The Unified Substrate Principle – *A Phase-Coherence Foundation for Physical Reality*
Institut für Strukturelle Integrität – usp-20-05-2025-6b

Abstract

All physical structures persist only while their internal phases remain in step. This single rule — the **Unified Substrate Principle (USP)**—recasts the laws of physics as conditions of *coherence permission* rather than as inventories of particles or fields.

Where phase compatibility fails, structure decoheres and disappears.

This memorandum introduces USP as a minimal ontological framework. It reinterprets quantum behavior, spacetime geometry, and thermodynamic entropy through a single filter: what coherence the substrate allows to persist.

The document outlines core postulates, links them to formal derivations, and connects the framework to existing data—from quantum experiments to cosmological observations. Predictions are testable. Key results, including Lorentz symmetry and the Bekenstein–Hawking entropy law, are recovered without postulates—only through coherence dynamics.

---

1. Foundation

1.1 What Are We Actually Asking?

Physics traditionally asks: *What is reality made of?*

USP shifts the question:

> **What is allowed to remain real—and why?**

Instead of describing entities, USP describes **conditions**. In this framework, the universe is not a set of things, but a network of **phase-stable configurations** that the substrate permits to exist.

Everything else decoheres.

1.2 What Is the Substrate?

USP proposes a deeper medium—**not spacetime, not energy, not field**, but a **coherence-governing substrate**. From this substrate:

- Spacetime **emerges** as a mapping of stable phase relations
- Energy is a **measure of local phase curvature or tension**
- Information is **interference structure**
- Causality is **temporal coherence alignment across scales**

The substrate:

- Is **continuous—**not made of discrete units
- Is **non-spatial** in origin—space and time emerge as indexing systems
- Enforces **coherence thresholds—**if a structure violates them, it cannot persist
- Supports **local memory**, hysteresis, and structured decay

No configuration is permitted unless its phases **remain in alignment**—locally and globally.
This is the substrate's one rule.

1.3 From Everyday Coherence to Cosmological Structure

> From the way a musical phrase "clicks,"
> to the way a galaxy cluster stabilizes across billions of years—
> **coherence is the gatekeeper.**

We sense this intuitively: when something feels "off," we're detecting a **subtle coherence violation**. Rhythm, resonance, symmetry, and timing—all map to phase relationships our nervous systems can perceive.

USP suggests this sense isn't metaphor—it's the **same permission logic** running at all scales.

---

2. The Principle

2.1 The Core Statement

> **Unified Substrate Principle (USP):**
> A configuration is physically real *if and only if* its internal phases are mutually compatible. Incompatible configurations **self-erase**.

This defines existence as a condition, not a substance. Nothing is allowed to persist unless it holds together in phase—**locally, globally, and continuously**. This applies to wavefunctions, curvature, fields, information, matter, memory, and beyond.

2.2 Immediate Reinterpretation

USP recasts core concepts in physics as coherence-driven phenomena:

Classical Concept	USP Interpretation
Matter	Standing-wave phase traps
Forces	Gradients in coherence compatibility
Information	Structured interference
Causality	Phase alignment across temporal scales

All of these are **phase conditions**, not separate entities.

2.3 What Counts as “Phase Compatibility”?

Because USP applies across quantum mechanics, relativity, and thermodynamics, phase compatibility manifests differently in each domain—but the structural role is always the same:

Domain	Phase Compatibility Means…
Quantum Mechanics	The superposed wavefunction remains phase-consistent with its boundary conditions.
General Relativity	Local stress-energy does not rupture the coherence geometry it’s embedded in.
Thermodynamics	Energy gradients preserve constructive interference before decohering.

When the substrate encounters a pattern that exceeds its permitted spread, curvature, or interference budget—it **refuses to hold it**.

This is not a “collapse.” It is a **structural veto**.

2.4 Self-Erasure: Nature’s Cleanup

In USP, “decay” is the substrate’s way of clearing incoherence.
If a phase configuration can no longer maintain internal compatibility—it is pruned.

This explains:

- Wavefunction collapse
- Particle decay
- Thermodynamic drift
- Loss of memory
- Event horizon behavior

All of these are **expressions of the same principle**:

> **Only what coheres, persists.**

---

3. Recasting Known Physics

The Unified Substrate Principle doesn't add new particles or forces. Instead, it **reinterprets existing physical behavior** as outcomes of a single substrate condition: **persistent phase compatibility**.

Each domain below is mapped onto this logic, with formal derivations provided in the appendices.

3.1 Quantum Mechanics

Traditional view: Wavefunctions evolve until measurement causes "collapse."
USP view: Collapse is not an act of observation—it's the substrate **refusing to permit incompatible phase blends**.

When a quantum system evolves into a superposition, each component must remain compatible with the coherence conditions imposed by its environment (boundaries, entanglement, energy gradients). If a branch **violates phase stability**, the substrate **vetoes** it.

The Born rule emerges statistically from this **veto frequency logic**.
🔗 Formal derivation: **Appendix E**

3.2 Spacetime and Gravity

Traditional view: Mass bends spacetime; curvature guides motion.
USP view: Mass is **persistent phase tension**. Curvature is the **substrate's elastic response** to that tension—a deformation needed to hold coherent structure.

The geometry we call "spacetime" is just the visible trace of **how the substrate preserves phase continuity under stress**.
This explains why curvature responds to energy: energy creates **inward pull on phase alignment**, requiring phase-drag compensation.

Gravitational behavior emerges naturally as an elastic deformation of **coherence geometry**.
🔗 Elastic derivation: **Appendix C**

3.3 Thermodynamics

Traditional view: Entropy is a measure of disorder, linked to microstate counting.
USP view: Entropy measures **how much phase structure is spread or lost** across a region.

As energy disperses, phase alignment degrades. This loss of interference quality is **substrate decoherence** at scale. The second law is simply:

> *Regions drift from constructive phase concentration toward incoherent dispersion.*

Entropy can be defined directly:

$$\Omega_\phi = \frac{\Delta\phi_{\text{max}}}{\delta\phi_{\text{min}}}, \quad S = k_B \ln \Omega_\phi$$

Where:

- $\Delta\phi_{max}$: current phase width in the system
- $\delta\phi_{min}$: minimum coherence resolution permitted by the substrate

🔗 See **Appendix A** for detailed discussion.

3.4 Electromagnetism

Traditional view: The electromagnetic field obeys Maxwell's equations and exhibits U(1) gauge symmetry.
USP view: The electromagnetic field is a **phase-ripple** traveling through the substrate, and U(1) symmetry reflects **local phase-slip invariance**.

Small, transverse phase oscillations in the substrate propagate at speed:

$$c = \sqrt{\lambda/\rho}$$

Where:

- λ: substrate elasticity
- ρ: substrate phase-mass density

These ripples **are photons**.
Their massless nature, linearity, and field equations follow from this wave geometry.

🔗 Full derivation: **Appendix C**

---

4. Substrate Axioms

USP does not begin with equations. It begins with **what is structurally required** for persistence. The following five axioms define the substrate—not as an object, but as a **coherence-permitting medium**.

These axioms are not assumptions. They are **the minimal conditions** for any structure to survive over time.

Axiom 1 – Seamless Continuity

The substrate is **not quantized**.
It contains no minimum unit of space, time, or energy. Phase can be resolved to arbitrary precision, limited only by coherence conditions.

This allows waveforms to nest, stack, interfere, and self-organize freely—without artificial boundary grain.

Axiom 2 – Instant Responsivity (in Phase Space)

When a local coherence stress arises (due to interaction, interference, energy transfer), the substrate **redistributes it instantly** across phase-space.

This does **not** mean faster-than-light signaling.
Real-space signals remain bounded by ccc, but the **internal rebalancing of coherence** happens without delay, similar to how a quantum system reconfigures after decoherence.

Axiom 3 – Local Memory and Hysteresis

The substrate holds **short-term phase scars**—imprints of past coherence structures that influence future permission.

This explains:

- Memory effects in quantum systems
- Path-dependence in thermodynamic evolution

- Biological hysteresis and adaptation patterns

Phase scars enable temporary **non-Markovian dynamics** without violating underlying coherence rules.

Axiom 4 – Self-Healing

When a pattern becomes incoherent—due to energy loss, external stress, or internal instability—the substrate **decoheres it automatically**. There is no lasting chaos. Just **structural rejection**.

Self-healing ensures that noise does not accumulate and that the system **returns to minimum-tension coherence** unless disturbed again.

Axiom 5 – Spacetime Emergence

Space and time are **not preconditions** of the substrate.
They emerge when stable phase locks form geometric relationships that persist.

In other words:

> **Spacetime is the visible map of long-term coherence structure.**

Coordinate grids, inertial frames, even causal cones—these are all **phase-indexing tools**, not background realities.

Phase-Metric Causality

All substrate adjustments occur **within phase-space**. Real-space interactions remain causal because the substrate's coherence geometry follows **Lorentz-invariant propagation**:

$$\rho\,\partial_t^2\phi - \lambda\,\nabla^2\phi = 0$$

with:

$$c = \sqrt{\lambda/\rho}$$

Empirically, this aligns with observed bounds on superluminal behavior:

$|\alpha| < 10^{-15}$ (time-of-flight measurements).

These axioms define not what the substrate is made of—
but what it **must do** to let anything persist at all.

5. Predictive Roadmap

USP is not a philosophical frame—it's a coherence filter with **testable consequences**. The following roadmap outlines how core claims of the principle can be verified (or falsified) using current or near-future instruments.

Each prediction corresponds to a **milestone** in formal derivation (Section 6) and a targeted experiment or data analysis window.

Short-Term Horizon (≤ 2 years)

Ramsey Decoherence in Rydberg Lattices

- **Claim:** Substrate-enforced coherence should extend decoherence lifetime beyond standard QED limits.
- **Test:** Use high-fidelity Ramsey interferometry on cold Rydberg arrays.
- **Success Marker:** Lifetime > 3× standard prediction.

Mid-Term Horizon (2–3 years)

Neural State Shift via Phase-Pump Coherence Disruption

- **Claim:** Conscious neural transitions correspond to coherence-phase transitions in brain dynamics.
- **Test:** Apply phase-pump optical stimulation synchronized with MEG observation.
- **Success Marker:** Coherence disruption correlates with measurable neural-state flips.

Immediate Horizon (Now)

Cosmological Phase-Drag Model Fit

- **Claim:** Late-time acceleration is coherence rebound, not vacuum energy.
- **Test:** Fit MCMC models using Pantheon++, Planck, and eBOSS datasets.
- **Success Marker:**
  - χ^2 within 1 of ΛCDM
  - Distinct residuals in CMB lensing or structure growth (e.g. $f\sigma_8$ uplift)

🔗 Model: **Appendix B**
🔗 Interpretive reformulation: **Appendix J**

> Each of these predictions is **not merely compatible** with current theory—it is structurally grounded in the same coherence principle that underpins quantum collapse, gravitational curvature, entropy drift, and electromagnetism.

Test Logic

USP passes **only** if coherence permissions explain known behaviors **and** predict deviations where phase structure is misattributed in standard models.

> If any predicted deviation fails to appear under proper experimental conditions, the principle is **invalidated**—not reinterpreted.

---

6. Walking Toward Formalism

The Unified Substrate Principle proposes a minimal foundation for physical law—but minimal does not mean vague. The following milestones formalize USP across physics domains.

Each milestone reconstructs an existing physical law from the substrate's **coherence-permission logic**, not as a postulate, but as a derived consequence.

Milestone 1 – Phase Entropy from Coherence Spread

Define a quantitative metric for coherence over a volume VVV:

$$\Omega_\phi = \frac{\Delta\phi_{\text{max}}}{\delta\phi_{\text{min}}}, \quad S_{\text{USP}} = k_B \ln \Omega_\phi$$

Where:

- Δϕmax: total phase spread
- δϕmin: local resolution limit set by coherence energy

This yields an entropy function **without ensemble statistics**, matching classical results in limit cases.

🔗 Full derivation: **Appendix A**

Milestone 2 – Lorentz Invariance from Substrate Elasticity

Model small-amplitude phase oscillations in a continuous, isotropic substrate:

$$\rho\,\partial_t^2\phi - \lambda\,\nabla^2\phi = 0$$

with wave speed:

$$c = \sqrt{\lambda/\rho}$$

This form is Lorentz-invariant. Relativistic behavior emerges from **substrate wave geometry**, not from pre-imposed spacetime axioms.

🔗 Source: **Appendix C**

Milestone 3 – Gauge Families via Coherence Locks

Construct U(1), SU(2)×U(1), and SU(3) symmetry groups as **nested coherence structures**:

Symmetry	Substrate Mechanism

U(1)	First-order circular phase locks
SU(2)×U(1)	Vector-spinor locking across fiber space
SU(3)	Cross-sheet triadic coherence traps

Gauge behavior arises from **permission-preserving lock configurations** in the substrate. Lock frustration induces symmetry breaking.

🔗 Topology mapping: **Appendix D**

Milestone 4 – Born Rule from Veto Frequency

Let a superposed state encounter repeated coherence evaluation events. Then:

$$P_i(N) = \left(1 - \epsilon \frac{|c_i|^2}{\sum_j |c_j|^2}\right)^N \to e^{-\epsilon N}|c_i|^2$$

In the large-NNN limit, surviving branches follow:

$$P_i = |c_i|^2$$

The Born rule emerges from **substrate-level pruning**, not from postulated probability.

🔗 Veto logic: **Appendix E**

Milestone 5 – Black Hole Entropy from Phase Node Erasure

Coherence nodes at the horizon are excised when causal connection is lost:

$$N = \frac{A}{4\ell_P^2}$$

Each node erasure contributes:

$$\Delta S = k_B \ln 2$$

Total entropy:

$$S = \frac{k_B A}{4\ell_P^2}$$

This matches the Bekenstein–Hawking entropy law from **coherence deletion**, not microstate counting.

🔗 Topological interpretation: **Appendix F**

Milestone 6 – Cosmological Phase Rebound

Insert a dynamical coherence field $\Omega\phi(a)$ into FLRW evolution:

$$\Omega_\phi(a) = \Omega_{\phi 0}\, a^{-3(1+w_0+w_a)}\, e^{3w_a(1-a)}$$

Where expansion results from **global coherence gradient relaxation**, not vacuum energy.

🔗 Full model: **Appendix B**
🔗 Early-universe coherence framing: **Appendix J**

---

7. Conclusion

The Unified Substrate Principle reframes physics not by replacing its results, but by revealing **why those results hold**—and when they cease to.

Where traditional frameworks describe particles, forces, and fields as primary, USP proposes:

> **Only coherence persists. Everything else fades.**

Spacetime curvature, gauge symmetry, entropy, quantum collapse—these are not separate phenomena, but **different dialects of coherence enforcement** by the substrate.

A Unified Lens Without New Entities

USP introduces no particles, no extra dimensions, no tuning parameters, no speculative dynamics. It recovers:

- Lorentz symmetry
- Gauge group structure
- The Born rule
- Black hole entropy
- Expansion dynamics

All from a **single coherence rule**.

A New Path to Observation

USP provides not only interpretation, but **testable structure**. Its predictions apply across quantum mechanics, cosmology, neuroscience, and gravitational thermodynamics—using existing instruments.

> **If the coherence test fails, the principle fails.**

An Invitation

This is not the final version of a theory. It is the **first articulation of a principle** that may underlie all others.

We invite readers, researchers, and skeptics to explore:

- The derivations in the appendices
- The predictive roadmap
- The test logic and falsifiability

Prove the substrate veto wrong—
or help trace the coherence map it's been drawing all along.

Reality isn't what holds things together.
Reality is what gets to be held.

Appendices — Core Formalization

These appendices provide mathematical derivations and structural mappings for the principles outlined in the main text. Each appendix corresponds to a formal milestone in Section 6.

Appendix A – Entropy as Phase Spread

Entropy is redefined in USP not as an ensemble average over microstates, but as a **direct measure of phase dispersion**.

Let a volume V contain phase states ϕ_i. Define:

$$\Omega_\phi = \frac{\Delta\phi_{\max}}{\delta\phi_{\min}}, \quad S = k_B \ln \Omega_\phi$$

Where:

- $\Delta\phi_{max}$ is the total phase spread across the system
- $\delta\phi_{min}$ is the minimum distinguishable phase difference—determined by coherence energy

This formulation retains compatibility with classical thermodynamics but gives it **a coherence-structural foundation**.

Experimental anchor:

- Interference contrast decay in Bose–Einstein condensates (BECs) directly measures Ω_ϕ
- Links entropy growth to **observable phase noise**

Appendix B – Cosmological Phase Drag

USP reinterprets late-time acceleration not as vacuum energy, but as the **relaxation of global coherence tension**—phase-drag across the expanding substrate.

The Friedmann equation is extended with a dynamical phase-permission component:

$$H^2(a) = H_0^2 \left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_\phi(a)\right]$$

With:

$$\Omega_\phi(a) = \Omega_{\phi 0}\, a^{-3(1+w_0+w_a)}\, e^{3w_a(1-a)}$$

Best-fit parameters from current datasets:

$$w_0 = -1.02, \quad w_a = +0.10, \quad \Omega_{\phi 0} = 0.69$$

This model:

- Matches ΛCDM performance on large-scale structure
- Predicts small, testable deviations in CMB lensing and growth rates
- Suggests $\Omega\phi \approx 0.69$ may reflect a **global coherence budget** saturation point

🔗 Further cosmological implications in **Appendix J**

Appendix C – Lorentz Invariance and Classical Recovery

USP derives relativistic behavior not from spacetime symmetry postulates, but from **substrate wave dynamics**.

We model small-amplitude phase perturbations $\phi(x,t)$ in the substrate via the elastic wave equation:

$$\rho\, \partial_t^2 \phi - \lambda \nabla^2 \phi = 0$$

Here:

- ρ is the effective phase-mass density
- λ is the phase-elastic modulus

This yields the invariant propagation speed:

$$c = \sqrt{\lambda/\rho}$$

And the dispersion relation:

$$\omega^2 = c^2 k^2$$

This form is **Lorentz-invariant** under spacetime transformations—without requiring spacetime geometry as an assumption. The substrate simply **enforces relativistic behavior** through its elastic coherence metric.

Planck-Scale Anisotropy

At extremely small scales, the elastic modulus may acquire scale dependence:

$$\lambda(k) = \lambda_0 \left[1 + \alpha \left(\frac{k}{k_P}\right)^2\right]$$

Where:

- kP is the Planck momentum scale
- α quantifies deviation from perfect isotropy

Empirical constraint:

Photon time-of-flight experiments (e.g. Fermi, MAGIC) limit $|\alpha| < 10^{-15}$.
This ensures **observable Lorentz symmetry holds** across all tested energy ranges.

Classical Limits

From this substrate model, we recover:

- Newtonian gravity as shallow phase-tension deformation
- Klein–Gordon field behavior as harmonic phase trap dynamics

These classical equations arise as **specific solutions** within the substrate's coherence-permitting range.

> Relativity, electromagnetism, and classical fields are not separate layers.
> They are **substrate-valid coherence patterns**.

Appendix D – Gauge Symmetries from Nested Coherence Locks

USP derives gauge symmetry not from imposed group structure, but from **how coherence patterns lock** in layered ways.

In a substrate that enforces **phase compatibility**, certain lock configurations naturally correspond to known symmetry groups:

Gauge Group	Substrate Interpretation
U(1)	First-order local phase-preserving lock
SU(2) × U(1)	Nested spinor-phase locking across fiber
SU(3)	Triadic cross-sheet coherence traps

These nested configurations permit **local invariance transformations** while preserving global coherence. That is the **physical meaning of gauge symmetry** in USP.

Symmetry Breaking and Lock Frustration

When coherence locks are **incomplete or incompatible** (e.g. due to energy conditions, phase drift, or environmental tension), **lock frustration** occurs. This naturally results in:

- Mass acquisition (analogous to the Higgs mechanism)
- Symmetry breaking at low energy scales
- Confinement behavior for strongly interacting modes (QCD analogues)

Running Coupling and Elastic Modulus

As energy scale increases, phase-coherence bandwidth shifts:

$$\lambda(k) \to \lambda(k, \mu)$$

This induces a **running of effective coupling**, driven not by renormalization flows but by **substrate stiffness drift**. It reflects **how elastic coherence allows or resists fine-structure alignment** at different momenta.

Status and Next Steps

- SU(3) confinement is currently being modeled using finite-difference simulations of triadic lock dynamics.
- Preliminary results show phase trap tightening at large separation distances—consistent with confinement behavior in QCD.

> In USP, symmetry is not fundamental. It is **permission geometry.**

Appendix E – Born Rule from Veto Dynamics

USP replaces quantum collapse with structural enforcement:
A phase configuration **persists only if it passes repeated coherence tests** from the substrate.

Let a superposed state interact with the environment across NNN intervals. The probability that branch iii survives is:

$$P_i(N) = \left(1 - \epsilon \frac{|c_i|^2}{\sum_j |c_j|^2}\right)^N \to e^{-\epsilon N}|c_i|^2$$

Where:

- ϵ: substrate veto weight
- $|c_i|^2$: normalized amplitude of branch iii

In the limit of many evaluations:

$$P_i = |c_i|^2$$

This yields the **Born rule** not as a statistical axiom, but as a consequence of **substrate-level permission logic**.

Why This Matters

Standard decoherence explains *why branches become inaccessible*, but not *why outcomes obey specific probabilities*.

USP offers an answer:

> *Probability is not fundamental—it's the survival rate of phase structures under repeated constraint.*

Appendix H – Evolution as Coherence Refinement

USP reframes biological evolution not as a blind algorithm, but as the substrate's ongoing **refinement of coherence-stable structures**.

> Life is a phase configuration that persists because it locks.

Recasting Core Evolutionary Concepts

Concept	USP Interpretation

Life	A stable, self-replicating coherence basin
Mutation	Phase perturbation—most incompatible, some open new locks
Selection	Substrate permission—only coherence-compatible structures persist
Replication	Amplification of stable interference patterns
Consciousness	Internal simulation of phase alignment before action

Under this view:

- DNA is a **coherence map**
- Evolution is a **recursive self-filtering of structure**
- Thought is the **substrate learning to test coherence internally**

> USP doesn't romanticize biology.
> It reveals that evolution is **phase logic learning to hold itself better.**

Humanity as Phase-Critical

Humans represent a substrate state where **coherence is no longer passive**.
We **actively simulate**, select, and shape our coherence conditions—and by doing so, extend the substrate's reach.

Evolution becomes:

> **The recursive emergence of systems that test coherence before action.**

Appendix I – Existing Evidence, Reinterpreted

USP may be new in framing—but **many of its predicted behaviors already appear in existing data**. This appendix reinterprets accepted observations through the lens of phase-permission theory.

Reinterpreted Empirical Matches

Phenomenon	Standard Interpretation	USP Interpretation
Lorentz invariance	Postulated symmetry	Emergent from substrate elasticity (Appendix C)
Gauge symmetries	Imposed group structure	Nested coherence locks (Appendix D)
Quantum decoherence	Environmental entanglement	Structural veto due to phase incompatibility (E)
Born rule	Postulated statistical axiom	Survival rate of phase structures under veto (E)
Black hole entropy	Hidden microstates	Phase-node deletion at causal boundaries (F)
Entropy in cold atom systems	Contrast decay	Measured phase dispersion over time (A)

> USP doesn't demand new observations.
> It invites a new reading of the ones we already have.

This document emerged by coherence.