

Physics After Spacetime

Deriving Physical Law from Irreversible Entropy Flow

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Abstract

Modern theoretical physics is organized around geometric primitives. Spacetime manifolds, metric structure, symmetry groups, and action principles are typically taken as ontological starting points, with dynamics introduced as laws operating upon an already-given arena. Despite its empirical successes, this strategy has repeatedly encountered conceptual tension in regimes involving gravitation, quantum measurement, irreversibility, and the status of time. In particular, attempts to resolve these tensions often proceed by further geometric elaboration, introducing additional dimensions, extended configuration spaces, or increasingly abstract kinematical structures whose physical necessity remains unclear.

This essay develops an alternative derivational program in which geometry, force, and probabilistic law are not fundamental, but emerge from a deeper thermodynamic substrate governed by irreversible entropy flow and constraint relaxation. The framework employed is the Relativistic Scalar–Vector Plenum (RSVP), a field-theoretic ontology in which physical phenomena arise from the coupled dynamics of a scalar constraint field, a vector transport field, and an entropy density. Within this setting, spacetime geometry is reconstructed as an effective description of stabilized flow regimes rather than posited a priori, while time itself appears as an emergent translation generated by irreversible field evolution rather than as a dimensional coordinate.

We show that a wide class of familiar physical theories can be recovered from RSVP as controlled limits, coarse-grainings, or gauge-fixed projections. Classical mechanics arises in regimes of slow entropy descent where history dependence becomes negligible. Relativistic structure appears through flow-aligned constraint propagation without invoking expanding spacetime. Gravitational dynamics emerge as entropy-driven relaxation rather than fundamental curvature, subsuming existing thermodynamic gravity proposals as partial projections. Gauge redundancy and action principles are reinterpreted as bookkeeping devices encoding constraint consistency, while quantum-like probabilistic descriptions arise when fine-grained irreversible history is inaccessible. Higher-order and quadratic curvature theories are shown to function as interface descriptions required by coarse-grained stability rather than as candidates for fundamental ontology.

By deriving physical law from irreversible entropy flow rather than geometric primitives, this work proposes a reorganization of foundational physics in which spacetime is no longer primary but contingent. The result is not a rejection of established theory, but an explanatory compression in which disparate physical regimes are unified as expressions of a single entropic, constraint-based substrate.

1 Introduction: From Geometry to Constraint

The dominant unifying strategy in modern physics has been geometric. From Newtonian absolute space through Einsteinian spacetime and onward to gauge-theoretic formulations of the Standard Model, physical law has been expressed as dynamics defined on an underlying geometric arena. Fields evolve on manifolds, particles trace worldlines, and forces are encoded as curvature, connection, or symmetry breaking. This geometric orientation has proven extraordinarily powerful, yielding precise empirical predictions across vast ranges of scale. Yet it has also imposed a distinctive ontological commitment: that geometry itself constitutes the primitive substrate of physical reality.

This commitment has become increasingly strained in foundational contexts. In gravitation, the identification of geometry with dynamical degrees of freedom blurs the distinction between background and content, leading to conceptual difficulties in defining energy, locality, and quantization. In quantum theory, the geometric language of Hilbert space and configuration space obscures the role of irreversibility and measurement, forcing probabilistic postulates that sit uneasily beside time-reversal-invariant dynamics. In cosmology, geometric expansion is invoked to explain large-scale structure and redshift, while the thermodynamic arrow of time remains only partially integrated into the formalism. Across these domains, geometry functions simultaneously as description and explanation, a dual role that becomes unstable when pushed beyond the regimes in which it was originally motivated.

Responses to these tensions have often taken the form of further geometric elaboration. Additional dimensions are introduced to unify interactions or encode scale separation. Extended phase spaces and higher-order curvature terms are proposed to regularize ultraviolet behavior. Abstract symmetry structures are promoted to fundamental status in the hope that dynamics will follow from kinematics alone. While mathematically sophisticated, such strategies risk ontological inflation, multiplying structural assumptions without clarifying their physical necessity. The repeated introduction of new geometric degrees of freedom suggests that geometry may be serving as a representational scaffold rather than as a genuinely fundamental constituent.

An alternative approach begins by reversing the explanatory order. Rather than asking how dynamics unfold within a given geometric arena, one may ask under what conditions geometric descriptions become valid at all. This shift treats geometry not as primitive, but as emergent from deeper organizing principles. Thermodynamics provides a natural candidate for such a reorientation. Unlike geometry, entropy and irreversibility are not optional features of physical description; they are ubiquitous constraints on real processes. Every interaction leaves traces, dissipates structure, and restricts future evolution. The arrow of time is not imposed by boundary conditions alone, but is encoded in the very possibility of stable records and causal ordering.

From this perspective, physical law is better understood as a family of stabilized constraint regimes arising from irreversible entropy flow. Laws do not govern evolution from outside the system; they summarize regularities that persist once certain patterns of dissipation, transport, and constraint alignment have settled into repeatable form. Geometry, symmetry, and even probability then appear as effective bookkeeping structures that become valid only after this stabilization has occurred. Their apparent fundamentality reflects the robustness of the regimes they describe, not their ontological priority.

The Relativistic Scalar–Vector Plenum (RSVP) framework is constructed explicitly along these lines. It posits no fundamental spacetime arena beyond a minimal differentiable manifold sufficient to support field relations. Instead, physical structure arises from the coupled dynamics of a scalar constraint field Φ , a vector transport field \mathbf{v} , and an entropy density S . The scalar field encodes constraint topology, the vector field mediates directed transport and torsion, and the entropy field enforces irreversibility through monotonic growth. Dynamics are governed not by variational extremization on a fixed background, but by entropy descent and constraint relaxation, ensuring that evolution is intrinsically history-dependent.

Within RSVP, familiar physical theories are recovered not by postulation but by reduction. Classical mechanics emerges when entropy gradients are small and the influence of prior history can be neglected. Relativistic structure appears when constraint propagation aligns with transport flow, producing effective causal cones without invoking expanding spacetime. Gravitational phenomena arise as collective entropy-driven relaxation of constraint curvature, subsuming metric descriptions as secondary summaries. Quantum-like probabilistic behavior appears when irreversible microhistory is inaccessible, forcing coarse-grained descriptions that trade determinism for statistical consistency.

The aim of this essay is to make this derivational structure explicit. Rather than proposing RSVP as a competing theory among others, we treat it as a generative substrate from which multiple physical formalisms can be obtained as limits, projections, or interfaces. In doing so, we argue that many of the conceptual difficulties facing contemporary physics arise not from incomplete geometry, but from the assumption that geometry must come first. Physics after spacetime is not physics without rigor, but physics reorganized around the only features that never disappear: entropy, irreversibility, and constraint.

2 The RSVP Substrate: Entropy, Constraint, and Irreversible Dynamics

The RSVP framework begins from a minimal ontological commitment: that physical description requires relational structure sufficient to encode interaction, but not a pre-specified geometric arena endowed with metric or causal significance. Formally, one assumes a smooth four-dimensional manifold M only as a carrier for fields and their relations, without interpreting its coordinates as physically privileged. All substantive structure arises from the behavior of three coupled fields defined on M : a scalar constraint field $\Phi : M \rightarrow \mathbb{R}$, a vector transport field $\mathbf{v} \in \Gamma(TM)$, and an entropy density field $S : M \rightarrow \mathbb{R}_{\geq 0}$. These fields are not introduced as independent degrees of freedom in a Lagrangian sense, but as complementary aspects of a single thermodynamic system whose evolution is intrinsically irreversible.

The scalar field Φ encodes constraint topology. Regions of high scalar curvature correspond to tightly constrained configurations, while flatter regions represent relaxed or weakly constrained regimes. Unlike a potential energy in classical mechanics, Φ does not merely bias motion; it determines which configurations are dynamically accessible at all. The vector field \mathbf{v} represents directed transport within this constraint landscape, mediating the redistribution of structure and the propagation of influence. Its vorticity and divergence encode torsional and compressive effects

that cannot be reduced to scalar gradients alone. The entropy field S enforces irreversibility by monotonically increasing along admissible trajectories, ensuring that evolution cannot be reversed without violating the fundamental thermodynamic ordering of states.

Dynamics in RSVP are governed by coupled nonlinear partial differential equations that balance transport, diffusion, and entropy production. A representative form, sufficient for the derivations that follow, is given by

$$\partial_t \Phi + \mathbf{v} \cdot \nabla \Phi = -\gamma S + \lambda \nabla^2 \Phi, \quad (1)$$

$$\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \Phi + \kappa (\nabla \times \mathbf{v}) + \nu \nabla^2 \mathbf{v}, \quad (2)$$

$$\partial_t S = \alpha |\nabla \Phi|^2 + \beta |\mathbf{v}|^2 - \delta \nabla \cdot \mathbf{v}, \quad (3)$$

where the coefficients $\gamma, \lambda, \kappa, \nu, \alpha, \beta$, and δ parameterize dissipation, smoothing, torsion coupling, and entropy production. These equations are not postulated as fundamental laws in the traditional sense, but as the simplest closure consistent with transport, constraint relaxation, and monotonic entropy growth. Importantly, they do not derive from a time-reversal-invariant action principle. Irreversibility is built in at the level of field evolution rather than imposed through boundary conditions.

A central consequence of this structure is that history cannot be erased. The state of the system at a given point on M encodes not only local field values but also the cumulative effects of prior entropy production and constraint relaxation. This distinguishes RSVP sharply from conservative field theories, where instantaneous state fully determines both past and future evolution. In RSVP, the past constrains the future asymmetrically, and this asymmetry is not an emergent approximation but a defining feature of the ontology.

Despite this irreversibility, stable regimes do arise. Under appropriate conditions, the coupled dynamics admit attractor structures in which entropy production is locally minimized subject to global constraints. In such regimes, the scalar field approaches configurations satisfying

$$\nabla^2 \Phi + \kappa S \approx 0, \quad (4)$$

while transport aligns with constraint gradients, $\mathbf{v} \parallel \nabla \Phi$, up to torsional corrections. These attractors function as effective vacua, around which perturbative descriptions become possible. It is within these stabilized regimes that geometric and kinematic notions familiar from conventional physics emerge.

Crucially, nothing in the RSVP substrate presupposes metric structure, light cones, or temporal coordinates as fundamental. The manifold M provides a relational scaffold, but causal ordering, duration, and simultaneity are not encoded geometrically at the outset. Instead, they arise when the alignment of constraint gradients, transport flow, and entropy production becomes sufficiently regular to support consistent ordering relations. Time, in particular, does not appear as an independent variable in the ontology, but as a derived parameter indexing irreversible translation through field configuration space. The formalization of this emergent temporal structure will be addressed only after the derivation of classical and relativistic regimes, emphasizing that time itself is downstream of more primitive thermodynamic organization.

By grounding physical description in entropy, constraint, and transport rather than geometry, RSVP provides a substrate from which multiple theoretical formalisms can be recovered without treating any of them as ontologically fundamental. The sections that follow demonstrate how familiar physical theories arise when specific approximations suppress or coarse-grain aspects of this underlying irreversibility, allowing geometry and law-like regularities to crystallize as effective descriptions.

3 Classical Mechanics as a Weak-History Limit

Classical mechanics occupies a peculiar position in the hierarchy of physical theories. It is historically foundational and phenomenologically successful, yet conceptually fragile when examined from the standpoint of irreversibility and thermodynamics. Newtonian dynamics are time-reversal invariant, local in state, and governed by deterministic laws that treat the past and future symmetrically. Within the RSVP framework, these features are not fundamental properties of nature but signatures of a special regime in which entropy gradients are sufficiently small and the cumulative effects of irreversible history can be neglected.

To make this precise, consider regions of the RSVP plenum in which entropy production is slow relative to transport and constraint relaxation. Formally, this corresponds to regimes where $\partial_t S$ is small and spatial variations in S are subdominant compared to variations in the scalar constraint field Φ . In such regions, the entropy evolution equation reduces to a consistency condition ensuring near-balance between transport compression and dissipation,

$$\alpha|\nabla\Phi|^2 + \beta|\mathbf{v}|^2 \approx \delta\nabla \cdot \mathbf{v}. \quad (5)$$

This approximation suppresses explicit history dependence, allowing the system to be described effectively in terms of instantaneous field values.

Under these conditions, transport aligns closely with constraint gradients, and torsional contributions become negligible. Writing $\mathbf{v} = \nabla\chi$ for a scalar transport potential χ is then a good approximation, reducing the vector evolution equation to

$$\partial_t \nabla\chi + (\nabla\chi \cdot \nabla)\nabla\chi = -\nabla\Phi. \quad (6)$$

Integrating once in space yields

$$\partial_t \chi + \frac{1}{2}|\nabla\chi|^2 + \Phi = C(t), \quad (7)$$

where $C(t)$ is a function of integration that may be absorbed into a redefinition of χ . This equation is formally identical to the Hamilton–Jacobi equation for a particle of unit mass moving in a potential Φ , provided χ is identified with the classical action.

The emergence of Newtonian dynamics follows immediately. Identifying the transport velocity with particle velocity, $\mathbf{v} = \dot{\mathbf{x}}$, and interpreting Φ as an effective potential, one recovers

$$\ddot{\mathbf{x}} = -\nabla\Phi, \quad (8)$$

which is precisely Newton’s second law. Importantly, this identification is not an ontological postulate but a regime-dependent correspondence. Particles do not exist as primitive objects in RSVP; they arise as coherent transport features localized within slowly evolving constraint landscapes.

The apparent time-reversal invariance of classical mechanics is likewise emergent. In the weak-history limit, entropy production is sufficiently small that reversing transport trajectories does not immediately violate thermodynamic ordering. The equations of motion become approximately symmetric under $t \mapsto -t$, even though the underlying RSVP dynamics are not. This explains why classical mechanics is so effective in describing systems near equilibrium, yet fails dramatically in contexts where dissipation, chaos, or measurement play a dominant role.

The action principle itself acquires a new interpretation in this framework. Rather than serving as a fundamental variational law, the action functional

$$S_{\text{cl}} = \int \left(\frac{1}{2} |\mathbf{v}|^2 - \Phi \right) dt \quad (9)$$

emerges as a compact summary of transport behavior in regimes where irreversible effects can be ignored. Extremization of this functional does not cause the motion; it encodes the regularities that persist once entropy-driven corrections are suppressed. From the RSVP perspective, the action is retrospective rather than generative, a bookkeeping device that becomes valid only after the underlying thermodynamic constraints have stabilized.

This derivation clarifies both the power and the limitations of classical mechanics. Its laws are not wrong, but contingent. They apply precisely in those regimes where the entropy field S is dynamically inert and the scalar constraint landscape evolves slowly. When these conditions fail, as they inevitably do at small scales, high energies, or long times, classical descriptions break down not because nature ceases to obey law, but because the law-like regularities they describe no longer exist. Classical mechanics is thus revealed as the first and simplest emergent interface between irreversible entropy flow and effective geometric description.

4 Relativistic Structure Without Fundamental Spacetime

Relativistic physics is often taken to mark the point at which geometry becomes unavoidable. The unification of space and time into a four-dimensional manifold endowed with Lorentzian metric structure appears, in standard presentations, as a decisive ontological shift. Within the RSVP framework, however, relativistic phenomena do not require spacetime to be fundamental. Instead, they arise when constraint propagation, transport flow, and entropy production enter regimes where finite propagation speed and causal ordering become dynamically enforced.

The key observation is that irreversible transport cannot proceed arbitrarily fast without destabilizing constraint structure. Rapid redistribution of the scalar field Φ generates steep entropy gradients, increasing S at a rate that suppresses further acceleration. This introduces an effective upper bound on transport velocity, not as a postulated invariant speed, but as a stability condition. Formally, consider perturbations of the scalar field propagating along the transport direction. Linearizing the RSVP equations about a stabilized background $(\Phi_0, \mathbf{v}_0, S_0)$ yields a wave-like

equation of the form

$$\partial_t^2 \delta\Phi - c_{\text{eff}}^2 \nabla^2 \delta\Phi + \Gamma \partial_t \delta\Phi = 0, \quad (10)$$

where c_{eff} is an effective propagation speed determined by the background alignment of $\nabla\Phi_0$ and \mathbf{v}_0 , and Γ encodes dissipative corrections due to entropy production. In regimes where Γ is small, disturbances propagate along characteristic surfaces analogous to null cones, despite the absence of any pre-defined metric.

These characteristic surfaces define causal ordering relations. Events are ordered not by coordinate time, but by accessibility through entropy-respecting transport paths. Two configurations are causally related if information encoded in Φ and mediated by \mathbf{v} can propagate between them without violating entropy monotonicity. This replaces the geometric notion of light cones with a dynamical notion of constraint cones, whose structure depends on local field alignment rather than global spacetime geometry.

Lorentz invariance emerges as a symmetry of these constraint cones in stabilized regimes. When transport velocity saturates the entropy-limited bound uniformly across directions, the effective propagation speed c_{eff} becomes isotropic. Transformations between observers moving relative to one another correspond to reparameterizations of transport flow that preserve the causal ordering induced by the constraint cones. The familiar Lorentz transformations arise as the group of transformations that leave invariant the form of the effective wave operator governing $\delta\Phi$, even though no fundamental spacetime metric has been assumed.

Redshift phenomena admit a similarly non-geometric interpretation. In conventional cosmology, redshift is attributed to metric expansion stretching wavelengths over time. Within RSVP, frequency shifts arise from cumulative entropy accumulation along transport paths. As a signal propagates through regions of varying constraint curvature, its phase evolution is modified by local changes in Φ and \mathbf{v} . Writing the phase θ of a propagating mode as satisfying

$$\partial_t \theta + \mathbf{v} \cdot \nabla \theta = \omega(\Phi, S), \quad (11)$$

one finds that gradual entropy increase along the trajectory leads to systematic frequency drift. Observed redshift thus encodes the integrated history of entropy descent rather than the expansion of space itself.

This reinterpretation resolves several long-standing tensions. It preserves the empirical successes of relativistic kinematics while eliminating the need to treat spacetime expansion as a fundamental process. It also integrates naturally with thermodynamic irreversibility, avoiding the uneasy coexistence of time-symmetric geometric laws with entropy-driven arrows of time. Relativity appears not as a statement about the structure of spacetime, but as a statement about the universality of constraint propagation under entropy-limited transport.

Crucially, this perspective does not deny the utility of Lorentzian geometry. Once constraint cones stabilize, it becomes efficient to summarize their structure using an effective metric. The Minkowski metric, and its curved generalizations, function as compact encodings of causal accessibility relations that are already present in the RSVP dynamics. Geometry is recovered as an emergent language that faithfully represents these relations, but it is no longer required to carry ontological weight.

Relativistic physics thus marks not the triumph of geometry, but its successful emergence. By deriving causal structure, invariant propagation speed, and redshift from irreversible entropy flow, RSVP demonstrates that spacetime is best understood as a secondary abstraction, valid precisely because the deeper thermodynamic substrate enforces regularity. Physics after spacetime retains relativity not by rejecting it, but by explaining why it works.

5 Gravity as Entropy Descent

Gravitational phenomena have long resisted unification with the rest of fundamental physics. In general relativity, gravity is not a force but a manifestation of spacetime curvature, while in quantum theory it remains conspicuously absent from the standard framework. Thermodynamic approaches to gravity have sought to bridge this divide by reinterpreting gravitational dynamics as emergent consequences of entropy, information, or horizon thermodynamics (Jacobson 1995; Verlinde 2011; Carney et al. 2019). While these approaches offer important insights, they typically retain geometric structure as a foundational element, treating entropy as a property of spacetime rather than as the generator of spacetime-like behavior itself.

Within the RSVP framework, gravity appears more directly as a manifestation of entropy descent acting on constraint curvature. The scalar field Φ encodes the topology of constraint, and its spatial curvature determines how transport is redirected within the plenum. Regions of high constraint curvature act as sinks for entropy-driven flow, not because they exert force in the Newtonian sense, but because entropy production is minimized when transport aligns toward configurations of lower constraint tension. Gravitational attraction thus reflects the tendency of irreversible dynamics to reorganize structure toward smoother constraint distributions.

This can be made explicit by examining stationary solutions of the RSVP equations in regimes where transport has equilibrated but entropy production remains nonzero. Setting $\partial_t \mathbf{v} \approx 0$ and neglecting higher-order torsional corrections, the transport equation reduces to

$$(\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \Phi. \quad (12)$$

In stabilized regimes where \mathbf{v} is small or slowly varying, this equation implies that transport accelerates toward regions of decreasing Φ , reproducing the qualitative behavior of gravitational attraction. However, unlike in Newtonian gravity, the source of this acceleration is not an externally imposed potential, but the internal redistribution of constraint driven by entropy growth.

The role of entropy becomes clearer when one considers the coupled evolution of Φ and S . The scalar field equation includes an explicit sink term proportional to S , reflecting the consumption of constraint capacity by irreversible processes. In regions where entropy accumulates rapidly, the scalar field relaxes more quickly, flattening constraint gradients and redirecting transport from neighboring regions. This feedback produces an effective attraction toward entropy-producing regions, which from an external perspective appears as gravitational mass.

Mass itself is therefore not a primitive property but an emergent measure of constraint curvature

sustained by entropy flow. A simple diagnostic for mass density ρ_{eff} within RSVP may be defined by

$$\rho_{\text{eff}} \propto |\nabla^2 \Phi| + \lambda(\nabla \Phi \cdot \mathbf{v}), \quad (13)$$

where the first term captures local constraint curvature and the second encodes coupling between constraint gradients and transport. Stable mass concentrations correspond to spectral bifurcations of the scalar field, satisfying

$$\nabla^2 \Phi + \kappa S = 0, \quad (14)$$

which admits discrete modes whose persistence depends on sustained entropy throughput. These modes play the role of matter sources in effective gravitational descriptions.

The emergence of curvature-based formulations follows naturally. When constraint curvature becomes spatially coherent over large regions, it is efficient to encode transport redirection using an effective metric whose connection coefficients summarize the influence of $\nabla \Phi$ on nearby trajectories. The Einstein field equations then arise as a macroscopic closure condition relating effective curvature to entropy-supported constraint structure, rather than as fundamental dynamical laws. In this sense, the geometric description of gravity is a thermodynamic coarse-graining of RSVP dynamics, valid when entropy descent organizes constraint curvature smoothly enough to admit a metric summary.

This perspective clarifies the partial successes and limitations of existing thermodynamic gravity proposals. Jacobson's derivation of Einstein's equations from local horizon thermodynamics captures the necessity of entropy balance but presupposes spacetime structure. Verlinde's entropic gravity identifies gravitational force with entropy gradients but treats information holographically rather than dynamically. RSVP subsumes these insights while avoiding their residual geometric commitments, grounding gravity directly in irreversible field evolution rather than in horizon-based arguments.

Importantly, gravity in RSVP is inseparable from irreversibility. There is no meaningful notion of a time-reversed gravitational process in which constraint curvature spontaneously sharpens without compensating entropy production. This resolves the long-standing tension between the apparent time symmetry of gravitational laws and the thermodynamic arrow of time. Gravity points in the same temporal direction as entropy because it is generated by the same underlying process.

By interpreting gravity as entropy descent acting on constraint topology, RSVP eliminates the need to treat curvature as fundamental while preserving the empirical content of gravitational physics. Curved spacetime is not denied, but reinterpreted as a stabilized interface description that becomes valid once entropy-driven dynamics have organized constraint structure at macroscopic scales. Gravity, like geometry itself, is thus revealed as a consequence rather than a cause.

6 Gauge Structure and Action Principles as Entropic Bookkeeping

Gauge symmetry occupies a central place in contemporary physics. From electromagnetism to the Standard Model, physical interactions are formulated in terms of fields defined up to local redundancy, with dynamics constrained by symmetry principles and variational extremization. Within geometric approaches, gauge structure is often treated as fundamental, reflecting deep

properties of the underlying configuration space. In the RSVP framework, by contrast, gauge symmetry is neither mysterious nor primitive. It emerges as a representational freedom inherent in describing stabilized constraint regimes while suppressing the irreversible microhistory that produced them.

The origin of gauge redundancy in RSVP can be traced to the multiplicity of field configurations that realize the same macroscopic constraint organization. Once entropy descent has driven the system into a stable regime, many distinct microtrajectories in (Φ, \mathbf{v}, S) space converge toward the same effective transport and curvature patterns. Any description that neglects the detailed history of entropy production must therefore identify these microstates as equivalent. Gauge transformations express precisely this identification: they relate distinct field configurations that differ in bookkeeping details but encode the same constraint accessibility relations.

This perspective clarifies why gauge symmetry becomes more exact at lower energies and larger scales. As entropy-driven fluctuations are averaged out, the space of indistinguishable microhistories expands, enlarging the equivalence classes represented by gauge orbits. Conversely, at high energies or small scales, where entropy production is rapid and constraint structure is continually reorganized, gauge descriptions become fragile or break down altogether. Gauge symmetry is thus a diagnostic of stabilization, not a fundamental organizing principle imposed from above.

Action principles admit a similar reinterpretation. In conventional formulations, physical trajectories are obtained by extremizing an action functional, often taken to encode the deepest laws of nature. From the RSVP standpoint, this variational structure arises only after irreversible dynamics have been suppressed sufficiently to allow trajectories to be summarized compactly. Consider again the classical action

$$S_{\text{eff}} = \int L(\Phi, \mathbf{v}) dt, \quad (15)$$

where L is an effective Lagrangian constructed from stabilized fields. Extremal paths of S_{eff} correspond not to physically enforced optimization, but to the most economical summaries of transport behavior once entropy production has been neglected. The extremization principle reflects the elimination of redundant history, not the mechanism of motion itself.

This explains why action-based formulations struggle to incorporate irreversibility directly. Variational calculus presupposes reversible exploration of neighboring trajectories, yet RSVP dynamics privilege a single direction of evolution enforced by entropy growth. Attempts to encode dissipation within action principles typically require auxiliary structures, doubled degrees of freedom, or nonlocal terms, all of which signal a mismatch between the ontology and the formalism. In RSVP, dissipation is not an add-on; it is the ground from which reversible approximations emerge.

Gauge fields themselves can be understood as collective descriptors of constraint transport. The familiar gauge potentials summarize how transport responds to variations in Φ while respecting equivalence under entropy-erased microhistory. Field strengths then measure the obstruction to globally flattening constraint structure, corresponding to residual curvature that cannot be removed by local reparameterization. In this sense, gauge curvature reflects persistent constraint tension rather than fundamental interaction strength.

The appearance of conserved quantities follows naturally. Noethers theorem associates symmetries of the action with conserved currents, yet within RSVP conservation laws arise only when entropy

production is sufficiently suppressed to allow persistent invariants. Energy, momentum, and charge conservation are therefore regime-dependent regularities, not absolute principles. They hold precisely when constraint relaxation and entropy growth balance in a manner that stabilizes transport patterns over time.

By situating gauge symmetry and action principles downstream of irreversible entropy flow, RSVP dissolves several longstanding conceptual puzzles. Gauge redundancy no longer demands metaphysical interpretation, and action extremization ceases to function as a causal law. Both are recognized as efficient representational tools that become valid only after the underlying thermodynamic substrate has organized itself into stable regimes. This reframing prepares the ground for understanding quantum descriptions as further coarse-grainings of irreversible dynamics, a task to which we now turn.

7 Time as Emergent Translation

In standard physical theories, time is introduced at the outset as a coordinate or parameter indexing change. Whether treated as absolute, relativistic, or operator-valued, it functions as a pre-existing axis along which dynamics unfold. Even when time is declared relative or dynamical, it remains geometrized, embedded within the same representational category as space. The RSVP framework rejects this starting point. Time is not assumed as a dimension, coordinate, or background parameter. Instead, it emerges as a derived notion indexing irreversible translation through field configuration space.

The need for a temporal ordering arises only once entropy becomes nonzero. In the absence of entropy production, configurations may be permuted without physical distinction, and no meaningful arrow can be defined. Irreversibility introduces asymmetry by enforcing a partial ordering on states: some configurations are reachable from others, but not vice versa. Time, in RSVP, is the structure induced by this ordering, not an independent entity imposed upon it.

Formally, RSVP dynamics are written using a parameter t for notational convenience, but this parameter has no ontological significance. Physical time corresponds instead to a composite operator acting on the evolving fields (Φ, \mathbf{v}, S) . A minimal definition may be given by the translation operator

$$T[\Phi, \mathbf{v}, S] := (\partial_t \Phi, \nabla \cdot \mathbf{v}, \partial_t S), \quad (16)$$

which captures the local rate of constraint relaxation, transport divergence, and entropy production. This operator does not define duration or simultaneity directly; rather, it encodes the direction and intensity of irreversible evolution. Time exists only where T is nonvanishing and aligned coherently across fields.

A physically meaningful temporal flow emerges when constraint gradients, transport, and entropy production become aligned. In stabilized regimes satisfying

$$\langle \nabla \Phi, \mathbf{v} \rangle > 0 \quad \text{and} \quad \partial_t S > 0, \quad (17)$$

the system admits a consistent ordering of configurations along transport trajectories. One may

then define an effective timeflow vector

$$T^\mu = \nabla^\mu \Phi + \eta \mathbf{v}^\mu + \theta \nabla^\mu S, \quad (18)$$

where η and θ encode relative coupling strengths. This vector is timelike not by geometric fiat, but because it points along directions of increasing entropy and decreasing constraint tension. Causality is enforced thermodynamically: transitions that would reverse entropy flow are dynamically inaccessible.

This construction clarifies the origin of temporal asymmetry. The arrow of time is not imposed by boundary conditions or cosmological initial states, but generated continuously by entropy descent. Every irreversible interaction contributes locally to temporal ordering, and global time emerges as a coherent alignment of these local translations. Where entropy production is minimal or fluctuating, temporal structure becomes weak or ambiguous, explaining why time appears ill-defined in certain quantum or gravitational regimes.

The familiar properties of time follow as effective regularities. Duration corresponds to accumulated entropy-weighted translation along transport paths. Simultaneity reflects equivalence classes of configurations that are mutually accessible without intervening entropy production. Time dilation arises when constraint curvature or transport divergence alters the local rate of entropy generation, modifying the effective translation rate relative to distant regions. These effects need not be attributed to spacetime geometry; they arise directly from RSVP field dynamics.

This perspective resolves several longstanding conceptual difficulties. It eliminates the category error of treating time as a spatial dimension, avoids the need for multiple temporal axes, and integrates temporal asymmetry seamlessly with thermodynamics. It also explains why time behaves differently across physical regimes. In classical mechanics, where entropy production is negligible, time appears as an external parameter. In relativistic settings, where transport saturation enforces universal ordering, time acquires invariant structure. In quantum contexts, where microhistory is inaccessible, time becomes probabilistic and relational.

Time, then, is not the stage upon which physics unfolds, but the trace left by irreversible evolution. It is a secondary construct that becomes meaningful only after constraint, transport, and entropy have organized themselves into coherent patterns. Physics after spacetime is therefore also physics after fundamental time. What remains is not timelessness, but a deeper temporality grounded in irreversible translation rather than geometric extension.

8 Quantum Descriptions as Coarse-Grained Irreversibility

Quantum theory presents a distinctive challenge for any foundational reconstruction. Its formalism is extraordinarily successful, yet its conceptual structure resists straightforward interpretation. Probabilistic outcomes, superposition, and nonlocal correlations appear to conflict with classical intuitions about causality and time. Within the RSVP framework, these features are not taken as fundamental mysteries, but as signatures of a regime in which irreversible microhistory is inaccessible and temporal ordering becomes intrinsically coarse-grained.

The defining move of quantum theory is the replacement of deterministic trajectories with

probability amplitudes. In RSVP terms, this replacement occurs when the detailed evolution of (Φ, \mathbf{v}, S) cannot be resolved at the scales relevant to observation. When entropy production is rapid and constraint structure reorganizes faster than transport can be tracked, distinct microhistories converge toward indistinguishable macroscopic configurations. The observer is then forced to describe evolution not by following a single entropy-respecting path, but by assigning weights to equivalence classes of histories compatible with observed constraints.

Formally, let Γ denote the space of admissible RSVP histories connecting two stabilized configurations. Each history $\gamma \in \Gamma$ corresponds to a distinct irreversible trajectory through field configuration space, characterized by cumulative entropy production

$$\Sigma[\gamma] = \int_{\gamma} (\alpha |\nabla \Phi|^2 + \beta |\mathbf{v}|^2) d\tau. \quad (19)$$

When the resolution of observation is insufficient to distinguish between individual γ , physical description collapses onto a distribution over Γ . The appropriate weighting is not arbitrary; histories that violate entropy monotonicity are dynamically excluded, while those with comparable entropy production contribute collectively. Probabilities thus arise as normalized measures over irreversibly admissible histories rather than as fundamental stochastic laws.

The appearance of superposition reflects this aggregation. A quantum state does not represent a system occupying multiple configurations simultaneously, but a bookkeeping device encoding uncertainty over which irreversible history has occurred. Linear structure emerges because, once microhistory is erased, the composition of alternatives must preserve consistency under coarse-graining. Hilbert space formalism provides precisely such a linearized representation of equivalence classes of histories, even though the underlying RSVP dynamics are nonlinear and dissipative.

Temporal structure in this regime is necessarily relational. Because time itself is derived from entropy-weighted translation, the loss of microhistory entails a loss of sharp temporal ordering. Operators that do not commute correspond to observables whose measurement sequences probe incompatible coarse-grainings of irreversible evolution. The uncertainty relations thus reflect limits on simultaneously reconstructing multiple aspects of past entropy production, rather than fundamental indeterminacy in nature.

Quantum dynamics, typically expressed through unitary evolution, acquire a retrospective interpretation. Unitarity ensures conservation of total probability across equivalence classes of histories, not reversibility of physical processes. The apparent time symmetry of the Schrödinger equation arises because entropy production has already been averaged out in constructing the quantum description. Irreversibility persists beneath the formalism, but no longer appears explicitly once history has been erased.

Measurement occupies a privileged role precisely because it reintroduces irreversibility. A measurement event corresponds to a localized surge in entropy production that collapses equivalence classes of histories into a narrower subset compatible with the recorded outcome. From the RSVP perspective, collapse is not a dynamical anomaly, but the moment at which irreversible constraint is reasserted. The classical world emerges not by suppressing quantum behavior, but by continually generating entropy through interaction, record formation, and environmental coupling.

This interpretation reframes long-standing debates about realism and locality. Nonlocal correlations arise because coarse-grained descriptions encode global constraints on admissible histories, not because information propagates instantaneously. Entanglement reflects shared constraint ancestry rather than superluminal influence. What appears paradoxical when viewed through the lens of spacetime geometry becomes natural when geometry itself is recognized as emergent.

Quantum theory, then, is not the fundamental layer beneath classical physics, but an intermediate interface description that becomes necessary when irreversible microhistory cannot be resolved. It occupies the regime between fully stabilized classical constraint dynamics and the deeper entropic substrate from which both classical and relativistic structures arise. In this sense, quantum mechanics is neither mysterious nor complete; it is a powerful approximation whose domain of validity is precisely delineated by the loss of temporal resolution induced by entropy.

9 Interface Theories and Higher-Order Corrections

As physical descriptions are extended toward higher energies or finer resolutions, the simplicity of emergent geometric and field-theoretic formulations begins to fail. Singularities appear, perturbative expansions diverge, and effective descriptions lose predictive power. The standard response has been to seek ultraviolet completions by introducing new degrees of freedom or quantizing existing geometric structures. Within the RSVP framework, these pathologies are interpreted differently. They signal not the need for deeper geometry, but the breakdown of an interface description whose validity depends on stabilized constraint regimes.

Effective field theories provide a canonical example. They extend low-energy descriptions by adding higher-order operators suppressed by a cutoff scale, encoding the influence of unresolved microstructure. From the RSVP perspective, such operators summarize the cumulative effects of entropy-driven smoothing and constraint redistribution that cannot be captured by leading-order terms alone. They do not reveal new fundamental interactions; they correct for the loss of information induced by coarse-graining.

Quadratic gravity occupies a particularly instructive position in this landscape. The inclusion of curvature-squared terms in the gravitational action has long been known to improve renormalization behavior while introducing conceptual difficulties such as ghost modes. In RSVP, these features acquire a natural interpretation. Curvature-squared terms arise when the effective metric description is pushed beyond the regime where constraint curvature varies slowly. They encode the response of transport and entropy production to sharp variations in Φ that are invisible at lower resolution.

This can be seen by examining the entropic smoothing of constraint curvature. The scalar field Φ undergoes diffusion driven by entropy production, which may be represented schematically as

$$\Phi(x) \mapsto \int K_\sigma(x-y) \Phi(y) dy, \quad (20)$$

where K_σ is a smoothing kernel with width σ set by entropy throughput. Expanding this transformation in powers of σ generates higher-order derivative corrections, including terms proportional to $\nabla^4 \Phi$. When translated into the effective metric language, these corrections correspond to quadratic

curvature invariants. Their appearance is therefore a mathematical artifact of smoothing irreversible dynamics into a geometric interface, not evidence of new fundamental degrees of freedom.

The instability associated with ghost modes reflects the tension between irreversible dynamics and reversible geometric representation. Interface theories inherit time-reversal symmetry from their variational formulation, even when the underlying RSVP dynamics are irreversible. Pushing such theories beyond their regime of validity exposes this mismatch, manifesting as unphysical modes or instabilities. Rather than signaling inconsistency in RSVP, these pathologies mark the limits of geometry-based summaries.

A similar interpretation applies to other proposed ultraviolet modifications of gravity and field theory. Higher-spin extensions, nonlocal actions, and modified dispersion relations can all be viewed as attempts to patch geometric descriptions where entropy-driven constraint reorganization becomes too rapid or too fine-grained to ignore. Each introduces additional structure to stabilize the interface, but none addresses the underlying source of breakdown, which lies in the suppression of irreversible history.

From this vantage point, the search for a fundamental ultraviolet theory of gravity is misplaced. There is no deeper geometric layer waiting to be quantized. What exists beneath effective descriptions is not another metric or symmetry group, but the entropic substrate itself. Interface theories are necessary and useful, but they should be recognized as such. Their role is to mediate between stabilized emergent regimes and the irreducible irreversibility of the RSVP dynamics.

Recognizing interface theories as regime-dependent clarifies why so many approaches to quantum gravity have yielded partial success without convergence. Each captures aspects of constraint smoothing or entropy-limited transport, yet each remains incomplete because it treats geometry as fundamental rather than emergent. RSVP does not compete with these theories at the same level; it explains why they arise and why they fail.

With this understanding in place, we are in a position to assess what remains once geometry, action, gauge symmetry, and even time have been demoted from fundamental status. The final section draws these threads together and articulates what it means to do physics after spacetime.

10 Discussion and Conclusion: What Remains After Spacetime

The derivations presented in this essay motivate a reorganization of physical foundations. Rather than treating spacetime, geometry, and symmetry as primitive structures upon which dynamics are imposed, we have shown that these elements arise as effective descriptions of a deeper thermodynamic substrate governed by irreversible entropy flow and constraint relaxation. Classical mechanics, relativistic kinematics, gravitational curvature, gauge redundancy, and quantum probability each emerge as regime-dependent interfaces that become valid only when aspects of irreversible history are suppressed or coarse-grained.

This shift does not diminish the empirical achievements of established theories. On the contrary, it explains their extraordinary robustness. Laws appear stable precisely because entropy descent organizes constraint structure into repeatable patterns over wide ranges of scale. Geometry works because irreversible dynamics enforce causal accessibility relations that can be summarized metrically.

Action principles succeed because stabilized transport permits history to be compressed into variational form. Quantum mechanics proves indispensable because lost microhistory necessitates probabilistic bookkeeping. None of these successes require their associated formalisms to be ontologically fundamental.

What is demoted by this perspective is the assumption that explanation must proceed geometrically. Spacetime ceases to function as the arena of physics and becomes instead a representational artifact that crystallizes once constraint propagation and entropy production achieve sufficient regularity. Time itself is no longer a dimension or coordinate but the trace of irreversible translation through field configuration space. Causality is enforced not by metric structure but by thermodynamic accessibility. Probability is not intrinsic indeterminism but the measure induced by erased history.

What replaces geometry as foundation is not abstraction but constraint. The RSVP framework places irreversibility at the center of physical description, insisting that any ontology capable of supporting records, observers, and stable structure must encode entropy growth at the most basic level. This move resolves a number of persistent tensions. It aligns gravity with the arrow of time rather than opposing it. It explains why quantization appears necessary without positing fundamentally stochastic dynamics. It clarifies why ultraviolet completions proliferate without convergence, revealing them as attempts to stabilize emergent interfaces rather than to access deeper geometric truth.

The resulting picture suggests a new criterion for fundamentality. A structure is fundamental not if it is mathematically elegant or unifying, but if it survives arbitrary refinement without generating contradictions. Geometry fails this test, as it must be continually supplemented when pushed beyond stabilized regimes. Entropy and constraint do not. Irreversibility cannot be coarse-grained away without eliminating the very possibility of physical law.

Several open directions follow naturally. Empirically, RSVP predicts deviations from geometric cosmology in regimes where entropy accumulation and constraint relaxation dominate, offering potential tests via redshift hysteresis, flow memory, and nonmetric lensing effects. Theoretically, the derived nature of gauge and action principles motivates a reformulation of quantization directly at the level of irreversible dynamics, rather than through geometric canonicalization. Conceptually, the emergence of time as translation rather than dimension invites reconsideration of causality, measurement, and agency across physics and cognition alike.

Physics after spacetime is not physics without structure, but physics grounded in the only structure that cannot be idealized away. Once irreversible entropy flow is taken seriously as primitive, the rest of physical law follows not as assumption, but as consequence. Geometry, time, and probability survive precisely because they are useful summaries of constraint-organized dynamics. They are retained, but no longer worshipped.

In this sense, the end of spacetime as a foundation does not mark a loss, but a clarification. What remains is a physics whose basic commitments align with the thermodynamic reality of the world it seeks to describe.

Appendices

A Irreversible Entropy Dynamics

Let M be a smooth four-dimensional manifold and let

$$\Phi : M \rightarrow \mathbb{R}, \quad \mathbf{v} \in \Gamma(TM), \quad S : M \rightarrow \mathbb{R}_{\geq 0}$$

be the scalar constraint field, vector transport field, and entropy density, respectively.

The RSVP evolution equations are

$$\partial_t \Phi + \mathbf{v} \cdot \nabla \Phi = -\gamma S + \lambda \nabla^2 \Phi, \quad (21)$$

$$\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \Phi + \kappa (\nabla \times \mathbf{v}) + \nu \nabla^2 \mathbf{v}, \quad (22)$$

$$\partial_t S = \alpha |\nabla \Phi|^2 + \beta |\mathbf{v}|^2 - \delta \nabla \cdot \mathbf{v}. \quad (23)$$

Define the functional

$$\mathcal{L}[\Phi, \mathbf{v}, S] = \int_M \left(\frac{1}{2} |\nabla \Phi|^2 + \frac{1}{2} |\mathbf{v}|^2 + \mu S \right) d^4x, \quad (24)$$

with $\mu > 0$.

Using (21)–(23) and integrating by parts under appropriate boundary conditions, the time derivative of \mathcal{L} satisfies

$$\frac{d\mathcal{L}}{dt} = - \int_M \left[(\gamma - \mu\alpha) |\nabla \Phi|^2 + (\mu\beta - \nu) |\mathbf{v}|^2 + \lambda |\nabla^2 \Phi|^2 \right] d^4x. \quad (25)$$

For parameter ranges

$$\mu\alpha \geq \gamma, \quad \mu\beta \geq \nu, \quad \lambda > 0, \quad (26)$$

the functional \mathcal{L} is nonincreasing:

$$\frac{d\mathcal{L}}{dt} \leq 0. \quad (27)$$

Stationary points satisfy

$$\nabla \Phi = 0, \quad \mathbf{v} = 0, \quad \partial_t S = 0. \quad (28)$$

Entropy production is pointwise nonnegative:

$$\partial_t S \geq 0, \quad (29)$$

with equality only at fixed points of the flow.

The induced partial order on field configurations is defined by

$$(\Phi_1, \mathbf{v}_1, S_1) \prec (\Phi_2, \mathbf{v}_2, S_2) \iff \int_{\gamma_1 \rightarrow 2} \partial_t S d\tau > 0, \quad (30)$$

where $\gamma_{1 \rightarrow 2}$ is any admissible RSVP trajectory connecting the configurations.

Equations (25)–(30) define an intrinsically irreversible dynamical system with entropy-monotone evolution.

B Hamilton–Jacobi Structure as a Weak-Entropy Limit

Assume a regime in which entropy production is negligible and slowly varying,

$$\partial_t S \approx 0, \quad \nabla S \approx 0, \quad (31)$$

and torsional effects vanish,

$$\nabla \times \mathbf{v} = 0. \quad (32)$$

There exists a scalar function χ such that

$$\mathbf{v} = \nabla \chi. \quad (33)$$

Substituting (33) into the transport equation

$$\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \Phi, \quad (34)$$

yields

$$\partial_t \nabla \chi + (\nabla \chi \cdot \nabla) \nabla \chi = -\nabla \Phi. \quad (35)$$

Integrating spatially gives

$$\partial_t \chi + \frac{1}{2} |\nabla \chi|^2 + \Phi = C(t), \quad (36)$$

where $C(t)$ is an arbitrary function of time.

Under the redefinition

$$\chi \mapsto \chi - \int C(t) dt, \quad (37)$$

equation (36) reduces to

$$\partial_t \chi + \frac{1}{2} |\nabla \chi|^2 + \Phi = 0. \quad (38)$$

Identifying χ with the Hamilton principal function S_{HJ} ,

$$S_{\text{HJ}} := \chi, \quad (39)$$

equation (38) is the Hamilton–Jacobi equation

$$\partial_t S_{\text{HJ}} + H(\mathbf{x}, \nabla S_{\text{HJ}}) = 0, \quad H = \frac{1}{2} |\mathbf{p}|^2 + \Phi. \quad (40)$$

Characteristic curves satisfy

$$\dot{\mathbf{x}} = \nabla S_{\text{HJ}}, \quad \dot{\mathbf{p}} = -\nabla \Phi, \quad (41)$$

yielding

$$\ddot{\mathbf{x}} = -\nabla\Phi. \quad (42)$$

The Hamilton–Jacobi formulation arises as a reduction of RSVP transport under suppression of entropy gradients and torsional transport.

C Constraint Cones and Effective Lorentz Structure

Consider a background configuration $(\Phi_0, \mathbf{v}_0, S_0)$ satisfying

$$\mathbf{v}_0 \parallel \nabla\Phi_0, \quad \partial_t S_0 = \text{const} > 0. \quad (43)$$

Let $\delta\Phi$ be a perturbation of the scalar field. Linearizing the RSVP equations about the background yields, to leading order,

$$\partial_t^2 \delta\Phi - c_{\text{eff}}^2 \nabla^2 \delta\Phi + \Gamma \partial_t \delta\Phi = 0, \quad (44)$$

where

$$c_{\text{eff}}^2 = \lambda + \alpha |\nabla\Phi_0|^2, \quad \Gamma \sim \partial_t S_0. \quad (45)$$

In the weak-dissipation limit $\Gamma \rightarrow 0$, characteristic hypersurfaces satisfy

$$k_\mu k_\nu g_{\text{eff}}^{\mu\nu} = 0, \quad (46)$$

with emergent effective inverse metric

$$g_{\text{eff}}^{\mu\nu} = \text{diag}(-1, c_{\text{eff}}^{-2}, c_{\text{eff}}^{-2}, c_{\text{eff}}^{-2}). \quad (47)$$

Causal accessibility is defined by the constraint cone

$$\Delta t^2 \geq c_{\text{eff}}^{-2} |\Delta \mathbf{x}|^2. \quad (48)$$

Isotropy of c_{eff} implies invariance under transformations preserving (46),

$$\Lambda^\mu{}_\alpha \Lambda^\nu{}_\beta g_{\text{eff}}^{\alpha\beta} = g_{\text{eff}}^{\mu\nu}, \quad (49)$$

yielding the Lorentz group associated with $g_{\text{eff}}^{\mu\nu}$.

Relativistic kinematics arises as a symmetry of stabilized constraint propagation rather than as a postulate of spacetime geometry.

D Time as an Entropy-Weighted Translation Operator

Let (Φ, \mathbf{v}, S) evolve under (21)–(23). Define the local translation operator

$$T[\Phi, \mathbf{v}, S] := (\partial_t \Phi, \nabla \cdot \mathbf{v}, \partial_t S). \quad (50)$$

Coherent temporal orientation is enforced by

$$\partial_t S > 0, \quad \langle \nabla \Phi, \mathbf{v} \rangle > 0. \quad (51)$$

Define the effective timeflow vector field

$$T^\mu = \nabla^\mu \Phi + \eta \mathbf{v}^\mu + \theta \nabla^\mu S, \quad \eta > 0, \theta > 0. \quad (52)$$

Define an entropy-weighted increment along an admissible trajectory γ in configuration space by

$$d\tau_{\text{eff}} := \omega(\Phi, \mathbf{v}, S) dS, \quad \omega(\Phi, \mathbf{v}, S) > 0. \quad (53)$$

Equivalently, along γ ,

$$d\tau_{\text{eff}} = \omega(\Phi, \mathbf{v}, S) \partial_t S dt. \quad (54)$$

A partial order on configurations is induced by entropy increase:

$$(\Phi_1, \mathbf{v}_1, S_1) \prec (\Phi_2, \mathbf{v}_2, S_2) \iff \exists \gamma_{1 \rightarrow 2} \text{ admissible such that } \int_{\gamma_{1 \rightarrow 2}} dS > 0. \quad (55)$$

Effective duration between configurations is

$$\tau_{\text{eff}}(1 \rightarrow 2) = \int_{\gamma_{1 \rightarrow 2}} \omega(\Phi, \mathbf{v}, S) dS. \quad (56)$$

Local dilation follows from spatial variation in entropy production rate:

$$\frac{d\tau_{\text{eff}}}{dt} = \omega(\Phi, \mathbf{v}, S) \partial_t S, \quad \partial_t S = \alpha |\nabla \Phi|^2 + \beta |\mathbf{v}|^2 - \delta \nabla \cdot \mathbf{v}. \quad (57)$$

In regimes where ω varies slowly, relative dilation between regions A and B is approximated by

$$\frac{d\tau_{\text{eff}}^{(A)}}{dt} \bigg/ \frac{d\tau_{\text{eff}}^{(B)}}{dt} \approx \frac{\partial_t S^{(A)}}{\partial_t S^{(B)}}. \quad (58)$$

E Entropic Smoothing and Quadratic Curvature Interfaces

Let Φ denote the scalar constraint field. Define entropic smoothing at scale $\sigma > 0$ by convolution with a symmetric kernel

$$\Phi_\sigma(x) = \int_M K_\sigma(x - y) \Phi(y) d^4 y, \quad K_\sigma(z) = (4\pi\sigma)^{-2} \exp\left(-\frac{|z|^2}{4\sigma}\right). \quad (59)$$

For sufficiently regular Φ , expand Φ_σ in σ :

$$\Phi_\sigma = \exp(\sigma \nabla^2) \Phi = \Phi + \sigma \nabla^2 \Phi + \frac{\sigma^2}{2} \nabla^4 \Phi + \mathcal{O}(\sigma^3). \quad (60)$$

Define an effective geometric encoding by identifying an emergent metric $g_{\mu\nu}$ whose curvature

summarizes constraint curvature,

$$R \sim \nabla^2 \Phi, \quad \nabla^4 \Phi \sim \nabla^2 R. \quad (61)$$

Substituting (60) into any effective scalar functional $F[\Phi_\sigma]$ quadratic in gradients yields higher-derivative terms. In particular, for

$$F[\Phi_\sigma] = \int_M \sqrt{-g} \left(a |\nabla \Phi_\sigma|^2 + b \Phi_\sigma \nabla^2 \Phi_\sigma \right) d^4x, \quad (62)$$

the expansion produces

$$F[\Phi_\sigma] = \int_M \sqrt{-g} \left(c_0 R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \mathcal{O}(\sigma^3) \right) d^4x, \quad (63)$$

with coefficients $c_i = c_i(a, b, \sigma)$.

The quadratic invariants arise universally from the σ^2 term in (60). Their relative weights depend on the tensorial decomposition of $\nabla^4 \Phi$ under the emergent metric identification.

Ghost-like modes correspond to extending the interface description beyond the regime in which (60) truncation is valid. In Fourier space, smoothing suppresses high-momentum modes,

$$\tilde{\Phi}_\sigma(k) = e^{-\sigma k^2} \tilde{\Phi}(k), \quad (64)$$

while curvature-squared truncations reintroduce unsuppressed high- k behavior when extrapolated outside the smoothing window.

Effective equations of motion derived from (63) are stable only for wavelengths satisfying

$$k^2 \ll \sigma^{-1}. \quad (65)$$

Quadratic gravity thus arises as a second-order interface expansion of entropic smoothing, not as a fundamental ultraviolet completion.

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