Universal Modular Dynamics:
A Unified Information-Theoretic Foundation of Geometry, Gravity, and Quantum Fields

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Abstract

We develop Universal Modular Dynamics (UMD), a structurally closed, domain-aware framework in which spacetime geometry, gravity-style response, quantum-field-like structure, and renormalization-group (RG) behavior emerge from a single primitive object: a density operator ρ and its modular generator $K = -\log \rho$. UMD replaces field-based primitives by a measurement-and-diagnostics architecture: locality is defined as a distinguishability gap relative to an optimal correlation factorization; criticality is defined as landscape flatness plus partition switching; RG flow is realized as CPTP-driven spectral redistribution tracked by quantile spectral coordinates; gauge structure is modeled as access-relative equivalence with patchwise (groupoid) transitions and holonomy-style diagnostics. The framework is supported by reproducible numerical evidence in declared finite-size domains and includes explicit stability gates and failure-domain reporting to prevent overclaim.

Contents

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1 Foundations of Modular Dynamics

1.1 Primitive object: state as canonical carrier of distinguishability

We take the quantum state as the single primitive descriptor:

$$\rho \in \mathcal{B}(\mathcal{H}), \qquad \rho \succeq 0, \qquad \mathrm{Tr}\rho = 1.$$

UMD treats ρ as the minimal basis-invariant container of a normalized probabilistic structure. All further objects must be defined as explicit functionals of ρ (and declared protocol/reference data), not as independent primitives.

Domain note (faithfulness). Modular objects require a logarithm. In finite dimensions we interpret $\log\rho$ on $\mathrm{supp}(\rho)$; when a strictly faithful state is required we either assume $\rho \succ 0$ or use a declared regularization $\rho \mapsto (1-\epsilon)\rho + \epsilon\,\mathbb{I}/d$.

1.2 Spectrum and modular generator

Let

$$\rho = \sum_i \lambda_i \, |\psi_i\rangle\langle\psi_i|, \qquad \lambda_i \geq 0,\ \sum_i \lambda_i = 1.$$

Define the modular generator

$$K(\rho) \equiv -\log\rho = \sum_i k_i \, |\psi_i\rangle\langle\psi_i|, \qquad k_i = -\log\lambda_i,$$

on $\mathrm{supp}(\rho)$.

Quantile spectral coordinates. For $q \in (0,1)$ define

$$k(q) \equiv -\log\lambda_q(\rho),$$

where $\lambda_q(\rho)$ is the q-quantile of the eigenvalue multiset.

1.3 Relative entropy: the canonical distinguishability functional

For states ρ, σ with $\mathrm{supp}(\rho) \subseteq \mathrm{supp}(\sigma)$ define

$$D(\rho\|\sigma) = \mathrm{Tr}\big(\rho(\log\rho - \log\sigma)\big) \in [0,\infty).$$

Theorem 1.1 (Positivity / Klein inequality). *$D(\rho\|\sigma) \geq 0$ with equality iff $\rho = \sigma$ on the common support.*

Theorem 1.2 (Data processing). *For any CPTP map Φ, $D(\Phi(\rho)\|\Phi(\sigma)) \leq D(\rho\|\sigma)$.*

1.4 Why pure modular commutator evolution is degenerate

A tempting "minimal" modular evolution is

$$\frac{d\rho}{d\lambda} = -i[K(\rho), \rho],$$

but $K(\rho)$ is a function of ρ, hence $[K(\rho), \rho] = 0$ identically. Therefore the evolution is trivial.

1.5 Relative modular generator and phase reference

Introduce a reference state σ (phase/access reference) and define the relative modular generator

$$K_{\rho|\sigma} \equiv -\log \rho + \log \sigma.$$

This removes the degeneracy since generally $[K_{\rho|\sigma}, \rho] = [\log \sigma, \rho] \neq 0$.

1.6 CPTP modular RG-proxy dynamics

We define the modular RG-proxy flow by a CPTP/GKSL generator:

$$\boxed{\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \mathcal{D}[\rho]}$$

with

$$\mathcal{D}[\rho] = \sum_\alpha \gamma_\alpha(\lambda)\Big(L_\alpha \rho L_\alpha^\dagger - \tfrac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\}\Big), \qquad \gamma_\alpha(\lambda) \geq 0.$$

The commutator part is isospectral; GKSL dissipation generates spectral redistribution.

1.7 Closure principle and stability gating

All physical structures admitted in UMD must be defined as explicit functionals of

$$(\rho,\ K(\rho),\ \text{reference/access data } \sigma \text{ or } (A_F, Z_F),\ \text{declared protocols}),$$

and any emergence statement must be paired with stability gates and explicit failure-domain reporting.

2 Partition Landscape Formalism

2.1 Partitions and product reconstruction

Let $P = \{X_1, \ldots, X_m\}$ be a partition of degrees of freedom. For each block $X \in P$ define the marginal $\rho_X = \mathrm{Tr}_{\bar{X}}(\rho)$ and the block-product reconstruction

$$\rho_P \equiv \bigotimes_{X \in P} \rho_X.$$

2.2 Landscape objective: gap + complexity penalty

Define the partition landscape functional

$$J_\eta(P; \rho) \equiv D(\rho \| \rho_P) + \eta\, \Omega(P),$$

where $\Omega(P)$ penalizes partition complexity and $\eta > 0$ sets the regularization strength.

2.3 Optimal partition and existence (finite domain)

Define

$$P^{(\rho) \in \arg\min_{P \in \mathcal{P}} J_\eta(P;\rho)},$$

with $\mathcal{P}$ a declared (typically finite) set of admissible partitions.

Theorem 2.1 (Existence; finite search). If $\mathcal{P}$ is finite, a minimizer P exists (not necessarily unique).

2.4 Locality functional (primary criterion)

We define operational locality by the block total correlation at the optimal partition:

$$\boxed{\mathcal{T}_{P(\rho)\equiv D\left(\rho \,\middle\|\, \otimes_{X\in P^{(\rho)}\rho_X}\right)}}.$$

Stable-local regimes require both small $\mathcal{T}_{P(\rho)}$ and stability of P under protocol perturbations.

2.5 Landscape gap and switching rate

Define the landscape gap

$$\Delta(\rho) \equiv \min_{P\neq P\left(J_\eta(P;\rho)-J_\eta(P^{;\rho)}\right)},$$

and the partition switching rate Γ along a trajectory $\rho(\lambda)$ as the (protocol-defined) rate at which $P^{(\rho(\lambda))}$ changes across the discretized parameter grid.

2.6 Criticality without correlation length

We define UMD criticality as

$$\boxed{\text{Criticality} \equiv (\Delta(\rho) \to 0) \;+\; (\Gamma > 0)}.$$

This replaces correlation-length divergence by observable landscape flatness and switching.

2.7 Phase triple

We define the phase/access triple

$$F \equiv (P^{,A_F,Z_F}),$$

where A_F is the access algebra induced by P and Z_F is the center/pointer subalgebra (domain-defined).

3 Unified Measurement Panel

3.1 Declared inputs and protocols

All panel outputs are conditional on explicit protocol declarations: state family, parameter grids, seed/boostrap plan, quantile grid q, commutator observables O (near/far), partition landscape settings $(\eta, \Omega, \mathcal{P})$, and MI-geometry settings (ε, ν_g).

3.2 Panel blocks

SP (spectral profile). Compute $k(q)$ and derived slopes/curvatures (e.g. k_{curv}).

MC (commutator diagnostics). For observable O define

$$\widehat{L}(\rho; O) = \frac{\|[K, O]\|_F}{\|K\|_F \, \|O\|_F}, \qquad K = -\log \rho_{\text{vis}}.$$

Extract running exponents ν via sliding log–log fits and retain only windows meeting a fit-quality threshold.

LP (partition/locality). Compute P, $\mathcal{T}_P$, Δ, and switching rate Γ.

GS (MI-geometry). From pairwise mutual informations build a correlation graph distance $d_\rho(i,j)$ and summaries (d_{nn}, d_{med}), and a stability proxy S_{geo} (e.g. seed-variance or protocol sensitivity).

BR (optional; gated). Estimate response coefficients linking spectral/entropic drifts to geometry drift only in stable-local regimes.

3.3 Stability gates and admissible claims

We enforce gates $G1$–$G5$: fit quality; seed robustness; partition stability; geometry stability; and explicit domain statement. Claims are stratified into levels (formal embedding; operational agreement; conservative interpretation; strong derivation reserved for future work).

4 From Landscape to Geometry Instability and Accelerated Spectral Flow

4.1 Chart dependence of geometry

Any geometry derived from correlations depends on a chart/organization of DOF. In UMD this chart is induced by the optimal partition $P^{(\rho)}$ (and protocol choices).

4.2 Flat landscapes imply non-unique charting

If $\Delta(\rho) \to 0$, then competing near-minimizers exist and P becomes protocol-sensitive, implying non-uniqueness of derived geometric constructions.

4.3 Switching makes instability observable

A positive switching rate Γ operationalizes criticality: chart changes occur across the trajectory/grid.

4.4 Geometry instability gate

Geometry is meaningful only when stable. Instability is detected by rising S_{geo} and/or strong protocol sensitivity in MI-geometry constructions.

4.5 Acceleration markers

Near critical bands one expects spikes in spectral curvature, tail-sensitive quantile drift, and shifts in commutator running exponents ν (all subject to gates).

5 Renormalization Group as Spectral Flow

5.1 Spectral coordinates as RG observables

Define $\beta_q(\lambda) = dk(q)/d\lambda$ as RG-proxy beta functions.

5.2 Isospectrality of commutator flow

Theorem 5.1. *If* $d\rho/d\lambda = -i[H,\rho]$, *then the spectrum of* ρ *(hence* $k(q)$*) is preserved.*

5.3 GKSL dissipation generates spectral flow

In the full CPTP evolution, spectral drift is generated by $\mathcal{D}[\rho]$. Fixed points correspond to $\beta_q \simeq 0$ (domain-defined) and/or stationary states of the full generator.

5.4 RG irreversibility

When applicable (e.g. detailed balance with a stationary reference), relative entropy acts as a Lyapunov functional, yielding domain-aware irreversibility.

5.5 Core statement

$$\boxed{\textbf{RG flow in UMD} \equiv \textbf{CPTP-driven spectral redistribution tracked by } k(q).}$$

6 Observable Diagnostics

6.1 Normalized commutator diagnostic

For observable O define $\widehat{L}(\rho; O)$ as in Section 3.

6.2 Spectral decomposition identity

Theorem 6.1. *In the eigenbasis of ρ, with $k_i = -\log \lambda_i$ and $O_{ij} = \langle \psi_i | O | \psi_j \rangle$,*

$$\|[K, O]\|_F^2 = \sum_{i,j} (k_i - k_j)^2 |O_{ij}|^2.$$

This exhibits $\widehat{L}$ as a measurable probe of modular spectral structure.

6.3 Running exponents and portability

Running exponents ν are extracted via sliding log–log fits with quality gating. Robustness is assessed by observable-class swaps (near vs far probes).

6.4 Scaling laws (domain-gated)

In stable domains one may observe laws of the form $\widehat{L} \sim k(q)^\nu$ and more refined closure relations linking ν to spectral coordinates.

7 Gauge Structure and Modular Defects

7.1 Access algebra and center

Define the access algebra

$$A_F \equiv \bigvee_{X \in P\mathcal{B}(\mathcal{H}_X),}$$

and a domain-defined center/pointer subalgebra $Z_F \subset A_F$.

7.2 Access equivalence (gauge as indistinguishability)

$$\rho \sim_F \rho' \iff \mathrm{Tr}(\rho A) = \mathrm{Tr}(\rho' A) \;\; \forall A \in A_F.$$

This is a strict operational notion of gauge redundancy.

7.3 Modular defects and patching

Defect regimes are characterized by loss of a single stable chart (flat landscape, switching, center instability), forcing patchwise descriptions.

7.4 Groupoid transitions

Transition maps $\phi_{\alpha\beta} : A_{F_\alpha} \to A_{F_\beta}$ defined on overlaps form a groupoid (identity, inverses on overlaps, partially defined composition).

7.5 Holonomy loop test

A loop composition

$$\mathcal{H}(\alpha \to \beta \to \cdots \to \alpha) \equiv \phi_{\cdots\alpha} \circ \cdots \circ \phi_{\beta\gamma} \circ \phi_{\alpha\beta}$$

is a nontrivial defect signature if $\mathcal{H} \neq \mathrm{id}$ beyond protocol thresholds (domain-gated).

8 Numerical Evidence

8.1 Evidence pillars

We organize evidence into three pillars: (i) reference spectral–commutator diagnostics in finite dimension, (ii) toy CPTP/locality verification, and (iii) MSRO-style (p, κ) maps with MI geometry targets and explicit proxy-vs-final labeling status.

8.2 Declared numerical domains (summary tables)

Table 1: Reference experiment domain (spectral–commutator layer).

Item	Value (declared)
Hilbert size	dim = 64 (working split: $N_{\text{vis}} = 5$, $N_{\text{hid}} = 1$)
Family	mixed / Gibbs-like + mixing parameter p
p-range	$p \in [0.01, 0.20]$, step $\Delta p = 0.01$
Seeds	$\{501, 503, 509, 521, 541, 557\}$ (bootstrap aggregation)
Commutator probes	near/far observables (e.g., $Z_0 Z_1$ vs $Z_0 Z_4$)
Sliding-fit window	$w = 0.05$ (step 0.01)
Fit gate	use ν only when $R^2 \geq R^2_{\text{min}}$ (protocol-declared)
Outputs	$k(q)$, $\widehat{L}$, running ν, R^2, robustness (swap/boot)

Table 2: Toy verification domain (CPTP/locality suppression; finite N).

Item	Value (declared)
System size	$N = 8$ (toy audit domain)
Dynamics	PROXY and FULL+LC (CPTP/GKSL template)
Grids	angular sets Θ (base and extended); stress tests use denser grids
Step schedule	discrete $\Delta\lambda$; multiple λ_{max} (stress)
Threshold protocol	worst-case calibration (e.g. $\theta = 90°$) + sweep checks
Key outputs	suppressed_all, calibrated μ_{hi}, robustness across grids/modes
Controls	e.g. $\mu = 0$ expected FAIL; parameter toggles for nontriviality

Table 3: MSRO domain (full (p, κ) grid with MI geometry targets; proxy labels if stated).

Item	Value (declared)
Grid	$p \in [0.01, 0.20]$ with $\Delta p = 0.01$; $\kappa \in [0, 0.20]$ with $\Delta\kappa = 0.02$
Spectral features	$k(q)$ on fixed quantile grid; curvature proxies k_{curv}
Geometry targets	MI matrix $I(i{:}j)$; graph distance d_ρ; summaries d_{nn}, d_{med}
Geometry stability	$S_{\text{geo}} = \text{std}_{\text{seeds}}(d_{nn})$ (minimal proxy)
Regime labels	proxy L/C/N only as stand-in; final uses P, Δ, Γ, flatness
Artifacts	full-grid CSV/JSON + figures + manifest (reproducibility pack)

8.3 Failure-domain table (what breaks and what we do)

Table 4: Failure domains and required actions (strict).

Failure domain	Symptom (gate)	Required action
Fit failure (FD1)	$R^2 < R^2_{\min}$ for sliding fits	Do not use ν; retune window/protocol or report N/A
Partition instability (FD2)	$\Delta \to 0$ and/or $\Gamma > 0$ outside declared band	Treat as defect/critical; forbid stable-geometry claims
Geometry instability (FD3)	large S_{geo} or high protocol sensitivity	Do not interpret geometry; report instability region
Out-of-family (FD4)	closure collapses on extreme random-pure ensembles	Mark out-of-domain; restrict universality claims
Holonomy ambiguity (FD5)	transitions not stable on overlaps	Forbid holonomy claims; improve overlap protocol

Gate discipline (applies to all domains). Claims are admitted only when the corresponding gates pass: fit-quality for ν (G1), seed/boot robustness (G2), partition stability (G3), geometry stability (G4), and explicit domain statement (G5). Failure domains are reported as part of the result.

8.4 Reference domain (spectral–commutator)

In the declared finite-size reference domain, extraction of ν is stable under fit-quality gating and robust under observable swaps and normalization choices, and closure relations linking ν to spectral scales are supported within mixed/Gibbs-like families (with explicit out-of-domain failure for extreme random-pure ensembles).

8.5 Toy verification (CPTP suppression/locality)

In a declared toy domain (finite N; controlled parameters and angular grids), worst-case calibration and robust suppression/locality checks support the operational protocols and demonstrate adaptive-vs-proxy threshold behavior. Control tests (e.g. $\mu = 0$) confirm nontriviality.

8.6 MSRO (p, κ) maps with MI geometry

On a full (p, κ) grid, spectral curvature and MI-geometry produce reproducible overlays and minimal geometry stability proxies. Current proxy labels are explicitly marked as stand-ins pending full partition-optimizer labeling.

9 Full Correspondence

9.1 Correspondence levels

We define: Level 0 (formal embedding), Level 1 (operational agreement within a domain), Level 2 (conservative interpretation under stability gates), Level 3 (strong derivation; program-level).

9.2 QM and OQS

QM is represented by ρ and expectation values $\mathrm{Tr}(\rho O)$. OQS correspondence is structural: the UMD evolution is CPTP/GKSL by construction, with data-processing discipline for distinguishability functionals (domain-aware for phase updates).

9.3 RG as spectral redistribution

RG correspondence is realized by quantile spectral coordinates $k(q)$ and beta functions $\beta_q = dk(q)/d\lambda$, with isospectral commutator motion and GKSL-driven drift.

9.4 QFT and GR (conservative)

Field-like objects are treated as modular fluctuations (δK) in stable domains. GR-like correspondence is stated as a domain-gated distinguishability-response program requiring stability of emergent geometry and additional scale calibration for stronger claims.

9.5 Gauge and dark sectors

Gauge is access-relative equivalence with patching groupoids and holonomy tests. Dark-sector effects are treated as access-invisible structure, expressed diagnostically (not as cosmological proof by default).

10 Conceptual Structure

UMD is a measurement–flow program: start from ρ, build modular generators and monotone distinguishability functionals, evolve via CPTP modular RG-proxy dynamics, and admit emergent structure only when certified by stability gates. In this sense the conceptual chain is:

$$\rho \Rightarrow K \Rightarrow (\text{locality/criticality/geometry/RG/observable diagnostics/gauge patching}).$$

11 Predictions

11.1 P0: spectral drift as a dissipation signature

If $\mathcal{D} = 0$ (pure commutator flow), then $k(q)$ is constant; any observed drift in $k(q)$ indicates nonunitary spectral redistribution (testable in simulations and controlled OQS settings).

11.2 P1: criticality without correlation length

Critical windows are predicted by $(\Delta \to 0) + (\Gamma > 0)$ rather than by correlation-length divergence, and are expected to coincide with instability of charting/geometry (domain-gated).

11.3 P1: acceleration markers

Near critical bands, UMD predicts spikes in spectral curvature, tail-sensitive quantile drift, and shifts/crossovers in commutator exponents ν (subject to fit-quality gates).

11.4 P2: gauge defects and holonomy

In defect regimes, patching transitions yield a nontrivial holonomy loop test beyond protocol thresholds, providing an operational gauge signature.

11.5 P3: dark-sector diagnostic signatures

Access-invisible structure can produce stable diagnostic separation in planes such as $(\Lambda_{\mathrm{eff}}, R_{\mathrm{br}})$ without altering access-algebra expectation values, yielding a falsifiable diagnostic program (not a cosmology claim by default).

11.6 P4: portability and negative predictions

UMD predicts portability of qualitative profiles across observable classes (near/far) within domain, and forbids geometry claims when stability gates fail (large S_{geo} or unstable P).

12 Limitations

UMD claims are domain-aware. Current evidence is finite-size and protocol-dependent; continuum and full SM/GR identifications require separate scaling and calibration. Closure relations may fail outside mixed/Gibbs-like families. Partition instability and geometry instability are treated as explicit failure domains that prohibit strong emergence claims.

13 Conclusion

Scientific value

UMD provides a unified, operational language in which locality is a distinguishability gap relative to optimal correlation factorization, criticality is landscape flatness plus partition switching, RG flow is CPTP-driven spectral redistribution tracked by quantile coordinates, and gauge structure arises as access-relative equivalence with groupoid patching and holonomy diagnostics. The contribution is a strict measurement-and-diagnostics framework with explicit gates and failure domains.

Degree of development

The work specifies a closed pipeline: foundations (state, modular generators, CPTP evolution), partition landscape formalism (P, $\mathcal{T}_P$, Δ, Γ), a unified measurement panel (spectral, commutator, partition, MI-geometry blocks), and correspondence/prediction statements stratified by admissible levels. Numerical evidence is organized into declared pillars with explicit out-of-domain reporting.

Applied value and future directions

UMD yields reusable computational instruments for regime mapping, critical-band detection, geometry-stability screening, and observable-facing RG diagnostics. Immediate work includes replacing any proxy regime labels by the full partition-optimizer protocol on the same grids, pre-registering and validating closure models by seed-block CV, and extending stability analysis via protocol-sensitivity scans. Program-level directions include controlled scale calibration for GR-like correspondence and a systematic identification program for gauge/matter structures under strict stability gates.

14 References

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