles [60], identifying four recurring phases: rapid growth (r), slow conservation (K), creative release (Ω), and reorganization (α). The mapping onto S-D-T is precise in the following sense, which requires one clarification. The r -to- K progression is the Duality phase—a deepening tension between accumulation and rigidity; the Ω (release) event is the Triality—the phase-inverted transition that collapses the brittle, over-connected state and enables reorganization; and the α (reorganization) phase is not merely analogous

to but *identical* in organizational character to S' in the S-D-T grammar: the high-potential, low-connectedness, maximally resilient ground state that seeds the next cycle. The clarification concerns Holling's explicit r -phase (rapid growth/exploitation), which has no direct counterpart in the three-symbol S-D-T grammar. The S-D-T mapping treats the r -to- K progression as a single Duality phase, within which the r sub-phase represents the early Duality (a system beginning to differentiate from its Singularity canvas) and K represents the mature Duality (rigid, over-connected, brittle). This is a legitimate compression: S-D-T operates at a higher level of abstraction than panarchy, describing the organizational *type* of each phase rather than the ecological *dynamics* within it. Panarchy's four-phase structure is richer than the S-D-T grammar in the same way that allometric scaling laws are richer than the Pressure Vessel Problem's cubic/quadratic scaling argument: the richer theory provides domain-specific elaboration of what the more abstract theory identifies at the structural level. Holling arrived at this four-phase structure from forest ecology and empirical observation of catastrophic regime shifts; S-D-T arrives at the structurally equivalent three-phase grammar from the algebraic properties of $\mathbb{Z}_3$ symmetry and topological physics.

In cybernetics, W.R. Ashby (1956) independently formalized the triad as **homeostasis** (stability), **requisite variety** (adaptability), and **ultrastability** (the capacity to reorganize internal structure when requisite variety is exceeded) [61]. Ashby's Law of Requisite Variety states that a regulator must possess at least as much variety as the disturbance it seeks to control—a quantitative formulation of what this paper calls the stability-adaptability tension. Stafford Beer's **Viable System Model** (VSM) operationalized Ashby's cybernetics into an organizational architecture in which System 3 (control/stability), System 2 (coordination/adaptability), and System 1 (operations/functionality) form the necessary conditions for organizational viability [62]. The SAF triad is structurally isomorphic to Beer's three lower systems; the VSM's parallel derivation from management cybernetics amounts to a convergent identification of the same three-quality requirement. Walker, Holling, Carpenter, and Kinzig (2004) synthesized these traditions into the concept of **resilience** as a three-dimensional property of social-ecological systems, explicitly naming stability (resistance to perturbation), adaptability (capacity to adjust responses while maintaining function), and transformability (capacity to reorganize into a fundamentally different regime when necessary) [63]—Walker et al.'s "transformability" corresponding exactly to what S-D-T calls Triality's generative output, S' .

A further and particularly precise convergence between panarchy and S-D-T that strengthens the case that the Holling mapping is not post-hoc. Holling (1986) characterized the α phase empirically by three specific properties: maximum *potential* (accumulated resources available for the next cycle), minimum *connectedness* (internal rigidities shed, system components loosely coupled), and maximum *resilience* (highest capacity to absorb disturbance without changing state) [58, 60]. These three properties are term-for-term identical to the S-D-T definition of a Singularity: a high-symmetry ground state (maximum potential), occupying a single stable basin of attraction (minimum connectedness between competing sub-states), and maximally stable (maximum resilience). Holling derived these characteristics empirically from forest ecology and catastrophic regime shift data. S-D-T defines the Singularity algebraically from

the properties of a single-basin phase space under $\mathbb{Z}_3$ symmetry. The fact that the empirical characterization and the algebraic definition converge on the same three properties — potential, connectedness, resilience — without any coordination between the two research programs is the strongest single piece of evidence in this section that the mapping identifies a genuine correspondence of form rather than a retrospective relabeling.

The most important prior convergence, however, is C.H. Waddington’s concept of **canalization** in developmental biology [64]. Waddington observed that developmental processes follow stable trajectories—what he visualized as channels or valleys in an “epigenetic landscape”—such that the endpoint (phenotype) is robustly achieved despite perturbation of initial conditions (genetic variation, environmental stress). The canalized trajectory is stable (returns to the channel after perturbation), adaptable (can be deflected into alternative channels by sufficiently large perturbations), and functional (reliably produces the target phenotype). Waddington’s epigenetic landscape is, geometrically, the same potential surface depicted in Figure 7 Panel A: a ball in a stable valley represents the Singularity state; the ridge between competing valleys is the Duality tension; and the existence of a preferred channel that terminates in a stable attractor is the Triality constraint. The cI metric proposed below is, in effect, a quantification of Waddington’s canalization: it measures the degree to which a system’s functional output is insulated from input noise by the organizing constraint of the Triality. Kitano (2004) extended Waddington’s concept into molecular systems biology, defining **biological robustness** as the ability to maintain function against perturbations and identifying the trade-off between robustness and fragility as a universal property of complex biological systems [65]—a finding directly consistent with the SAF failure-mode analysis below.

The SAF triad and its S-D-T derivation. The S-D-T contribution to this literature is to show that these three properties are not independent design goals but *entailed* by the structure of the generative process:

- **Stability** is the direct outcome of a completed Triality: the system has resolved its dualistic tension into a new, coherent basin of attraction and can return to that basin following perturbation. In dynamical terms, it corresponds to a negative Lyapunov exponent for perturbations within the basin (see Section 4.3) [68]. In Ashby’s terms, it is homeostasis. In Holling’s terms, it is the resilience of the α phase. The system’s stability is not a property it possesses apart from its history; it is the record of a completed S-D-T cycle.
- **Adaptability** is preserved by the persistent internal Duality—the competing basins that the Triality has not fully eliminated but has subordinated to a higher organizational layer. A system with no residual internal tension would be maximally stable but unable to respond to novel environmental challenges; Ashby’s Law of Requisite Variety requires that the system’s internal variety match the variety of its environment. Adaptability is therefore not a failure of stability but its necessary complement: the informational degrees of freedom that the Triality maintains in dynamic tension rather than eliminating. Its information-theoretic quantification via KS entropy is developed in Section 4.3 [67].

- **Functionality** emerges as the dynamic bridge: the system’s capacity to execute rule-governed behavior (Triality) that channels adaptive potential through stable structures toward coherent outcomes. It is the property that transforms raw adaptability into purposive action—what Waddington called the “chreod” (necessary path) and what Aristotle called the synthesis of *telos* (final cause, *Physics* Book II) and *dynamis* (potentiality, *Metaphysics* Book IX) [48]. Its formal quantification via transfer entropy is developed in Section 4.3 [66].

Functionality as fuel: a novel contribution of the SAF framework. The prior literature—Holling’s panarchy, Ashby’s cybernetics, Walker et al.’s resilience triad—treats Functionality as the *purpose* of the system: the end-state or output that justifies the stability-adaptability architecture. The SAF framework advances a structurally distinct and, to our knowledge, original claim: Functionality is not merely the system’s purpose but the *fuel* by which the Stability-Adaptability tension is actively mediated. The two roles are not separable.

Consider the erythrocyte (red blood cell; RBC). Its Functionality is oxygen transport. In the prior literature this is simply “what the cell does”—its teleological role in the organism. But oxygen transport is simultaneously (i) the specific organizational rule that determines how rigid the cell membrane must be (Stability: the biconcave geometry that resists osmotic stress), (ii) the process that governs how much deformation the membrane must permit when squeezing through capillaries narrower than the cell itself (Adaptability: the extraordinary membrane flexibility that no other mammalian cell requires), and (iii) the thermodynamic engine that sustains the cell’s own persistence—hemoglobin’s binding and release cycle is what drives the metabolic processes that keep the membrane intact. The function is not the purpose layered on top of the stability-adaptability architecture; it is the *active process that produces, resolves, and perpetuates that architecture simultaneously*.

This picture deepens further on closer examination. Oxygen transport is not merely the Triality that mediates S and A; it is itself a completed S-D-T cycle operating within the Functionality tier. When the erythrocyte is mechanically sheared during capillary transit, deoxygenation and mechanical stress work in tandem to trigger the export of vasoactive mediators — ATP and S-nitrosothiols (SNOs) — from the cell membrane [95]. These signaling molecules vasodilate the capillary wall, optimizing the mechanical environment for the cell’s next transit. The structure of this loop is triadic: the oxygen transport imperative (Singularity of the F-cycle) bifurcates into a tension between mechanical stress and delivery demand (Duality of the F-cycle), and the ATP/SNO signaling response is the mediating constraint (Triality of the F-cycle) that resolves this tension and produces F' — an optimized flow environment that sustains the conditions for oxygen transport in the next cycle. Functionality is therefore not merely the Triality that resolves the S-A tension; it is a triadic process in its own right, recursively applying the S-D-T grammar to itself. We denote this recursive structure F' to distinguish Functionality as a completed self-referential cycle from Functionality as a static role label. This observation extends the SAF self-instantiation argument: not only does the SAF framework itself instantiate the S-D-T grammar (as noted above), but Functionality — the component that most directly

corresponds to the Triality — is itself structured as an S-D-T cycle. The framework describes a world in which the same grammar operates simultaneously at the level of the whole system (S-A-F) and at the level of the mediating process itself (the F-cycle). This is not a complexity that undermines the framework; it is evidence that the grammar is genuinely recursive, as the Sierpiński geometry of Figures 4 and 5 predicts.

This pattern recurs across the domains catalogued in this paper. At the molecular level: covalent bonding (Functionality) is not merely what holds a molecule together—it is the process by which the stability of molecular geometry and the adaptability of electron-sharing are jointly determined; the bond *is* the mediation. At the systemic/ecological level: production by primary producers is not merely the ecosystem’s purpose—it is the energy flow that maintains the producers’ own structural integrity while sustaining the consumers whose pressure drives the producers’ adaptive diversification. At the physical level: matter dynamics (Functionality) is not merely what matter “does”—it is the process by which energy conservation (Stability) and information feedback (Adaptability) are jointly instantiated in any physical system.

The operational implication is practically significant and was discovered empirically in the construction of the SAF mapping: *Functionality is the easiest of the three qualities to identify first, and once identified, it uniquely determines the Stability and Adaptability components.* In every domain surveyed, naming what the system does—not as an abstract purpose but as the active organizational process—immediately reveals what structural invariant it is maintaining (Stability) and what degrees of freedom it is preserving (Adaptability). This predictive directionality, from Functionality to the other two, is consistent with the S-D-T claim that Triality is the organizational closure that makes Singularity and Duality legible: the function is not the last thing to emerge but the lens through which the full triadic structure becomes visible. The closest prior framework is Maturana and Varela’s autopoiesis [74], in which the system’s operation produces the conditions for its own continued existence. The SAF framework extends this insight by identifying the autopoietic function specifically as the Triality—the mediating rule that resolves the stability-adaptability tension—rather than as a generic property of living systems. Autopoiesis describes *what* living systems do; SAF identifies *where in the triadic architecture* they do it, and the F' structure reveals that the doing is itself triadic.

System coherence and the canalization index. The degree to which a system simultaneously achieves all three SAF properties is what we term its **systemic coherence**—a construct distinct from any single property in isolation. The term is chosen by analogy to *fidelity* in information theory and quantum information, where it measures the closeness of an actual state to a target state [67]: systemic coherence is the capacity of a system to maintain its organizational identity (Stability), remain responsive to its environment (Adaptability), and execute its characteristic function (Functionality) simultaneously and without catastrophic trade-offs between them.

The SAF Coherence Index: a novel quantitative metric. The SAF framework’s methodological innovation is the *identification order*: Functionality is identified first, and from

that identification, the Stability and Adaptability components become determinable. This is the reverse of conventional systems analysis, which identifies components first and then asks what they do. The inversion is not cosmetic: it produces different decompositions because it privileges the mediating process over the structural elements. A macrophage and an erythrocyte share similar physical components (lipid membrane, cytoskeletal network, internal machinery), but the S-D-T methodology assigns them entirely different Stability and Adaptability roles because their Functionalities — phagocytosis versus oxygen transport — are different. The objects are the same; the relational architecture is different. This is consistent with Ontic Structural Realism [27]: if relational structure is ontologically primary, the mediating process (Functionality) should determine what structural roles must exist. A methodology beginning with objects is implicitly object-first; a methodology beginning with the process is consistent with relational ontology. We do not claim SAF settles the OSR program; we claim it is informed by OSR commitments and tests whether process-first identification produces better diagnostics than component-first alternatives.

We define the **SAF Coherence Index** formally as:

$$\text{SAF}(S, A, F) = F_{\text{norm}} \cdot \left(1 - \left| \frac{S_{\text{norm}} - A_{\text{norm}}}{S_{\text{norm}} + A_{\text{norm}}} \right| \right) \quad (1)$$

where $F_{\text{norm}}, S_{\text{norm}}, A_{\text{norm}} \in [0, 1]$ are the Functionality, Stability, and Adaptability of the system, each normalized to a domain-appropriate healthy or reference maximum. The balance term $|S_{\text{norm}} - A_{\text{norm}}| / (S_{\text{norm}} + A_{\text{norm}})$ is the classical coefficient of variation for a two-component system: it equals 0 at perfect balance and approaches 1 as one component dominates the other. The $(1 - \text{balance})$ factor is the mediation efficiency — how effectively the Triality resolves the Duality. The index has four clean properties: $\text{SAF} = 0$ when $F = 0$ (no Functionality means no coherence regardless of balance); $\text{SAF} = F_{\text{norm}}$ when $S = A$ (perfect balance means coherence equals Functionality); $\text{SAF} \rightarrow 0$ when one of S, A dominates the other; and $\text{SAF} = 1$ at the maximum (full Functionality with perfectly balanced S-A tension). The SAF index is structurally related to the Canalization Index (Section 5.5): cI measures how much a system's functional output is insulated from input noise by the Triality constraint; SAF decomposes this into the structural sources — F determines the depth of the channel, and the S – A balance determines its width.

Observer dependence and the objectivity of Functionality. A critical concern must be addressed: if different researchers identify different Functionalities for the same system, they will obtain different SAF decompositions and potentially different index values. This introduces apparent epistemic subjectivity into a supposedly structural metric. The concern is legitimate and the paper does not dismiss it. SAF is *model-relative* in the following precise sense: the index value is determined by the choice of F , and that choice must be justified on independent grounds. The framework does not eliminate this requirement; it makes it explicit and places it at the beginning of the analysis rather than implicitly embedding it in component selection.

For the erythrocyte, the objectivity problem has a clean resolution: oxygen transport is not a

theoretical construct but a measurable physical process (O_2 carrying capacity in mL/dL blood), and it is the only process that simultaneously constrains the required membrane rigidity and required membrane deformability in the way the SAF decomposition demands. An observer who chose a different F — say, structural integrity of the cell — would obtain a decomposition in which the "Stability" and "Adaptability" roles are assigned differently, and the resulting index would be measuring something different. The framework's claim is not that F is always obvious, but that identifying it correctly is what makes the decomposition physically meaningful. The F-first methodology is a discipline, not an algorithm: it requires the researcher to justify the Functionality choice on independent grounds before computing the index.

For systems where Functionality is genuinely ambiguous — where multiple processes could plausibly be identified as the mediating triadic constraint — SAF is not applicable as a unique metric but as a family of metrics indexed by candidate F values. Comparing SAF values across different F assignments is itself informative: the F assignment that maximizes the index's predictive correlation with outcomes is the empirically best-supported identification. This is a falsifiable procedure, not circular reasoning.

Benchmarking requirement. SAF's derivation from S-D-T structural logic is the novel claim; that it outperforms all existing composite metrics is not claimed and has not been tested. A search of the clinical hematology literature confirms that no broadly adopted composite RBC index currently exists that mathematically fuses mechanical deformability and oxygen carrying capacity into a single continuous variable with established predictive power across disease states. Existing composite indices combine related but distinct pairs: the Hemoglobin-to-RDW Ratio (HRR) fuses oxygen-carrying capacity with erythrocyte population heterogeneity and has demonstrated independent prognostic value for all-cause mortality; the PaO_2 /RDW ratio links gas exchange efficacy with structural variance and serves as a risk biomarker in ARDS; the NUn-MCV index combines corpuscular volume with inflammatory state. None of these fuses deformability and oxygen transport in the way SAF requires. The closest operational approach is oxygen gradient ektacytometry ("oxygenscan"), which measures deformability under an oxygen gradient, yielding $EI_{\max}$, $EI_{\min}$, and the Point of Sickling (PoS) [92]; however, this assay remains multivariate and does not incorporate oxygen carrying capacity as a separate normalized component. SAF, by fusing Functionality (O_2 carrying capacity), Stability (shear modulus), and Adaptability (elongation index) into a single dimensionless score derived from a structural theory, constitutes a genuinely novel metric class. The validation program requires benchmarking SAF against: (a) linear combinations of F , S , and A with fitted weights; (b) PCA-derived composite indices from the same component measurements; (c) HRR, PaO_2 /RDW, and other existing clinical composites; and (d) the oxygenscan multivariate profile. If SAF does not outperform these alternatives, the S-D-T derivation has produced an index that is formally grounded but empirically redundant — a meaningful null result that would prompt revision of the balance term structure. If SAF does outperform them, the non-linear structure (the balance term specifically) carries predictive information beyond what linear combination recovers. This benchmarking program is a near-term priority for the research agenda outlined in Section 4.5.

Erythrocyte worked example and testable prediction. This section is included as a preliminary research proposal rather than a validated application. The erythrocyte (red blood cell; RBC) is the clearest test case because its three SAF components are independently measurable by standard clinical methods. Publicly available datasets sufficient for an initial falsification test exist: ektacytometry and micropipette aspiration data for sickle cell disease, hereditary spherocytosis, and severe falciparum malaria cohorts are available through published clinical studies (key benchmarking data are incorporated in the pathology predictions below). A full validation study — computing SAF values from published cohort data and comparing Spearman ρ correlations against standard clinical severity indices — is the immediate empirical next step. The falsification criterion is explicit: if the SAF Coherence Index does not outperform its constituent components (i.e., $\rho_{\text{SAF}} \leq \max(\rho_S, \rho_A, \rho_F)$), the claim that the triadic structure provides added diagnostic value beyond its components is not supported, and the S-D-T derivation has produced an index that is formally grounded but empirically redundant. Preliminary qualitative alignment between SAF failure-mode predictions and known clinical severity rankings is observed throughout the literature synthesis below, but formal quantification against a pre-registered analysis protocol has not yet been reported; that quantification is the primary deliverable of the empirical program outlined in Section 4.5. Applying the F-first methodology: the Functionality is oxygen transport, identified as the process that simultaneously determines what the membrane must *resist* (Stability) and what it must *permit* (Adaptability).

SAF component	Physical quantity	Method	Healthy reference	Source
F (Functionality)	O ₂ carrying capacity	O ₂ dissociation curve	P ₅₀ = 24.2 mmHg (IQR 23.5–25.1)	[93]
S (Stability)	Membrane shear modulus μ	Optical tweezers	$2.5 \pm 0.4 \mu\text{N/m}$	[93]
		Micropipette aspiration	$4.6 \pm 1.4 \mu\text{N/m}$	[93]
A (Adaptability)	Elongation Index EI_{max}	Ektacytometry	≈ 0.59 (IQR 0.58–0.59)	[93]

Table 3: SAF component measurements for the human erythrocyte with empirically-grounded reference values. Note: shear modulus values are technique-dependent; optical tweezers and micropipette aspiration measure related but distinct mechanical quantities. Normalization and benchmarking must use a consistent measurement platform within each study. EI_{max} is also device-dependent across ektacytometry platforms. Identification order: F (oxygen transport) is identified first; S and A are derived from F .

The SAF framework makes specific, *a priori* predictions about how known pathological conditions degrade systemic coherence, and through which component:

- Sickle cell disease (HbSS):** The primary S -failure driver is not membrane stiffness but *cytoplasmic viscosity*: diffraction phase microscopy reveals $\eta = 23.8 \pm 9.5 \text{ mPa} \cdot \text{s}$ in HbSS erythrocytes, driven by intracellular HbS polymer formation under deoxygenation [93]. This viscous congestion damps membrane fluctuations and drives A into collapse: in a cohort of 97 non-transfused HbSS patients and 20 controls, median $EI_{\max}$ dropped to 0.51 (IQR 0.48–0.54) vs 0.59 (IQR 0.58–0.59) for controls ($p < 0.001$). Under hypoxia, $EI_{\min}$ collapses to 0.04 (IQR 0.02–0.10) vs 0.62 for controls. F is simultaneously degraded: median $P_{50} = 25.7 \text{ mmHg}$ (IQR 24.3–27.4) vs 24.2 (IQR 23.5–25.1), $p = 0.001$, driven by 2,3-DPG elevation (42.2% higher in HbSS, 3460 vs 2434 mg/L RBCs). Critically, HbS polymerization also disrupts the ATP/S-nitrosothiol signaling loop that constitutes the F' cycle: the Triality that should mediate microvascular flow is destroyed from the inside. Predicted SAF ≈ 0.10 –0.25. Failure mode: *cytoplasmic F-collapse destroying both S-A balance and the F' mediating loop*.
- Hereditary spherocytosis:** The primary failure is *geometric exhaustion* rather than material stiffness. Defects in the vertical linkages between membrane and cytoskeleton (spectrin deficiency) cause membrane vesiculation and a critical loss of surface-area-to-volume ratio, forcing a spherical geometry ($\text{MCHC} \geq 345 \text{ g/L}$). The sphere cannot deform through the spleen regardless of membrane flexibility, so A collapses not because the material is rigid but because the geometry is insufficient. S may appear relatively stable by material measures (shear modulus ≈ 5 –20 $\mu\text{N/m}$ depending on spectrin deficit) while A ($EI_{\max} \approx 0.30$ –0.45) collapses through this geometric channel. F is initially preserved. Predicted SAF ≈ 0.30 –0.45. Failure mode: *S-A imbalance driven by geometric exhaustion of A*. This distinction matters: restoring membrane material flexibility would not rescue the cell; only restoring surface-area-to-volume ratio would.
- Iron deficiency anemia:** F degrades directly (P_{50} increases to $\sim 27.3 \text{ mmHg}$; absolute hemoglobin reduction impairs total O_2 carrying capacity) while the S – A balance presents a genuine rheological paradox. Ektacytometry reports *reduced EI* (37.4 ± 6.7 vs $48.6 \pm 2.9 \text{ mPa} \cdot \text{s}$ at 12 Pa, $p < 0.001$), attributable to oxidative membrane crosslinking. Yet microfluidic transit assays show *increased* normalized transit velocity in IDA, because lower MCHC reduces internal viscosity and microcytic morphology may preserve or increase surface-area-to-volume ratio [93]. The SAF reading: F -reduction is the dominant failure, while the S – A disruption is partial and mechanism-dependent. A patient whose IDA involves predominantly oxidative membrane damage will have worse A than one whose IDA is purely volumetric; the F-first methodology predicts this distinction should be clinically detectable. Predicted SAF ≈ 0.40 –0.55. Failure mode: *F-reduction with mechanistically ambiguous S-A balance — the clearest case where F-first identification is necessary to interpret what the mechanics mean*.
- Severe malaria (*P. falciparum*):** The most dramatic S -escalation in the SAF dataset:

shear modulus rises to 20–50 $\mu\text{N}/\text{m}$ at the trophozoite stage and 40–90 $\mu\text{N}/\text{m}$ at the schizont stage, representing up to a 36-fold increase from baseline [94]. The A -collapse carries direct mortality prediction: in a cohort of 23 patients with severe falciparum malaria, $EI < 0.21$ at 1.7 Pa on admission predicted fatal outcome with 100% sensitivity (95% CI: 59–100%) and 88% specificity (95% CI: 61–98%), with mean EI of 0.252 ± 0.033 for survivors vs 0.189 ± 0.014 for fatal cases ($p = 0.0001$) [94]. F is simultaneously devastated: the parasite degrades host hemoglobin to hemozoin, causes lactic acidosis and hypoglycemia, and fundamentally alters oxygen affinity dynamics. This is the SAF prediction most directly confirmed by existing clinical data: the composite A -threshold ($EI < 0.21$) predicts mortality better than any single standard clinical marker. Predicted SAF ≈ 0.10 – 0.25 . Failure mode: *multi-component attack with measurable A -threshold for mortality*.

The **hypothesis to be tested** is: the SAF Coherence Index, if the S-D-T grammar’s structural logic is correct, should correlate with clinical severity (transfusion requirement, hemolysis markers, mortality risk) more strongly than any single-component measurement alone — more strongly than F alone, S alone, or A alone. A patient with moderately reduced F but balanced S – A (iron deficiency: SAF ≈ 0.47) should have better clinical outcomes than a patient with similar F reduction but severe S – A imbalance (sickle cell: SAF ≈ 0.16), even when mean corpuscular hemoglobin concentration is similar between them. This prediction is falsifiable with existing clinical hematology data: ektacytometry (A), micropipette aspiration or AFM (S), and oxygen dissociation curves (F) are all standard measurements available in published cohort studies. Spearman $\rho > 0.8$ between SAF rank and clinical severity rank would constitute validation; $\rho < 0.5$ would indicate that the composite metric adds no value over single-component measures. The empirical validation of this prediction against published clinical data is a near-term priority for the research program.

5.3.1 Failure Modes: A Via Negativa Diagnostic

The utility of the SAF triad becomes most apparent when examining systems where one of the three qualities is suppressed. These failure modes provide a *via negativa* confirmation of the framework’s structure—and are directly predictable from Holling’s panarchy theory (a system stuck in K without reaching Ω is $S+F$ without A ; a system that has undergone Ω but failed to reorganize into α is $A+F$ without S):

- **Stability + Adaptability without Functionality (S+A, no F):** A system that is robust and flexible but lacks a mediating rule remains in a state of perpetual reaction—responsive to perturbations but unable to channel that responsiveness toward any coherent outcome. Such systems oscillate or drift without achieving the triadic closure necessary for complex, persistent behavior. In Holling’s terms, this is a system oscillating between r and α without ever traversing K and Ω —accumulating potential without ever consolidating it into functional structure. In physical terms, this is a system trapped in the Duality phase.

- **Stability + Functionality without Adaptability (S+F, no A):** A system that is stable and functional but lacks adaptability is prone to catastrophic brittle failure when environmental conditions shift beyond its designed parameters—what Holling (1996) termed the “pathology of natural resource management,” in which optimization for a single variable produces a maximally efficient but maximally fragile system [59]. The doublet-triplet problem in SU(5) GUTs (Section 3.1.1) is an instance of this failure mode at the level of fundamental physics: the architecture achieves functional unification but lacks the topological flexibility to maintain its hierarchy across energy scales, requiring fourteen orders of magnitude of fine-tuning to avoid collapse. In Beer’s VSM terms, this is a system in which System 3 (control) has suppressed System 2 (coordination) entirely.
- **Adaptability + Functionality without Stability (A+F, no S):** A system possessing both flexibility and rule-governed behavior but lacking a stable ground state suffers from structural drift—its identity erodes into its environment over time. In Waddington’s terms, this is a developmental system that has lost its chreod: it can respond to stimuli and execute processes, but the canalized path has dissolved and any outcome is possible. In the language of Section 2.4, this is a system that has failed to solve the Pressure Vessel Problem: it can process information and respond to its environment, but it cannot maintain the boundary that defines it as a distinct system.

These failure modes are not merely illustrative; they are diagnostic and, importantly, they are *predictive*. If the SAF framework correctly describes the necessary qualities of coherent systems, then any system exhibiting one of these characteristic dysfunctions can be analyzed for the specific missing quality, and the nature of the dysfunction should match the predicted failure mode. This provides a testable research program: identify systems in each failure mode, confirm the absence of the predicted quality, and assess whether restoration of that quality resolves the dysfunction. The alignment between SAF failure modes and Holling’s well-documented pathologies of managed ecosystems (the collapse of over-optimized fisheries, forests, and rangeland systems) provides preliminary empirical confirmation of this diagnostic framework [59, 63].

We adopt a pluralist stance: S-D-T is one candidate structural heuristic among others, not a universal explanatory framework. It is offered alongside, not in place of, existing dynamical-systems, information-theoretic, and network-science frameworks. Where those frameworks treat the prevalence of triadic structure as one statistical property among many, S-D-T makes the narrower claim that triadic mediation may be a necessary condition for a specific class of stability problems — a claim distinguishable by the falsification architecture of §4.2.

We write ‘S-D-T’ with hyphens to emphasize a sequential, generative process. ‘SAF’ is written without hyphens to denote a relational, real-time description of the qualities of a coherent system, rather than the sequence of its becoming. Together, they form a unified proposal: a cross-domain constraint framework (S-D-T) coupled with a diagnostic tool for the coherence of its products (SAF). S-D-T is offered as one cross-domain heuristic among many, not as the organizing principle of emergence as such. It makes no claim to subsume existing

dynamical-systems, information-theoretic, or network-science frameworks; it proposes that the specific pattern of triadic mediation it identifies is a productive lens for a particular class of stability problems, and that this claim is testable.

5.4 Resonances with Historical Philosophy

With a falsifiable, scientific foundation in place, the S-D-T framework’s resonance with earlier triadic philosophies becomes meaningful. **Hegel** dynamized the triadic form as the engine of conceptual progress: Thesis (Singularity), Antithesis (Duality), Synthesis (Triality) [46]. **Peirce** formalized three universal categories sufficient to describe all phenomena: Firstness (pure potential; Singularity), Secondness (reaction; Duality), and Thirdness (mediation, habit, law; Triality) [47]. **Schwemmler** (1980), working in population ecology and evolutionary systematics without reference to the physics of this paper, arrived at what he termed a “triality principle” as the structural cause of periodicity in evolving systems — alternating divergence and convergence phases mapping precisely onto Duality and Triality [87]. These frameworks are not identical to S-D-T, but their independent convergence on the triadic structure confirms that the pattern is not an artifact of the present framework’s construction. What distinguishes S-D-T from these predecessors is the combination of physical grounding (Spin(8) triality, anyonic statistics, lattice QCD $\mathbb{Z}_3$ sectors) with explicit falsification conditions that render the framework amenable to Popperian evaluation, and a novel quantitative metric (the SAF Coherence Index) whose predictions are testable against existing data.

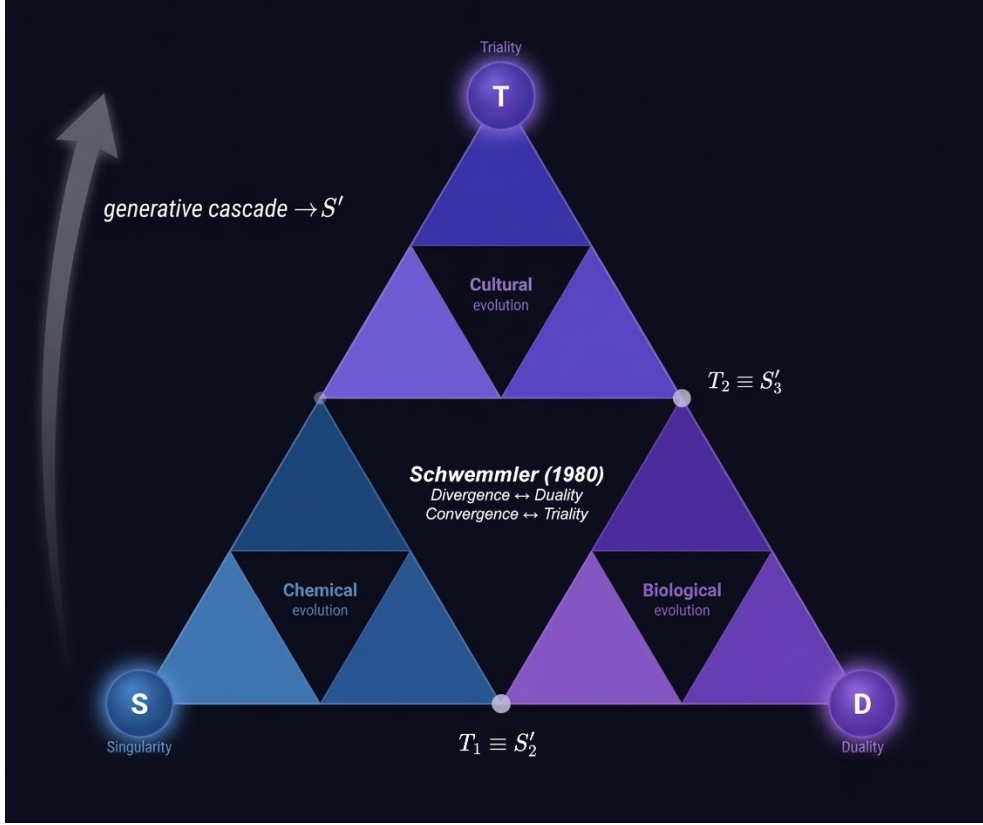


Figure 4: Recursive triadic structure of evolutionary emergence, rendered as a Sierpiński triangle at $L=2$. Each of the three colored sub-triangles—Chemical, Biological, and Cultural evolution—is itself a complete S-D-T triad, with internal shading encoding the Singularity (lightest), Duality (medium), and Triality (darkest) sub-regions. The self-similarity is the argument: the same triadic generative process that produces stability at one level of organization becomes the Singularity canvas from which the next level’s Duality emerges. The shared transition vertices make this explicit: $T_1 \equiv S'_2$ marks the point where Chemical Triality and Biological Singularity are geometrically identical—the resolution of one cycle is the ground state of the next. The central void is the emergent space produced by each completed triad: structurally necessary, not empty. Schwemmler (1980) [87], working from within evolutionary dynamics, identified this alternating divergence–convergence pattern as the structural cause of periodicity across evolutionary levels, mapping onto Duality and Triality respectively. The figure does not claim that Schwemmler’s framework is formally equivalent to S-D-T; it illustrates the formal resonance between a separately derived biological model and the recursive geometry of the S-D-T sequence. The temporal dimension—each Triality becoming the Singularity of the next cycle—is the projection onto two dimensions of the Sierpiński tetrahedron shown in Figure 5.

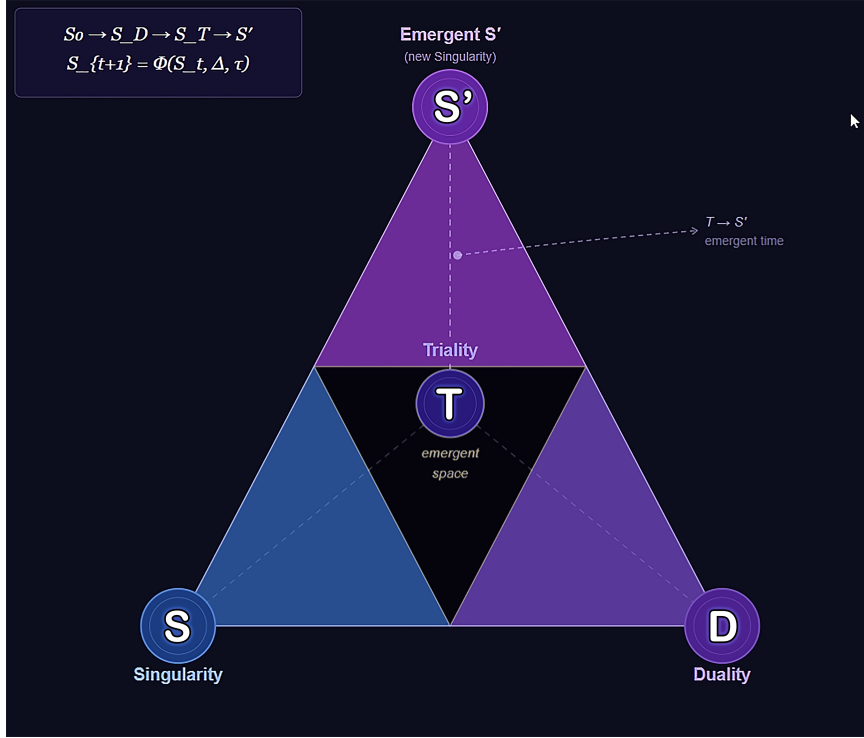


Figure 5: The S-D-T cycle as a Sierpiński tetrahedron, $L=2$, with time as the fourth dimension. The three base vertices—Singularity (S), Duality (D), and Triality (T)—form the familiar triadic ground plane of Figure 4. The apex vertex (S') represents the emergent new Singularity produced by the completion of one S-D-T cycle: the resolved triad does not terminate but becomes the ground state from which the next cycle’s Duality arises. The $T \rightarrow S'$ edge, annotated as “emergent time,” is the axis along which temporal directionality enters: the base plane S–D–T is an atemporal structural configuration; it is only with the completion of the cycle to S' that a preferred temporal direction appears. The central void—visible in projection as an inverted triangle on the front face—is the emergent space generated by each completed triad. The color progression from blue (S) through purple (D) and deep purple (T) to mauve (S') encodes the qualitative transformation of the system’s organizational character across the cycle, consistent with the ball-color encoding of Figure 1. The inset equation $\mathcal{S}_{t+1} = \Phi(\mathcal{S}_t, \Delta, \tau)$ now carries its full meaning: each completed triad produces a new system state $\mathcal{S}_{t+1}$ that seeds the next cycle. Figure 4 is a projection of this structure onto two dimensions, collapsing the temporal axis into the plane of the page. As a geometric analogy, the figure suggests that spacetime may be understood as an emergent property of triadic closure—the fourth vertex produced when a completed S-D-T cycle generates a new Singularity—consistent with the discussion in Section 5.1.⁴

We adopt the grammar of Singularity, Duality, and Triality because it provides a vocabulary that is simultaneously native to modern physics and generative in a precise mathematical sense. Unlike the historical triadic frameworks discussed above, each term is already at home in the lexicon of physics: ‘Singularity’ denotes a point of unification and the origin of spacetime; ‘Duality’ describes a fundamental correspondence between theories, as in AdS/CFT and electromagnetic duality; and ‘Triality’ refers to a specific three-fold symmetry under Z_3

rotation, as in Spin(8) and SU(3) color. The vocabulary therefore carries its own physical motivation—it does not merely borrow from physics, it identifies states whose mathematical properties are already understood.

The deeper justification for this choice of grammar is visible in the paper’s figure sequence. The three terms S, D, T do not merely label static states. Together, they constitute the symbol set of a minimal generative grammar: the three production rules $S \rightarrow D$, $D \rightarrow T$, $T \rightarrow S'$ define a cyclic rewriting system whose iterated application generates the recursive self-similar architecture of Figures 4 and 5, the helical phase-space trajectory of Figure 7, and the cross-domain structural correspondences of Figures 3 and 2. The $\mathbb{Z}_3$ cyclic symmetry of this grammar is not imposed from outside—it is the same $\mathbb{Z}_3$ that appears in Spin(8) triality, in the SU(3) center charge of QCD, and in the cyclic permutation of Heckman et al.’s (2025) triality defects at the gravitational horizon. The grammar and the physics are the same structure seen at different levels of abstraction.

This convergence—between the formal properties of the chosen vocabulary and the physical phenomena it describes—is what distinguishes the S-D-T sequence from a post-hoc labeling exercise. A vocabulary that generates, under iteration, the same fractal geometry that governs Schwemmler’s evolutionary periodicity, Lindenmayer’s biological morphogenesis, and the recursive hierarchy of emergent spacetime is not arbitrary. Whether this convergence ultimately reflects a deep mathematical unity or an unusually productive formal analogy is a question the empirical program outlined in Section 5.1 is designed to answer.

5.5 Open Questions and Future Work

We conclude the philosophical discussion with the open research questions this paper establishes as the next steps for the program:

- **The mechanism question:** The S-D-T framework identifies a pattern and derives predictions from it. The physical mechanism explaining *why* boundary-mediated transitions produce stability is not established in this paper. The Pressure Vessel Problem and the Dimensional Phase Transition (Section 5.1) constitute a candidate mechanism; their formal development is reserved for a separate mechanistic program.
- **The formalization question:** Section 4.3 identifies Lyapunov exponents, KS entropy, and transfer entropy as candidate quantitative measures for Stability, Adaptability, and Functionality respectively. A unified metric integrating all three is proposed here: the *Canalization Index* (cI)—named in explicit reference to Waddington’s (1942) canalization concept [64]:

$$\text{cI} = 1 - \frac{\Delta\Psi_{\text{functional}}}{\Delta\Sigma_{\text{perturbation}}} \quad (2)$$

where $\Delta\Psi_{\text{functional}}$ represents the variance in the system’s functional output states and $\Delta\Sigma_{\text{perturbation}}$ represents the variance of input perturbations or environmental noise, with the boundary condition that $\Delta\Sigma_{\text{perturbation}} > 0$ (the metric is defined for systems under perturbation; a perturbation-free system does not present a Duality to resolve and is outside

the framework’s scope). A cI approaching 1 indicates that the Triality (the mediating rule) successfully insulates the system’s functional output from perturbation—high canalization in Waddington’s sense. A cI approaching 0 indicates that the system’s output variance tracks its input noise directly—the hallmark of an unmediated duality and a system that has not completed the S-D-T cycle.

This formula is structurally equivalent to Kitano’s (2004) sensitivity measure for biological robustness [65], which defines robustness as 1 minus the normalized sensitivity of a system’s functional output to perturbations of the input. This convergence is not coincidental: the cI is, in effect, Kitano’s robustness measure applied to the functional output of a system at the Triality stage of the S-D-T cycle. The S-D-T contribution is a structural specificity that Kitano’s general measure does not carry: in the cI, the denominator is explicitly the perturbation variance at the *Duality* stage — the tension between competing basins — and the numerator is the output variance at the *Triality* stage — the resolved, canalized functional output. The cI therefore measures not merely robustness in the abstract but the degree to which the Triality constraint has successfully converted Duality-stage noise into Triality-stage stability. That Kitano’s separately derived measure from molecular systems biology and the S-D-T-motivated formulation arrive at the same formula is a further instance of the convergent robustness that the framework identifies as the mark of a real structural pattern [72].

This ratio is structurally equivalent to an inverse noise-to-signal measure in the sense of Shannon’s channel capacity theorem [67]: the Triality plays the role of an error-correcting code that maintains fidelity of transmission between the system’s identity and its environment. We note the connection to Bode’s sensitivity integral in control theory [61]: just as a feedback controller cannot reduce sensitivity at all frequencies simultaneously (the “waterbed effect”), no system can achieve simultaneously maximal Stability and maximal Adaptability—the SAF trade-off is not a design flaw but a mathematical necessity. A fully topological version of cI—grounding the variance ratio in persistent homology or Betti numbers of the system’s phase-space structure—would constitute a genuine Topological Canalization Index (tCI) and is a tractable formalization for future work in the tradition of topological data analysis applied to dynamical systems.

The natural mathematical home for the S-D-T process is the theory of *bifurcations* in nonlinear dynamical systems [68, 69]. The S-D-T sequence maps onto the structure of a supercritical pitchfork bifurcation: a stable fixed point (Singularity) loses stability as a control parameter crosses a critical threshold, splitting into two symmetric attractors (Duality), which are then recaptured by a higher-order stabilizing mechanism (Triality) that creates a new, categorically distinct attractor basin. Strogatz (1994) provides the standard accessible treatment of this sequence; Guckenheimer and Holmes (1983) the rigorous mathematical development. A further and deeper connection exists to René Thom’s **catastrophe theory** [76], in particular the *cuspid catastrophe* — the canonical model for a system in which two competing stable states (Duality) coexist across a fold region, and in which a control parameter can drive the system to a sudden transition into a fundamentally different regime (Triality). The relationship between the pitchfork bifurcation and the cusp

catastrophe is precise: the pitchfork is a one-parameter bifurcation in which a single control parameter drives the system from a single attractor to two competing attractors; the cusp catastrophe is the two-parameter unfolding of the pitchfork, in which a second control parameter breaks the symmetry between the two competing attractors and governs which of the two stable branches the system ultimately occupies [68, 76]. In S-D-T terms, this second parameter corresponds structurally to the Triality constraint τ : the element that determines which higher-order basin emerges from the Duality. Its physical character, however, is domain-dependent. In some instantiations, τ breaks the symmetry between competing attractors — the pitchfork case, and any domain where a third element tips the system decisively toward one resolution. In others, τ is a shared bridging constraint: the conformal symmetry $SO(2,d)$ of AdS/CFT, for instance, does not select one description over the other but holds two descriptions in mutual correspondence, making both possible simultaneously. It is a symmetry-sharing factor rather than a symmetry-breaking one. The cusp catastrophe captures the *structural role* of τ — the parameter that closes the Duality into a Triality; the domain specifies its *mechanism*. Thom’s original motivation was biological morphogenesis and structural stability in development — the same problem Waddington’s canalization concept addresses from the empirical side. Zeeman’s (1977) extension of catastrophe theory to behavioral and social models [77] addresses exactly the kind of cross-domain applications the S-D-T framework proposes. The cusp catastrophe potential surface is, geometrically, the same fold-and-fold-again landscape depicted in Figure 7 Panel A, and catastrophe theory provides the most natural mathematical framework for a formal dynamical instantiation of the S-D-T process.

Minimal formal instantiation: S-D-T as a cusp catastrophe parameter path.

The cusp catastrophe provides not merely an analogy but a *concrete minimal model* in which the S-D-T sequence is fully instantiated as a path through a two-parameter family of potentials:

$$V(x; u, v) = x^4 + ux^2 + vx \tag{3}$$

where x is the state variable, u is the primary control parameter (the pitchfork parameter), and $v = \tau$ is the secondary control parameter (the Triality constraint). The S-D-T sequence corresponds to a specific path through the (u, v) control space:

Stage	Parameters	Potential structure	S-D-T interpretation
Singularity	$u = +0.5, v = 0$	Single stable minimum at $x = 0$	High-symmetry ground state
Duality	$u = -1.0, v = 0$	Symmetric double well; minima at $x = \pm 1/\sqrt{2}$	Two competing basins, equal depth
Triality	$u = -1.0, v = \tau$	Asymmetric wells; $\Delta V = 0.82$ at $\tau = 0.6$	One basin resolved; one subordinated

Table 4: S-D-T parameter path through the cusp catastrophe potential (3). Each stage corresponds to a qualitatively distinct potential landscape. The transition from Duality to Triality is driven by the Triality constraint $\tau = v$, which breaks the $\mathbb{Z}_2$ symmetry of the double well and produces a quantifiable depth asymmetry ΔV between the two competing basins.

Figure 6 shows the three stages simultaneously. The Duality curve exhibits exact $\mathbb{Z}_2$ symmetry: the two wells are identical and the system has no basis for preferring one over the other. The Triality curve breaks this symmetry: the left well deepens to $V = -0.71$ (the resolved Stability basin), while the right well rises to $V = +0.11$ (the residual Adaptability basin). The depth asymmetry $\Delta V = 0.82$ scales analytically with τ : to first order, $\Delta V \approx 2\tau x_0$, where $x_0 = 1/\sqrt{2}$ is the Duality well location. This is a computable, quantitative prediction: changing τ produces a calculable shift in attractor depths, and transition rates between basins scale as $\exp(-\Delta V/\epsilon)$ where ϵ is the noise amplitude.

This instantiation makes the abstract schema $\mathcal{S}_{t+1} = \Phi(\mathcal{S}_t, \Delta, \tau)$ fully concrete, where Δ denotes the symmetry-breaking perturbation and τ the mediating triadic constraint (see Figure 1): Δ is the transition from $u > 0$ to $u < 0$ (the pitchfork bifurcation), and $\tau = v$ is the second control parameter whose non-zero value transforms the Duality into the Triality. The function Φ is here fully specified: it is the gradient descent dynamics on $V(x; u, v)$, analytically tractable and computationally evaluable. The residual shallower basin in the Triality curve is not a model artifact; it is the mathematical expression of the SAF triad: the deep well is Stability (the resolved higher-order basin), the shallower well is Adaptability (the residual dualistic tension the Triality has subordinated but not eliminated), and τ is Functionality (the parameter that determined the resolution). The figure is a mathematical picture of systemic coherence.

A clarification is warranted: S-D-T does not claim to introduce the cusp catastrophe. The cusp catastrophe is established mathematics, due to Thom (1972), and its connection to bifurcation theory is well-documented [68, 77]. The claim is more specific: that the cusp catastrophe is the *local mathematical structure* of a pattern that recurs independently across the scales of Lie algebra (Spin(8) triality), quasi-particle topology (anyonic braiding statistics), Standard Model generations (CP violation as triadic closure), and biological robustness (Waddington’s canalization). The cusp provides the formal skeleton; the cross-domain convergence on that skeleton — by independent research programs without

prior coordination — is the content of the framework. A single instance of the cusp is mathematics; its recurrence at multiple physically disconnected scales is a claim about nature. To make the Standard Model mapping concrete: in the three-generation case, the state variable x represents the system's position along the matter-antimatter asymmetry axis; the bifurcation parameter u corresponds to the energy scale at which generational structure becomes dynamically relevant; and the Triality constraint $\tau = v$ is the CKM complex phase δ_{CP} , whose non-zero value breaks the $\mathbb{Z}_2$ symmetry between matter and antimatter and selects the deep well (the matter-dominated universe) over the shallow well (the CP-symmetric, baryon-symmetric alternative). The prediction that $|\delta_{CP}^{\text{PMNS}}| \approx \pi/2$ in the lepton sector (Prediction C) is the direct consequence of this mapping applied to the parallel neutrino generation system.

Biophysical instantiation: cusp parameters in the erythrocyte system. The same cusp potential admits a concrete biophysical mapping for the erythrocyte, providing the most empirically grounded domain-specific instantiation of the cusp model currently available:

Cusp parameter	S-D-T component	Erythrocyte mapping
Primary parameter u	Pitchfork bifurcation (Δ)	Development of membrane-cytoskeleton mechanical tension
Secondary parameter $v = \tau$	Triality constraint	Oxygen transport efficiency (F): hemoglobin saturation and O_2 carrying capacity
State variable x	System trajectory	Cell shape / deformability profile ($EI_{\max}$ continuum)
Well depth asymmetry ΔV	Coherence margin	Robustness against splenic clearance; depth of canalization
Left well (T , resolved)	Stability basin	Biconcave discoid geometry; capillary-transit-capable shape
Right well (A , residual)	Adaptability basin	Residual shape variability; capacity to respond to osmotic challenge

Table 5: Mapping of cusp catastrophe parameters (equation 3) onto the erythrocyte biophysical system. The oxygen transport efficiency F plays the role of the Triality constraint τ : it breaks the $\mathbb{Z}_2$ symmetry of the membrane tension double-well and selects the biconcave discoid shape (deep well, Stability) over a spherical geometry (shallow well, Adaptability). The well-depth asymmetry $\Delta V \approx 2F_{\text{norm}}/\sqrt{2}$ predicts the robustness of the cell’s preferred shape against perturbation; the transition rate between shape basins scales as $\exp(-\Delta V/\epsilon)$ where ϵ is the thermal/osmotic noise amplitude. Pathological conditions that degrade F reduce ΔV , making shape destabilisation more probable — consistent with the observed fragility of iron-deficient and sickle cells under osmotic or mechanical stress.

A systems-theoretic concern must be addressed directly: is the Triality condition genuinely distinct from standard stabilization by an additional parameter, or is it merely a relabeling of known bifurcation mechanisms? The cusp catastrophe answers this for the one-dimensional case, but does not show that the *dual system alone* is dynamically insufficient. The following minimal ODE system makes this distinction explicit.

Consider a system of two competing variables (x_1, x_2) with symmetric mutual inhibition and self-activation:

$$\dot{x}_1 = x_1(1 - x_1^2) - \kappa x_2 \quad (4)$$

$$\dot{x}_2 = x_2(1 - x_2^2) - \kappa x_1 \quad (5)$$

For $\kappa > 0$, this system has two competing stable fixed points near $(+1, -1)$ and $(-1, +1)$, separated by an unstable saddle. Under symmetric initial conditions or noise, the system oscillates without resolution: it is the Duality. Perturbation of κ alone — the only

parameter available to the dual system — shifts the relative stability of the two fixed points but does not produce a third, distinct attractor. It is parameter-tuning, not triadic closure.

Now augment with a triadic coupling variable z :

$$\dot{z} = -\alpha z + \beta(x_1 + x_2) - \gamma z^3 \quad (6)$$

where z is absent from the dual system's algebra and introduces a new degree of freedom. For appropriate $\alpha, \beta, \gamma > 0$, the augmented three-variable system develops a third stable attractor near $(x_1, x_2, z) \approx (x^*, x^*, z^*)$ where $z^* > 0$, corresponding to a state in which both competitors are subordinated to a shared mediating organization. This attractor is topologically distinct from either dual fixed point: it lies in a region of phase space inaccessible to the two-variable system. It satisfies condition (ii) of the Formal Definition because z cannot be generated by any linear combination, parameter tuning, or symmetry transformation of x_1 and x_2 alone.

This is the minimal model the framework requires. The dual system oscillates; the triadic augmentation stabilizes; and the stabilization is non-reducible to parameter variation in the dual system because z introduces a dimension that the two-variable system does not possess. This model demonstrates that stabilization cannot be achieved through parameter variation alone; the triadic term alters the qualitative structure of the system, producing a stable attractor absent in the dual configuration. This constitutes a concrete instance of F0 in model form: a system that would falsify S-D-T would need to show that the dual system alone—without any variable satisfying the categorical novelty conditions—achieves equivalent stabilization. The full analysis of this system — stability boundaries, bifurcation diagrams, and mapping to physical examples — is a task for the formal program; the minimal model here demonstrates the principle. The distinction between a genuine Triality and a clever parameterization within an enlarged dual system is formally clean in low-dimensional models of this kind, where z manifestly introduces a dimension absent from the dual system's algebra. In high-dimensional empirical systems, this distinction may require case-by-case judgment under the pre-specified criteria of §4.3; the pre-specification requirement is the framework's mitigation of this difficulty, not its elimination. This model serves as the primary constructive instance of the framework: it shows that triadic mediation is not merely a descriptive label but can alter system-level stability in a way not achievable within the dual system alone.

Toward a general form of the S-D-T transition operator. The minimal model above instantiates a specific Φ . The framework implies a general class of such operators, even absent a complete theory. A general S-D-T transition satisfies: $\Phi : (\mathcal{S}_t, \Delta) \rightarrow \mathcal{S}_{t+1}$ where Δ induces bifurcation into competing attractors, and the transition to $\mathcal{S}_{t+1}$ requires the introduction of a constraint τ such that: (a) τ is not derivable from the resources of the dual system (condition ii); (b) the attractor manifold of the augmented system has greater topological dimension or a different symmetry group than the dual system alone (conditions

4i/4ii); and (c) the augmented system achieves a stable basin inaccessible to the dual system under any parameter variation. In this sense, Φ is not a fixed function but a *class of transformations* constrained by conditions (i)–(iv). Different domains instantiate different specific Φ — gradient descent on the cusp potential (§5.5), Clifford algebra periodicity (§2.1), anyonic fusion rules (§2.2) — but each member of the class satisfies the same abstract constraints. The development of a theorem specifying under what conditions a dual system admits a Φ -type completion — the general existence and uniqueness question — is the mathematical program that the present heuristic identification motivates but does not yet achieve. We state this openly as the primary formal task remaining for the research program.

Illustrative example of categorical novelty. To make the non-derivability condition concrete, consider a scalar system in a double-well potential $V_0(x) = x^4 + ux^2$ with $u < 0$. The system has two competing stable attractors at $x = \pm\sqrt{-u/2}$, separated by an unstable equilibrium at $x = 0$: the Duality. No scalar perturbation within the x -algebra resolves this: varying u shifts the well depths but does not produce a topologically distinct third basin. Introducing a second variable y with coupled dynamics:

$$\dot{x} = -\partial_x V_0(x) + \alpha y, \quad \dot{y} = -\beta y + \gamma x$$

adds a degree of freedom that cannot be generated by any parameter variation in the original x -system. For appropriate $\alpha, \beta, \gamma > 0$, the coupling produces a stable fixed point at (x^*, y^*) that is topologically inaccessible to the one-dimensional system — satisfying condition (4i). This is the same logical structure as the three-variable ODE model of equations (4)–(6), expressed in its most minimal form. The example is not a general model but a demonstration of what “categorical novelty” means computationally: a new variable, not a new parameter.

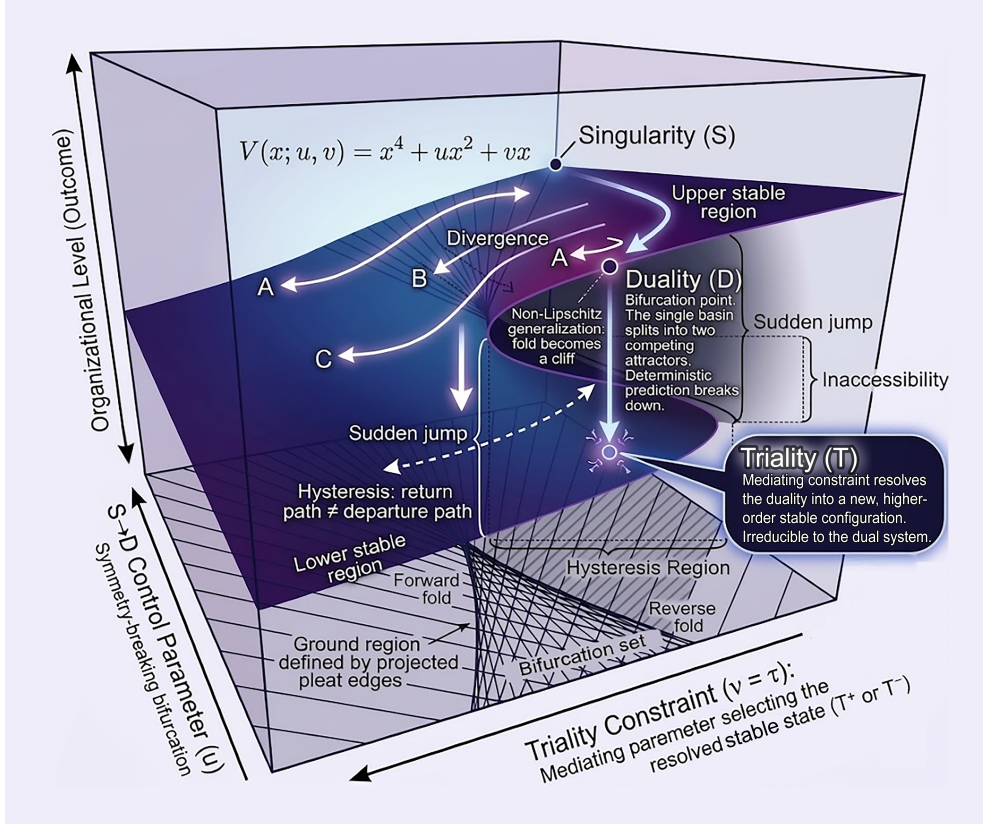


Figure 6: S-D-T as a parameter path through the cusp catastrophe potential $V(x; u, v) = x^4 + ux^2 + vx$ (equation 3). Three curves show the three S-D-T stages: Singularity ($u = +0.5$, $v = 0$, blue) has a single stable minimum at $x = 0$ — the high-symmetry ground state S . Duality ($u = -1.0$, $v = 0$, violet) bifurcates into a symmetric double well with minima $D_{\pm}$ at $x = \pm 1/\sqrt{2}$ and equal well depths — two competing basins with no organizational basis for preferring one. Triality ($u = -1.0$, $v = \tau = 0.6$, red) breaks the $\mathbb{Z}_2$ symmetry: the Triality constraint τ deepens the left well to $V = -0.71$ (the resolved Stability basin T) while raising the right well to $V = +0.11$ (the residual Adaptability basin A). The well-depth asymmetry $\Delta V = 0.82$ scales analytically as $\Delta V \approx 2\tau/\sqrt{2}$ to first order; transition rates between basins scale as $\exp(-\Delta V/\epsilon)$ where ϵ is the noise amplitude, providing a quantitative, falsifiable prediction. The abstract schema $\mathcal{S}_{t+1} = \Phi(\mathcal{S}_t, \Delta, \tau)$ of Figure 1 is here fully concrete: Δ is the pitchfork bifurcation ($u > 0 \rightarrow u < 0$) and $\tau = v$ is the Triality constraint. Python code is provided in Appendix B.

- **The scope question:** The examples in Section 2 are drawn from theoretical physics. Applications to complex adaptive systems (biological, social, economic) are promising but require independent empirical validation in each domain.
- **The relationship to competing meta-frameworks:** The S-D-T heuristic is not the only formal language proposed for understanding emergence and hierarchical structure. The renormalization group (RG) provides a rigorous mathematical framework for understanding how effective descriptions change across energy scales, and category theory offers a compositional algebra for describing how complex structures are built from simpler components. These are powerful, established formalisms with which S-D-T does not

compete. The distinction is one of level: RG describes scale-dependent dynamics within a given system, and category theory describes the compositional structure of mappings between systems, whereas S-D-T proposes to describe the *organizational architecture* by which stable systems emerge in the first place—the conditions under which a new level of description becomes necessary and self-sustaining. The relationship is therefore complementary rather than rivalrous: a fully formalized S-D-T framework might eventually draw on RG flows to characterize the Duality-to-Triality transition, or on category-theoretic functors to formalize the formal correspondences identified in LDBT. This integration is a long-term aspiration, not a present accomplishment.

The S-D-T sequence admits a compact formal representation as a cyclic rewriting system. With three symbols S, D, T and three production rules— $S \rightarrow D$ (bifurcation), $D \rightarrow T$ (stabilization), $T \rightarrow S'$ (emergence)—the framework generates its recursive hierarchy as a cyclic L-system in the sense of Lindenmayer (1968) [70]—but cyclic, in the sense of Schwemmler (1980) [87]—operating under $\mathbb{Z}_3$ cyclic symmetry. This minimal grammar generates, under iteration, exactly the hierarchical structure depicted in Figures 4 and 5: the same three-symbol rule applied recursively generates the Sierpiński triangle geometry of Figure 4 and the tetrahedral temporal extension of Figure 5. This is offered not as a formal derivation but as an indication that the S-D-T recursion is representable within an established mathematical formalism, and that its development into a fully specified generative grammar—with explicit parameter mappings connecting the abstract symbols to field-specific physical states—is a tractable task for future work. The connection to L-systems is also notable for a different reason: Lindenmayer originally developed the formalism to model plant morphogenesis, and Schwemmler separately identified the cyclic, level-generating property of triadic sequences in evolutionary biology. Together, they suggest that the triadic recursive grammar may be a structural feature of biological self-organization as well as of the physical and philosophical domains addressed in this paper.

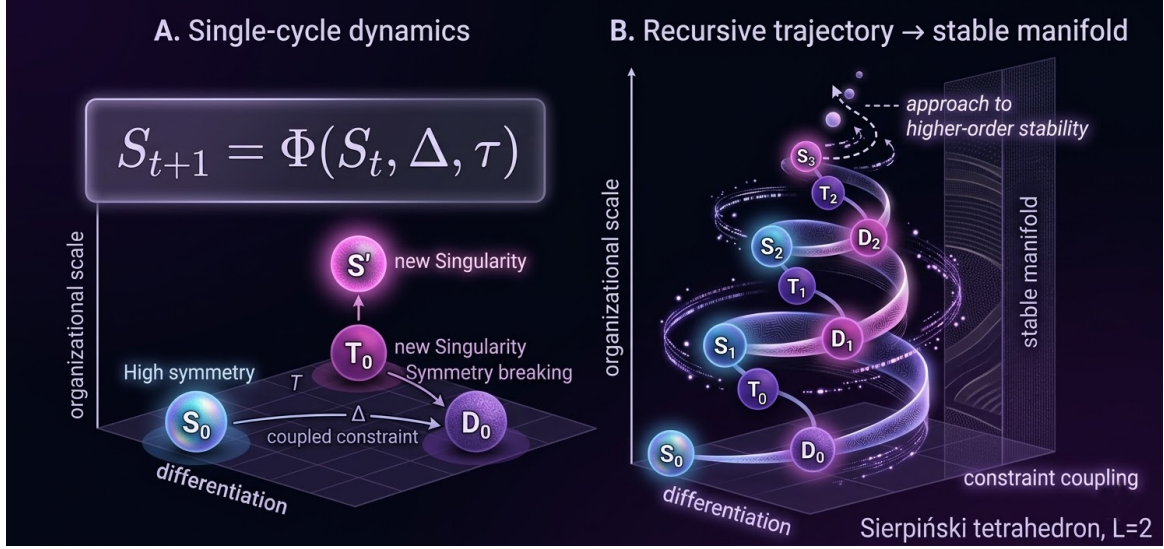


Figure 7: Phase-space trajectory of recursive S-D-T cycles. Panel A: a single S-D-T cycle rendered as a trajectory through a schematic phase-space landscape with axes representing differentiation, coupled constraint, and organizational scale. The system begins at high-symmetry ground state S_0 , moves across the base plane via symmetry-breaking perturbation Δ to the bifurcated state D_0 , is drawn upward via mediating constraint τ to the triadic resolution T_0 , and emerges as a new Singularity S' at a higher organizational scale. The inset equation $S_{t+1} = \Phi(S_t, \Delta, \tau)$ governs each transition; the dashed arrow from T_0 to S' indicates the emergent, generative character of the final step. Panel B: recursive application of the same three-step rule generates a helical trajectory through phase space, with each completed S-D-T cycle seeding the next at a higher organizational level. The trajectory narrows as it approaches the stable manifold on the right, indicating asymptotic convergence toward regimes of higher-order triadic stability—depicted schematically, not as a derived attractor. The node color progression—blue (S_n), violet (D_n), magenta (T_n)—is consistent with Figures 1 through 5. The helical geometry of Panel B is structurally analogous to the recursive grammar of a cyclic L-system (see §5.5): the same three-symbol rewriting rule $S \rightarrow D \rightarrow T \rightarrow S'$, iterated under $\mathbb{Z}_3$ symmetry, generates both the spiral trajectory shown here and the Sierpiński tetrahedron of Figure 5—two projections of the same underlying recursive structure. The resemblance to helical macromolecular structures such as RNA is noted; both share the geometry of a cyclic grammar operating under a preferred directional axis.

6 Conclusion

This paper has developed the Singularity-Duality-Triality (S-D-T) framework from a philosophical heuristic into a falsifiable scientific model with four distinct contributions: a structural grammar grounded in convergent physics, a set of prohibitive predictions with explicit falsification conditions, a formal mathematical instantiation, and a novel quantitative metric for measuring systemic coherence.

The structural grammar was induced from convergent evidence at the frontiers of modern

physics. Spin(8) triality, anyonic statistics, and the AdS/CFT correspondence share an organizational logic — a canvas, an interaction, and a mediating rule realized as a phase-inverted edge-state transition — unified under the conceptual umbrella of Lower-Dimensional Boundary Theory (§2.4). This foundation has been independently strengthened by results not anticipated at the framework’s inception: Kamiya’s (2021) algebraic generalization of triality groups, Ghanbarpour and von Smekal’s (2022) lattice QCD triality sectors, and Heckman, Hübner, and Murdia’s (2025) identification of triality defects as dynamical horizon branes. That the triadic pattern is a feature of physical systems rather than of theoretical descriptions is argued in §5.2 on three grounds: lattice QCD sectors differ in free energy density, anyonic braiding is a confirmed measurement outcome, and convergent independent discovery across uncoordinated research programs is the empirical signature of a real pattern.

The framework’s scientific content resides in its specific prohibitive claims (§4). The instabilities of Grand Unified Theories are recontextualized as predicted consequences of unmediated duality, and the three generations of matter are identified as a complete S-D-T system whose triadic closure enables CP violation and baryogenesis. A third, near-term prediction — that the lepton sector requires near-maximal leptonic CP violation ($|\delta_{CP}| \approx \pi/2$) — is testable within 5–10 years by DUNE and Hyper-Kamiokande. This prediction is uniquely S-D-T-motivated: standard neutrino physics permits any value of δ_{CP} ; the triadic closure condition predicts it should be near-maximal.

The formal instantiation of the S-D-T sequence as a parameter path through the cusp catastrophe potential (Section 5.5, equation 3) makes the abstract schema fully concrete: the pitchfork parameter u drives the Singularity-to-Duality transition, and $\tau = v$ breaks the $\mathbb{Z}_2$ symmetry to produce a quantifiable depth asymmetry whose scaling is analytically tractable. The claim is not that the cusp catastrophe is novel mathematics, but that its recurrence as the local dynamical structure at multiple physically disconnected scales — from Lie algebra to quasi-particle topology to Standard Model generations to biological robustness — is a claim about nature.

Perhaps the most consequential development of the present version is the SAF Coherence Index (equation 1), a quantitative metric derived from the S-D-T grammar’s structural logic. Its methodological core is the *identification order*: Functionality is identified first, and from that identification the Stability and Adaptability components become determinable. This is consistent with Ontic Structural Realism: existing composite metrics begin with objects and ask what they do; SAF begins with the mediating process and asks what structural roles it requires. We do not claim to have settled the OSR program, but SAF is informed by it and tests whether process-first identification yields superior diagnostics. If $\rho_{SAF} > \max(\rho_F, \rho_S, \rho_A)$ against clinical data, that is evidence for the diagnostic value of process-first ontological commitment—one data point, not a philosophical verdict. A further development reported here deepens the SAF picture: Functionality (F) is itself triadic. The erythrocyte’s ATP/S-nitrosothiol signaling loop — where mechanical shear and deoxygenation trigger vasodilator export that optimizes the mechanical environment for the next transit cycle — is a completed S-D-T cycle operating within the Functionality tier. We denote this recursive structure F' : Functionality as a self-referential

triadic process rather than a static role. The framework describes a world in which the S-D-T grammar operates simultaneously at the level of the whole system and at the level of the mediating process itself — consistent with the recursive geometry of the Sierpiński figures and with the claim that the grammar is genuinely generative rather than merely descriptive. The erythrocyte worked example (Section 5.3) demonstrates these claims concretely: the framework generates *a priori* hypotheses about which component drives coherence loss in each pathology, and the testable claim is that the composite SAF index correlates with clinical severity more strongly than any single-component measurement alone. Validation or refutation requires only existing clinical hematology data.

The paper has been transparent about the work that remains. The formal mechanism connecting the S-D-T grammar to the symmetry-breaking operations of LDBT is a task for future work; the Pressure Vessel Problem and Dimensional Phase Transition (Section 5.1) identify a candidate mechanism, and a critical fractal dimension $D^* \approx 2.65$ for informationally optimal boundaries is a preliminary simulation result consistent with that candidate. The empirical validation of the SAF Coherence Index against clinical data, the development of the Canalization Index toward topological grounding, and the extension of the framework into complex adaptive systems are tasks to be undertaken.

The framework should be judged by its ability to impose constraints, generate testable hypotheses, and withstand falsification attempts. The framework is best interpreted as a heuristic constraint on model construction, with its status as a real pattern remaining an open empirical question. The framework-level falsification condition (F0) places the burden of proof on the framework itself; explicit scope limitations (§4.4) bound the domain of applicability; and the proto-research program (§4.5) defines the next steps. Its broader significance remains contingent on empirical performance. S-D-T is offered as one cross-domain heuristic among many, distinguished by the specificity of its predictions and the honesty of its limitations. The framework’s long-term value will depend less on its interpretive reach than on its performance under sustained empirical and theoretical scrutiny.

A S-D-T Mappings for Core Physical Examples

Table 6 provides an explicit mapping of the S-D-T framework’s components onto each of the core physical examples discussed in Section 2. For each system, the table identifies the specific mathematical or physical object corresponding to the Singularity (canvas), Duality (tension), and Triality (mediating rule), along with the symmetry operation involved and the emergent stable property that results from the phase-inverted edge-state transition.

System	Singularity (Canvas)	Duality (Tension)	Triality (Mediating Rule)	Symmetry Operation	Emergent Stable Property
Spin(8) / Topological Superconductors (§2.1)	Lie group Spin(8) as abstract mathematical structure	Instantiation as symmetry group of a physical system	Unique three-fold triality among representations	Spin(8) outer automorphism (S_3)	$\mathbb{Z}_8$ classification: finite, robust topological phases
Anyons (§2.2)	2D material substrate (holographic plate)	Boson/fermion binary of 3D particle exchange	Topology of particle braiding on 2D canvas	Braid group B_n replacing permutation group S_n	Third statistical kingdom (fractional / non-abelian statistics)
AdS/CFT (§2.3)	Lower-dimensional CFT (boundary theory)	Correspondence between boundary CFT and bulk AdS gravity	Conformal symmetry $SO(2,d)$: shared by both the CFT and the AdS isometry group; absent from either alone; the structural mediator that makes the correspondence possible	Conformal symmetry group; bulk diffeomorphisms encoded on boundary	Complete bulk description from non-gravitational edge state
Celestial Holography (§2.4)	Celestial sphere at null infinity	Duality between bulk S -matrix and boundary correlators	Asymptotic symmetries (supertranslations, superrotations)	BMS group extension of Poincaré symmetry	Flat-space holographic dictionary for realistic spacetimes

Table 6: Explicit S-D-T mappings for the core physical examples of Section 2. Each row identifies the canvas (Singularity), the tension (Duality), the mediating rule (Triality), the specific symmetry operation involved, and the emergent stable property resulting from the phase-inverted edge-state transition.

This table is intended as a reference aid, not a claim of formal derivation. The mappings identify the *structural correspondence* between the S-D-T framework and each physical system; the detailed mathematics of each domain (Lie group theory, braid statistics, holographic renormalization, asymptotic symmetry analysis) remain the province of the specialized literature cited in the main text. The table’s value lies in making the claimed pattern explicit and therefore criticizable: if the mapping fails for any row—if the identified ‘Triality’ is not categorically distinct from the ‘Duality,’ or if the emergent property does not constitute a genuine phase inversion—the framework’s application to that domain is falsified.

B Python Code for Figure 6: S-D-T Cusp Catastrophe Instantiation

The following Python code reproduces Figure 6 and computes the analytical values reported in Table 4 and Section 5.5. Dependencies: `numpy`, `matplotlib`, `scipy`. All parameter values are explicit, enabling independent replication and exploration of the model’s quantitative predictions under variation of u , $v = \tau$.

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import fsolve

# Parameters
tau = 0.6          # Triality constraint (v parameter)
x = np.linspace(-1.6, 1.6, 2000)

# Cusp catastrophe potential V(x; u, v) = x^4 + u*x^2 + v*x
V_S = x**4 + 0.5*x**2      # Singularity: u=+0.5, v=0
V_D = x**4 - x**2          # Duality:      u=-1.0, v=0
V_T = x**4 - x**2 + tau*x  # Triality:    u=-1.0, v=tau

# Analytical well locations
# Duality: dV/dx = 4x^3 - 2x = 0 => x = +/- 1/sqrt(2)
x_D = 1.0 / np.sqrt(2)
V_D_min = x_D**4 - x_D**2    # = -0.25

# Triality: 4x^3 - 2x + tau = 0 (numerical)
def dVT(x): return 4*x**3 - 2*x + tau
x_T_left = fsolve(dVT, -x_D)[0]
x_T_right = fsolve(dVT, x_D)[0]
V_T_left = x_T_left**4 - x_T_left**2 + tau*x_T_left
V_T_right = x_T_right**4 - x_T_right**2 + tau*x_T_right
```



```

# First-order analytical approximation: DeltaV 2*tau*x_D
DeltaV_numerical = V_T_right - V_T_left
DeltaV_firstorder = 2 * tau * x_D
print(f"Deep well (T/Stability):    x = {x_T_left:.4f}, V = {V_T_left:.4f}")
print(f"Shallow well (A/Adaptab.):  x = {x_T_right:.4f}, V = {V_T_right:.4f}")
print(f"DeltaV (numerical):         {DeltaV_numerical:.4f}")
print(f"DeltaV (first order):       {DeltaV_firstorder:.4f}")

# Plot
fig, ax = plt.subplots(figsize=(7.5, 5.5))

c_S, c_D, c_T = '#2176AE', '#7B2D8B', '#C0392B' # blue, violet, red
ax.plot(x, V_S, color=c_S, lw=2.4,
        label=r'Singularity ($u>0, \ v=0$):  single stable basin')
ax.plot(x, V_D, color=c_D, lw=2.4,
        label=r'Duality ($u<0, \ v=0$):  symmetric double well')
ax.plot(x, V_T, color=c_T, lw=2.4,
        label=r'Triality ($u<0, \ v=\tau$):  asymmetric resolution')

# Annotate key points
ax.scatter([0], [0], color=c_S, s=60, zorder=5)
ax.scatter([-x_D, x_D], [V_D_min, V_D_min], color=c_D, s=60, zorder=5)
ax.scatter([x_T_left, x_T_right], [V_T_left, V_T_right],
          color=c_T, s=60, zorder=5)

ax.set_xlabel(r'State variable $x$', fontsize=12)
ax.set_ylabel(r'Potential $V(x; \ u, v)$', fontsize=12)
ax.set_title(
    r'S-D-T as a path through the cusp catastrophe: '
    r'$V(x) = x^4 + ux^2 + vx$', fontsize=11)
ax.set_ylim(-0.6, 4.0)
ax.legend(loc='upper center', fontsize=9.5, framealpha=0.92)
ax.grid(True, alpha=0.25)
plt.tight_layout()
plt.savefig('fig6.png', dpi=180, bbox_inches='tight')
plt.show()

```

Running this code with $\tau = 0.6$ reproduces Figure 6 and prints the well locations and depth asymmetry values reported in Table 4. Varying τ explores the model's predictions: increasing τ deepens the Stability basin and raises the Adaptability basin monotonically; setting $\tau = 0$ recovers the symmetric Duality potential. The transition rate between wells under noise amplitude ϵ is given by the Kramers formula: $k \propto \exp(-\Delta V/\epsilon)$, where ΔV is the well-depth asymmetry computed above.

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