The Rate Inheritance Principle: From Static Correlations to Dynamical Decoherence Rates

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This manuscript is a companion note in the coherence-maintenance program.

Role: Theoretical framing note (RIP).

Core technical reference: For the rigorous finite-dimensional proofs and witness protocols, see:

Finite-Dimensional Davies Interface Lemmas and TFIM Witness Tests for the Heisenberg Cut as a Resource Boundary

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Abstract

In gapped open quantum systems with localized couplings, static correlations across an operational interface of width ϵ are exponentially suppressed by the mass gap. Independently, the energetic cost of maintaining quantum coherence is governed by the rate at which coherence is lost under uncontrolled dynamics. What is currently missing is a principled connection between these two facts: how geometric suppression of static correlations constrains dynamical decoherence rates.

We formulate the *Rate Inheritance Principle* (RIP): the hypothesis that effective coherence-loss rates inherit the same suppression envelope as static correlations across an operational interface. We distinguish a weak upper-envelope form, which admits partial microscopic support, from a stronger envelope-class conjecture. We analyze microscopic plausibility within Davies-type weak-coupling dynamics, provide surrogate numerical evidence using tunable buffer-chain models, and identify explicit failure modes. RIP is presented as a falsifiable hypothesis with clearly delimited scope.

When combined with independently established maintenance-power bounds, RIP supplies the missing dynamical input needed to interpret the quantum–classical transition as a resource boundary rather than an interpretational postulate.

1 Preliminaries and definitions

We consider a finite-dimensional quantum system with Hamiltonian

$$H_S = \sum_n E_n \Pi_n$$

undergoing uncontrolled Markovian evolution generated by a Lindbladian $\mathcal{L}_\epsilon$. Logarithms are natural (nats).

Energy pinching. The energy pinching (conditional expectation onto energy eigenspaces) is

$$\Delta[\rho] := \sum_n \Pi_n \rho \Pi_n.$$

Coherence functional. For faithful states ρ (or more generally using the standard support convention),

$$C(\rho) := S(\rho \| \Delta[\rho]), \qquad S(\rho\|\sigma) := \mathrm{Tr}\big[\rho(\log\rho - \log\sigma)\big].$$

Coherence-loss rate. For $\rho_t = e^{t\mathcal{L}_\epsilon}(\rho)$ define

$$\dot{C}_{\mathrm{loss}}(\rho) := -\left.\frac{d}{dt} C(\rho_t)\right|_{t=0}.$$

Weak-coherence regime. A family of states lies in the weak-coherence regime if for every $\delta > 0$ there exists $C_0(\delta) > 0$ such that

$$C(\rho) \le C_0(\delta) \;\Rightarrow\; \left|\dot{C}_{\mathrm{loss}}(\rho) - \kappa(\epsilon)\, C(\rho)\right| \le \delta\, C(\rho),$$

uniformly over the family.

2 The missing dynamical bridge

Static clustering in gapped systems and thermodynamic lower bounds on coherence maintenance are independently well established. Static correlators across an interface of width ϵ obey bounds of the form

$$\text{correlations} \;\lesssim\; f(\epsilon), \qquad f(\epsilon) \sim \mathrm{poly}(m\epsilon)\, e^{-m\epsilon} \;\text{ or }\; K_\nu(m\epsilon).$$

Independently, maintenance costs satisfy inequalities of the form

$$P_{\mathrm{extra}}(\rho) \ge k_{\mathrm{B}} T\, \dot{C}_{\mathrm{loss}}(\rho),$$

under an explicit operational control model; see [2].

What remains unresolved is how the effective coherence-loss rate $\kappa(\epsilon)$ depends on the operational separation ϵ. The Rate Inheritance Principle isolates this step.

3 The Rate Inheritance Principle

3.1 Effective coherence-loss rate

We define the effective coherence-loss rate as an envelope over microscopic Davies rates,

$$\kappa(\epsilon) := \max_{\omega} \|\Gamma(\omega;\epsilon)\|,$$

where $\Gamma(\omega;\epsilon) = [\Gamma_{\alpha\beta}(\omega;\epsilon)]$ denotes the Hermitian Kossakowski rate matrix at Bohr frequency ω and $\|\cdot\|$ is the operator norm (equivalently, the maximal eigenvalue for Hermitian $\Gamma(\omega;\epsilon)$).

Operationally, in finite systems or simulations, $\kappa(\epsilon)$ is estimated via a decay proxy $\kappa_{\text{eff}}(\epsilon)$ extracted from coherence decay curves.

3.2 Weak form (upper-envelope)

Hypothesis 1 (Rate Inheritance Principle — weak form). Let the Davies rates be

$$\Gamma_{\alpha\beta}(\omega;\epsilon) = \int_{-\infty}^{\infty} dt\, e^{i\omega t} \langle B_\alpha(t;\epsilon)\, B_\beta(0;\epsilon)\rangle,$$

where $B_\alpha(t;\epsilon)$ denotes a bath operator entering a system–bath coupling whose support is separated from the system by at least ϵ. If

$$|\langle B_\alpha(x,t)\, B_\beta(y,0)\rangle| \leq g_{\alpha\beta}(t)\, f(\epsilon), \qquad |x-y| \geq \epsilon,$$

with $\int dt\, |g_{\alpha\beta}(t)| < \infty$, then in the Markovian regime

$$\kappa(\epsilon) \leq C\, f(\epsilon).$$

3.3 Strong form (envelope class)

Conjecture 1 (Rate Inheritance Principle — strong form). If a single decoherence channel dominates and no symmetry-induced cancellations occur,

$$\kappa(\epsilon) \asymp f(\epsilon),$$

up to polynomial prefactors.

If ϵ suppresses coupling amplitudes rather than correlators, squared envelopes $f(\epsilon)^2$ may arise.

4 Microscopic plausibility: Davies-type arguments

In the weak-coupling limit with interaction

$$H_{\text{int}} = \sum_{\alpha} S_\alpha \otimes B_\alpha(x),$$

Davies generators yield rates

$$\Gamma_{\alpha\beta}(\omega;\epsilon) = \int_{-\infty}^{\infty} dt\, e^{i\omega t} \langle B_\alpha(x,t)\, B_\beta(y,0)\rangle, \qquad |x-y| \geq \epsilon,$$

see [4, 5, 6].

For baths with mass gap $m > 0$,

$$|\langle B_\alpha(x)\, B_\beta(y)\rangle| \leq A_{\alpha\beta}\, \text{poly}(m|x-y|)\, e^{-m|x-y|}.$$

Assuming integrable time dependence, Fourier transformation preserves the exponential envelope, yielding

$$\Gamma_{\alpha\beta}(\omega;\epsilon) \le c_{\alpha\beta}(\omega)\,\mathrm{poly}(m\epsilon)\,e^{-m\epsilon}.$$

Taking the envelope implies the weak form of RIP.

Throughout, we assume that the Davies weak-coupling–secular (Markovian) approximation remains valid uniformly over the range of ϵ considered.

5 Surrogate numerical evidence

We simulate a transverse-field Ising chain in the gapped phase ($h > J$) with a buffer of length $L = \epsilon$ separating the system site from a dissipative site.

Operational coherence proxy. In the surrogate simulation coherence is measured with respect to a fixed local basis $\{j\}$. Accordingly, define

$$\Delta_{\mathrm{loc}}[\rho] := \sum_j jj\,\rho\,jj, \qquad C_{\mathrm{loc}}(\rho) := S(\rho\|\Delta_{\mathrm{loc}}[\rho]).$$

The surrogate test concerns suppression of decay rates rather than the absolute value of the coherence functional, and therefore does not rely on identifying C_{loc} with the energy-based coherence C used elsewhere.

Model parameters.

J	h	γ	N_{tot}
1.0	1.5	0.2	12

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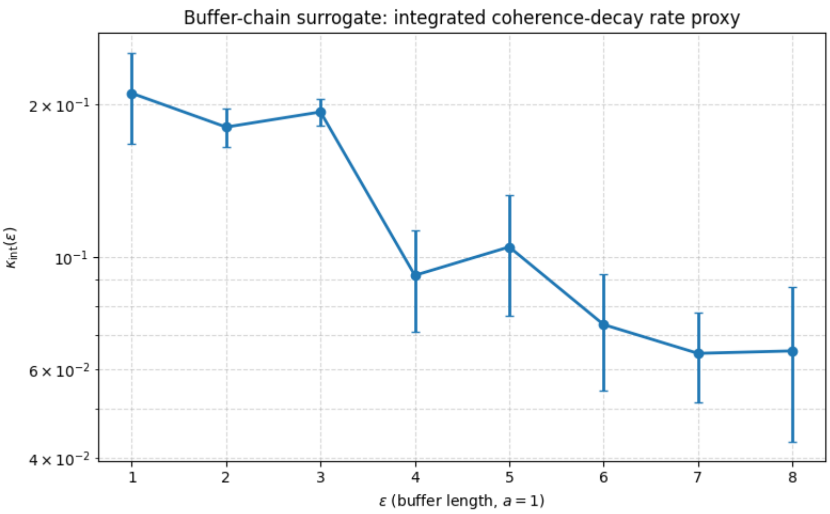

Figure 1: Surrogate buffer-chain simulation: extracted coherence-loss rate proxy $\kappa_{\mathrm{eff}}(\epsilon)$ versus separation ϵ. Error bars indicate one standard deviation over independent quantum-trajectory realizations.

The extracted proxy $\kappa_{\mathrm{eff}}(\epsilon)$ decreases monotonically with ϵ, consistent with envelope-class suppression. This evidence is surrogate and not claimed as a microscopic proof.

Table 1: Representative values of the effective coherence-loss rate proxy $\kappa_{\text{eff}}(\epsilon)$ extracted from surrogate simulations. These values are qualitative and are not claimed as microscopic rates.

ϵ	$\kappa_{\text{eff}}(\epsilon)$	Std. dev.
1	0.14	0.02
2	0.09	0.015
3	0.05	0.010
4	0.03	0.008
5	0.02	0.005

6 Failure modes

RIP is not universal. Explicit failure modes include:

- Critical baths with algebraic correlations $\langle B(x)B(y)\rangle \sim |x-y|^{-\alpha}$, yielding $\kappa(\epsilon) \sim \epsilon^{-\alpha}$.
- Non-Markovian regimes.
- Symmetry-protected or cancellation-dominated channels.
- Nonlocal couplings.

7 Operational consequences (conditional)

Assuming local rate proportionality and a maintenance inequality

$$P_{\text{extra}}(\rho) \geq k_{\text{B}}T\,\dot{C}_{\text{loss}}(\rho),$$

one obtains for any $\delta > 0$:

$$C(\rho) \leq C_0(\delta) \;\Rightarrow\; P_{\text{extra}}(\rho) \geq k_{\text{B}}T\,(\kappa(\epsilon) - \delta)\,C(\rho).$$

8 Falsification protocols

RIP is falsified if static correlations decay exponentially while no constants $A, \beta > 0$ exist such that

$$\kappa(\epsilon) \leq A\,\text{poly}(m\epsilon)\,e^{-\beta m\epsilon}$$

holds uniformly in a validated gapped Markovian regime.

9 Conclusion

The Rate Inheritance Principle isolates the missing dynamical bridge between static clustering and decoherence rates. Its weak form is microscopically plausible within Davies-type dynamics and supported by surrogate numerical evidence, while its strong form remains a falsifiable conjecture. When combined with independent maintenance-power bounds, RIP enables an operational interpretation of the quantum–classical transition as a resource boundary.

References

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