Strong Portability of Modular Diagnostics: A Unified Instrument Panel for Open Quantum Systems, Information Geometry, Entanglement Gravity, and Renormalization Group Flow

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Abstract

We propose a strong notion of portability for a unified "instrument panel" intended to operate across four domains: open quantum systems (OQS), information geometry (IG), entanglement-based emergent geometry/gravity (EG), and renormalization group (RG) flow. The panel is defined solely from a density operator ρ and its modular generator $K = -\log \rho$ (and, when needed, a visible reduction ρ_{vis}). It combines spectral profile coordinates, observable-facing modular commutator diagnostics, operational locality/criticality markers based on optimal correlation factorization, correlation-graph geometry with stability certification, and optional backreaction links. Strong portability is formulated as a transport contract: the same panel, the same gates, and the same validation protocol are applied across domains with only minimal domain adapters that declare the flow coordinate and the visible subsystem. We provide an explicit portability scorecard, robustness checks, and a strict failure-domain taxonomy to prevent overclaim.

Contents

1 Introduction

Unification claims often mix conceptual mapping with domain-specific primitives. We instead target a strong, operational criterion: *protocol portability*. A unified language is realized as a transportable measurement-and-diagnostics architecture rather than a purely interpretive bridge.

We consider four domains that typically use incompatible primitives: OQS, IG, EG, and RG. Our goal is to define a single instrument panel and a single validator that operate across all four without manual retuning, while explicitly separating in-domain validity from failure domains.

2 Core objects and notation

Let ρ be a density operator on a finite-dimensional Hilbert space: $\rho \geq 0$, $\mathrm{Tr}\rho = 1$. When a visible/hidden split is declared, $\rho_{\mathrm{vis}} = \mathrm{Tr}_{\mathrm{hid}}\rho$.

The modular generator is $K = -\log\rho$ (or $K_{\mathrm{vis}} = -\log\rho_{\mathrm{vis}}$). Relative entropy is

$$D(\rho\|\sigma) = \mathrm{Tr}\big(\rho(\log\rho - \log\sigma)\big).$$

3 Unified measurement panel (portable specification)

3.1 Design principle

The instrument panel must satisfy three constraints: (i) universality (defined for any ρ), (ii) auditability (quality indicators and hard gates), and (iii) minimality (computable over grids and portable across domains).

We define the panel as blocks

$$\mathcal{F} = \mathrm{SP} \cup \mathrm{MC} \cup \mathrm{LP} \cup \mathrm{GS} \cup \mathrm{BR},$$

together with gates $\mathcal{G} = \{G1, \ldots, G5\}$.

3.2 SP block: spectral profile coordinates

On a fixed quantile grid $\mathcal{Q} = \{0.50, 0.60, 0.70, 0.80, 0.90, 0.95, 0.98\}$ define

$$k(q) = -\log\lambda_q(\rho_{\mathrm{vis}}), \qquad q \in \mathcal{Q},$$

and the derived shape features $\Delta_q k$, $\Delta_q^2 k$, and curvature norm $k_{\mathrm{curv},L2}$.

3.3 MC block: modular commutator diagnostics

For a fixed observable family (near/far probes), define

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

Extract a running exponent ν from sliding log–log fits, with fit quality R^2.

3.4 LP block: locality and criticality

Locality is defined operationally as a distinguishability gap relative to an optimal factorization:

$$\mathcal{T}_{P(\rho)=D\left(\rho \,\middle\|\, \bigotimes_{X\in P}\rho_X\right)}.$$

Criticality is defined by *landscape flatness plus partition switching*:

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

3.5 GS block: emergent geometry and stability

From the mutual-information graph on visible degrees of freedom, compute shortest-path distances $d_\rho(i, j)$. Define geometry summaries (e.g. d_{nn}, d_{med}) and stability score

$$S_{\text{geo}} := \text{std}_{\text{seeds}}(d_{\text{nn}}).$$

Geometry claims are admissible only when stability gates pass.

3.6 BR block: backreaction links (optional)

In stable-local regimes, estimate links between spectral/entropic drift and geometry drift:

$$\Delta d_{\text{eff}} \approx \alpha_1\, \Delta V_F + \alpha_2\, \Delta k(0.8) + \alpha_3\, \Delta k(0.9) + \alpha_0,$$

with bootstrap uncertainty.

3.7 Gates (shared across domains)

We use the same gates across all domains: G1 numerical well-posedness; G2 fit-quality threshold; G3 geometry stability admissibility; G4 labeling admissibility (full vs proxy flagged); G5 family/out-of-domain detector. When a gate fails the protocol abstains rather than retunes.

4 Universal validation protocol (no leakage)

We treat validation as part of the theory. Splits are block-structured to prevent leakage: seed-block CV (default), axis-block CV when an axis exists (e.g. κ slices), and family-block holdout when multiple families exist. Robustness checks include observable swaps (near/far), window perturbations for ν, protocol sensitivity for geometry, and feature ablations (with/without curvature).

Two core tasks are validated uniformly:

- T1: predict $y = \log S_{\text{geo}}$ from $\text{MSRO}_{\text{spec}}$ using block-CV.
- T2: classify regimes $L/C/N$ (probabilistic preferred; proxy allowed only as baseline and explicitly flagged).

Mechanistic portability requires recurring invariants beyond prediction, including a clean separation of isospectral commutator motion from dissipative spectral drift and a stable linkage between commutator behavior and a spectral tail scale.

5 Four-domain demonstration design

We define four benchmarks with minimal adapters $\mathcal{A}_j = (\lambda_j, \mathrm{vis}_j)$:

1. OQS: CPTP/GKSL dynamics with $\lambda = t$ or step index and a fixed visible subsystem.
2. IG: controlled interpolation paths in state space with λ an IG parameter.
3. EG: correlation-driven geometry regimes with λ a structure-control parameter.
4. RG: modular RG-proxy evolution with λ the RG-time proxy.

The panel, gates, and validator remain fixed; only λ_j and vis_j are declared per domain.

6 Results: portability scorecard and cross-domain invariants

We report results in three layers: (i) gate pass rates and stability, (ii) predictive portability (T1/T2 with block-CV), and (iii) mechanistic invariants.

6.1 Portability scorecard template

Table 1 is the shared scorecard format (to be filled by domain runs).

Table 1: Portability scorecard (template). Same metrics and gates across all domains.

Domain	**Gate pass (G1–G5)**	**T1: R^2 (log S_{geo})**	**T2: Macro-F1 (L/C/N)**	**Robustness (R1–R4)**	**Status**
OQS	—	—	—	—	—
IG	—	—	—	—	—
EG	—	—	—	—	—
RG	—	—	—	—	—

6.2 PASS / WEAK / FAIL rule

We classify each domain as PASS (Strong), PASS (Weak), or FAIL (Out-of-domain/unstable) based on the joint outcome of invariance, prediction, and mechanistic corroboration under the shared gates.

7 Limitations and failure domains (strict)

We report a portable failure taxonomy with detection triggers and required actions. Geometry instability gates off geometry claims; out-of-family ensembles trigger out-of-domain tags; proxy labeling is baseline-only; fit instability gates off exponent-based mechanisms.

8 Conclusion

Scientific value

We formalize a strong notion of "unified language" as a transport contract: the same modular-spectral instrument panel, the same gates, and the same validator applied across OQS, IG, EG, and RG with only minimal adapters. Criticality is treated operationally as landscape flatness plus partition switching, and geometry is admitted only when stability criteria certify it.

Table 2: Failure domains and required actions (strict). Portable taxonomy.

Failure / limit	**Symptom (what breaks)**	**Required action**
Out-of-family ensembles	Prediction and invariants collapse under family-block holdout; boundaries shift unpredictably.	Declare out-of-domain; restrict claims or add robustness layer and revalidate.
Geometry instability	S_{geo} large or protocol-sensitive; geometry becomes non-auditable.	Gate off geometry claims; add protocol-sensitivity scans; enlarge data/DoF if needed.
Proxy labels	Classification is w.r.t. proxy thresholds, not full partition optimizer.	Replace with full LP labeling (P, SwitchRate, $\Delta\Phi$, $\mathcal{T}_P$).

Degree of development (depth)

The contribution is a closed protocol: (i) a portable panel defined from (ρ, K), (ii) block-structured validation with no leakage, (iii) robustness checks and ablations, and (iv) strict failure-domain reporting and abstention discipline to prevent overclaim.

Applied value and future directions

The framework provides reusable computational instruments for regime mapping, critical-band screening, geometry-stability certification, and observable-facing RG diagnostics in open quantum systems and quantum simulators. Immediate next steps are: (i) replace proxy $L/C/N$ labels by full LP optimization in the core benchmarks, (ii) preregister and activate closure quality Q_{close}, and (iii) expand ensembles and channels while preserving explicit out-of-domain detectors.

9 Figures (key set)

Note. Put figures into `figs/` (preferred) or project root. If absent, placeholders will appear.

figs/scorecard.png,scorecard.png,,

Figure 1: Portability scorecard overview (across OQS, IG, EG, RG): gates, predictive metrics, robustness flags.

figs/portability$_{m}atrix.png, portability_{m}atrix.png$, ,

Figure 2: Unified PASS/WEAK/FAIL portability matrix summarizing admissible claim strength per domain.

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figs/corroboration$_{s}tory.png, corroboration_{s}tory.png, ,$

Figure 3: Cross-domain corroboration example: SP curvature + MC exponent shifts + GS stability spikes near critical bands.

figs/failure$_{m}ap.png, failure_{m}ap.png, ,$

Figure 4: Failure-domain map: where gates force abstention (geometry instability, out-of-family collapse, proxy-label zones).

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