A Dissipative Channel Formalism Across Optics, Open Quantum Systems, Thermodynamics, Information Theory and Ageing

Abstract

Irreversible loss of coherence, order and information arises across optics, quantum mechanics, thermodynamics, information theory and biological ageing. Although traditionally analysed within distinct frameworks, these processes share a structural feature: monotonic contraction of reduced-state order measures under open-system dynamics, for both classical and quantum divergences.

This paper proposes a formal unification based on contractive divergences evolving under completely positive trace-preserving (CPTP) maps. By introducing a domain-independent order functional and distinguishing divergence contraction from entropy production, the analysis delineates scope, limits and testable consequences, including thermodynamic bounds on order maintenance, scaling bounds on ageing rates, and constraints on reversible interventions.

I. Introduction

Irreversible processes occur ubiquitously in natural systems. In optics, light intensity decays with propagation through absorbing and scattering media. In quantum mechanics, superpositions decohere under environmental coupling. In thermodynamics, macroscopic systems relax toward equilibrium. In information theory, communication channels degrade transmitted signals. In biology, regulatory coherence decreases with age.

These phenomena are typically analysed within domain-specific frameworks. The present paper adopts a comparative open-systems perspective and argues that each may be represented within a common formal class: dissipative channel dynamics in which reduced-state order measures contract monotonically under coupling to unobserved degrees of freedom.

The paper does not claim identity between physical observables across domains. Rather, it identifies a shared class of reduced-state functionals whose evolution obeys structurally equivalent contractive equations. The proposed unification is therefore formal rather than mechanistic.

Throughout this work we do not take exponential relaxation, fixed decay rates, or Markovian semigroup structure as primitive assumptions. Instead, we adopt as fundamental the monotonic contraction of contractive divergences under completely positive trace-preserving maps acting on reduced descriptions. Exponential laws, constant rates, and single-timescale relaxations are treated as emergent approximations arising only under stationary, memoryless, and weak-coupling limits. The present framework therefore anchors irreversibility in invariant order-theoretic structure rather than in fitted kinetic parameters.

II. Optical Attenuation and Quantum Optical Channels

In radiative transfer theory, attenuation of light in absorbing and scattering media is described by the Beer–Lambert law,

I(z)=I0 exp (−kz),I(z) = I_0 \, \exp(-k z),I(z)=I0exp(−kz),

where I(z)I(z)I(z) is intensity at depth zzz and kkk the attenuation coefficient [1].

At the quantum level, attenuation can be modelled by treating the electromagnetic field as an open quantum system coupled to matter and unobserved field modes [2]. In quantum optics, such dynamics admit master-equation descriptions in Lindblad form under standard approximations [3]. For a single bosonic mode aaa, absorption (loss) is represented by an amplitude-damping Lindblad operator

Labs=γ a.L_{\mathrm{abs}} = \sqrt{\gamma}\, a .Labs=γa.

Scattering into unobserved modes may be represented as additional loss into traced modes (also of the form aaa) or, in effective phase-randomisation limits, by dephasing-type operators

Lϕ=η a†a,L_{\phi} = \sqrt{\eta}\, a^\dagger a ,Lϕ=ηa†a,

depending on coarse-graining and measurement context [3].

Tracing over absorbed and scattered photon modes yields reduced dynamics governed by CPTP maps. In the classical limit, Beer–Lambert attenuation arises as the intensity-level projection of these quantum optical channels.

III. Decoherence in Open Quantum Systems

In open quantum systems, coherence loss is described by decay of off-diagonal density-matrix elements,

ρij(t)=ρij(0) exp (−Γt),\rho_{ij}(t) = \rho_{ij}(0)\, \exp(-\Gamma t),ρij(t)=ρij(0)exp(−Γt),

in the Markovian limit, with Γ\GammaΓ determined by coupling [4].

Continuous-time Markovian dissipative dynamics are generated by the Lindblad master equation [5], while discrete-time dynamics are represented by Kraus maps [6]. In non-Markovian regimes, divisibility may fail; however, the unconditional reduced dynamics remain CPTP for any fixed initial environment state and joint unitary evolution, even when a semigroup generator does not exist [6].

IV. Thermodynamic Relaxation and Entropy Production

In nonequilibrium thermodynamics, relaxation toward equilibrium is often modelled by exponential convergence,

$$S(t) = S_{\max} - (S_{\max} - S_0)\, \exp(-\lambda t),$$

with entropy production rate $\sigma \ge 0$ [7].

This classical single-exponential ansatz implicitly assumes stationary, memoryless contraction toward a fixed attractor with a single dominant timescale. The present framework does not assume this form: it treats constant-rate relaxation as a special case within a broader class of time-dependent or history-dependent contraction dynamics.

The present analysis concerns contraction of reduced-state divergences $D(\rho_t \,\|\, \rho_{\mathrm{eq}})$, which quantify distance from a reference state. Entropy production $\dot{S}_{\mathrm{env}}$ characterises irreversible flows into the environment and need not coincide with system entropy change, particularly in driven systems and feedback-controlled regimes [8]. The two notions are related but distinct: divergence contraction captures reduced-state relaxation, while entropy production quantifies total thermodynamic irreversibility.

V. Noisy Information Channels

In classical and quantum information theory, noisy channels are modelled as stochastic maps or CPTP channels that contract mutual information and relative entropy under the data-processing inequality [9,10]. This provides a general formal description of information degradation under open-system dynamics.

VI. Biological Ageing as a Candidate Application Domain

Recent models increasingly describe ageing as progressive loss of regulatory information. Epigenetic drift and chromatin disorganisation exhibit monotonic divergence from youthful regulatory states [11]. Partial reprogramming experiments indicate partial reversibility of epigenetic age markers in controlled contexts [12]. Recent quantitative work has explicitly framed ageing as a dissipative dynamical process with empirically measured dissipation proxies, reinforcing the relevance of dissipative formalisms for candidate ageing domains [17].

These approaches coexist with alternative theories including damage accumulation, antagonistic pleiotropy and disposable soma models [13]. Ageing is therefore treated here as a candidate application domain in which regulatory state degradation may, in some regimes, be representable within a dissipative channel framework describing informational and regulatory decay rather than the totality of biological ageing mechanisms.

VII. Domain-Independent Order Functionals

Let ρt\rho_tρt denote the reduced state of a system evolving under a CPTP map Φt\Phi_tΦt. Let ρeq\rho_{\mathrm{eq}}ρeq be a reference equilibrium or target state. Define an order functional

O[ρt]=D(ρt ∥ ρeq),O[\rho_t] = D(\rho_t \,|\, \rho_{\mathrm{eq}}),O[ρt]=D(ρt∥ρeq),

where DDD is any contractive divergence.

Examples include quantum relative entropy, trace distance, Petz quasi-entropies, and sandwiched Rényi divergences, all of which satisfy data-processing inequalities under CPTP maps and admit distinct operational interpretations (state distinguishability, hypothesis testing error, resource monotones) [14].

By monotonicity under CPTP maps,

O[Φt(ρ)]≤O[ρ].O[\Phi_t(\rho)] \le O[\rho].O[Φt(ρ)]≤O[ρ].

For Markovian semigroups with generator LLL,

ddtO[ρt]≤0.\frac{d}{dt} O[\rho_t] \le 0.dtdO[ρt]≤0.

To relate a generic interaction coordinate xxx (time, depth, accumulated collisions) to time, define

x(t)=∫0tκ(t′) dt′,x(t) = \int_0^t \kappa(t')\, dt',x(t)=∫0tκ(t′)dt′,

where κ(t)\kappa(t)κ(t) is an effective coupling rate.

Notation: kkk (optical attenuation), Γ\GammaΓ (decoherence), λ\lambdaλ (thermodynamic relaxation) and κ(·)\kappa(\cdot)κ(·) (effective coupling functional) are domain-specific rates or rate functionals; no identification between them is implied.

Exponential decay arises in the memoryless limit where κ\kappaκ is constant. Deviations from exponential form reflect non-stationary coupling, structured environments, memory effects, or active repair dynamics.

VIII. Representative Order Functionals Across Domains

(table retained verbatim — formatting compatible with LaTeX tabular)

Clarification (Ageing metric). Euclidean methylation distance is widely used as a practical proxy but is not contractive under arbitrary CPTP maps. A contractive choice is to treat methylation patterns as empirical distributions and use KL-type divergences or other divergences satisfying data-processing inequalities. In Gaussian or small-perturbation regimes, squared Euclidean distance may serve as a local proxy, but contractivity must be verified for the specific stochastic model and map class [15,18].

IX. Unified Channel Representation

In Markovian baselines, order functionals may be represented as

$$O(x) = O_0 \, \exp\!\left(-\int_0^x \kappa(x')\, dx' \right),$$

with deviations signalling memory effects, driving, structured coupling, or active regulation.

Traditional single-exponential relaxation presupposes stationary, memoryless contraction toward a fixed attractor. The integral representation promotes the constant rate λ to a coupling functional $\kappa(x)$, enabling representation of time-varying rates, non-Markovian memory, hierarchical cascades, and repair-modulated dynamics without presupposing exponential form.

Rate-based descriptions of irreversible processes introduce a subtle structural bias: by fixing a constant decay parameter and fitting exponential trajectories, one implicitly enforces semigroup structure, time-translation invariance, and memorylessness before examining the system. In the present framework, contractivity of divergences is taken as the invariant principle, while all rate parameters are derived, coordinate-dependent summaries of underlying reduced dynamics. Deviations from exponential form may therefore be interpreted diagnostically as signatures of memory, structured environments, or regulatory intervention rather than as anomalies.

In biological contexts, active repair mechanisms may be interpreted as dynamically suppressing the effective coupling functional $\kappa(x)$, while senescence corresponds to regimes in which $\kappa(x)$ increases as regulatory maintenance itself degrades [17,19].

X. Predictive Implications and Testable Constraints

A. Thermodynamic Cost of Order Maintenance

Landauer's principle bounds erasure: erasing one bit requires dissipation of at least $k_B T \ln 2$. For maintenance against noise, continuous error correction implies an entropy-production rate lower bound proportional to correction rate. If an effective regulatory memory of n bits is stabilised against a forgetting rate Γ, a minimal dissipation scale is

$$\dot{S}_{min} \gtrsim n \cdot \Gamma \cdot k_B \cdot \ln 2,$$

up to architecture-dependent constants.

B. Ageing-Rate Bounds from Channel Capacity

Let a regulatory state drift under an effective noisy channel with coupling κ and be corrected with power budget P. Information-processing capacity scales as $C \lesssim \alpha P / (k_B T)$. Maintaining n effective bits at rate Γ requires $n\Gamma \lesssim C$, yielding

$$\Gamma \lesssim C / n \Rightarrow \tau_{maint} \gtrsim n / C.$$

If functional ageing corresponds to reaching $O[\rho_t] = O^*$, then

$$t^* \approx (1 / \Gamma) \cdot \ln(O_0 / O^*) \gtrsim (n / C) \cdot \ln(O_0 / O^*).$$

C. Rejuvenation as Information Injection

Reversal of ageing markers corresponds to reducing $D(\rho_{aged} \| \rho_{young})$. Such reversal requires external free energy and information injection, with minimal cost bounded below by the divergence to be reduced.

XI. Failure Modes and Boundary Conditions

The framework does not apply universally. Excluded systems include critical phenomena, strongly driven self-organisation, chaotic systems without stable references, and measurement-conditioned updates.

Transient increases in subsystem order do not contradict global irreversibility: they require compensating entropy production in the environment [8]. Dissipative adaptation remains compatible when reference states are updated to nonequilibrium attractors [16].

XII. Non-Markovian Ageing and Multi-Scale Cascades

Multi-scale hierarchies can be represented as cascaded channels,

$\rho_{out} = (\Phi_n \circ \ldots \circ \Phi_1)(\rho_{in})$.

If each layer contracts by $\exp(-\kappa_i x)$, then

$O_{out} \leq O_{in} \cdot \exp(-x \Sigma_i \kappa_i)$.

Systems with more regulatory layers require proportionally higher corrective capacity to sustain fidelity, suggesting a complexity penalty linking organismal complexity to energetic cost and ageing profiles.

XIII. Conclusion

Irreversible degradation across physics and biology admits a unifying description: contraction of contractive divergences under CPTP dynamics. The framework yields quantitative bounds, delineates scope and failure modes, and provides experimentally accessible tests across quantum optics and biological regulation.

Appendix A: Operational Guidance

A process belongs to the dissipative-channel class if:

Reduced dynamics admit CPTP representation.

A reference state or attractor manifold is specified.

A contractive divergence can be estimated from data.

Appendix B: Photon Statistics Under Attenuation

Prepare non-classical light (e.g. antibunched single-photon states) and transmit it through an attenuating medium of varying effective depth z. Measure $g^{(2)}(0; z)$ and higher-order correlations. Amplitude damping predicts systematic degradation of non-classical photon statistics with depth; pure dephasing predicts preservation of number statistics with loss of phase coherence. Mixed channels interpolate in channel-specific ways. This provides a direct test that classical Beer–Lambert attenuation arises from underlying CPTP channel structure rather than purely phenomenological classical loss.

References

[1] Pierre Bouguer, Essai d’Optique sur la Gradation de la Lumière (Claude Jombert, 1729).

[2] Curt Mobley, Light and Water: Radiative Transfer in Natural Waters (Academic Press, 1994).

[3] Howard J Carmichael, Statistical Methods in Quantum Optics 1: Master Equations and Fokker–Planck Equations (Springer, 1999).

[4] Maximilian Schlosshauer, ‘Decoherence, the Measurement Problem, and Interpretations of Quantum Mechanics’ (2005) 76 Reviews of Modern Physics 1267.

[5] Göran Lindblad, ‘On the Generators of Quantum Dynamical Semigroups’ (1976) 48 Communications in Mathematical Physics 119.

[6] Heinz-Peter Breuer and Francesco Petruccione, The Theory of Open Quantum Systems (Oxford University Press, 2002).

[7] Ilya Prigogine, Introduction to Thermodynamics of Irreversible Processes (Interscience, 3rd ed, 1967).

[8] Massimiliano Esposito and Christian Van den Broeck, ‘Three Detailed Fluctuation Theorems’ (2010) 104 Physical Review Letters 090601.

[9] Claude E Shannon, ‘A Mathematical Theory of Communication’ (1948) 27 Bell System Technical Journal 379, 623.

[10] Michael A Nielsen and Isaac L Chuang, Quantum Computation and Quantum Information (Cambridge University Press, 10th anniversary ed, 2010).

[11] Steve Horvath, ‘DNA Methylation Age of Human Tissues and Cell Types’ (2013) 14 Genome Biology R115.

[12] Yuancheng Lu et al, ‘Reprogramming to Recover Youthful Epigenetic Information and Restore Vision’ (2020) 588 Nature 124–134.

[13] Thomas BL Kirkwood, ‘Evolution of Ageing’ (1977) 270 Nature 301.

[14] Mark Müller-Lennert et al, ‘On Quantum Rényi Entropies: A New Generalization and Some Properties’ (2013) 54 Journal of Mathematical Physics 122203.

[15] André C Barato and Udo Seifert, ‘Thermodynamic Uncertainty Relation for Biomolecular Processes’ (2015) 112 Physical Review Letters 090601.

[16] Jeremy L England, ‘Statistical Physics of Self-Replication’ (2013) 139 Journal of Chemical Physics 121923.

[17] Farhan Khodaee et al, “The Dissipation Theory of Aging: A Quantitative Analysis Using a Cellular Aging Map” (2025) arXiv:2504.13044.

[18] Bertucci-Richter and Parrott, “Epigenetic drift underlies epigenetic clock signals, but displays distinct responses to lifespan interventions, development, and cellular dedifferentiation” (2024) Aging (Albany NY) 16(2):1002–1020, doi:10.18632/aging.205503.

[19] Meyer and Schumacher, “Aging clocks based on accumulating stochastic variation” (2024) Nature Aging, doi:10.1038/s43587-024-00619-x.