Phase–Echo Theory: Action Histories, Coarse–Grained Observers, and the Operational Disappearance of the Past

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Abstract

Microscopic physical laws are typically reversible, yet actions and events appear irreversible at macroscopic scales. We present *Phase–Echo Theory (PET)*, a framework that shifts the focus from state evolution to the recoverability of action histories by observers embedded in the physical system. Actions are modeled as physical interventions within reversible dynamics, while observers are characterized by coarse–graining maps representing limited access to degrees of freedom. We define the *echo* of an action as the information about that action recoverable from observer–accessible data and show that apparent irreversibility corresponds to the collapse of distinguishability between action histories under coarse–graining, not to destruction of information. We formalize operational reality as an equivalence class of global states, introduce quantitative measures of recoverability and action significance, and provide explicit quantum and classical models demonstrating generic echo collapse. The theory explains the emergence of time's arrow and the finality of past actions without invoking fundamental irreversibility or modifying microscopic dynamics.

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1 Introduction

Fundamental physical laws governing microscopic dynamics are largely reversible. Classical Hamiltonian systems preserve phase–space volume, and closed quantum systems evolve unitarily. Despite this reversibility, macroscopic experience is characterized by irreversibility: once an action has occurred, its alternatives appear inaccessible, and the past seems fixed and unrecoverable.

Traditional approaches explain this discrepancy through coarse–graining, typicality, and environmental decoherence. These frameworks emphasize that information is not destroyed but becomes distributed into degrees of freedom inaccessible to realistic observers. However, most treatments focus on the evolution of states rather than on the recoverability of *action histories*—the question of whether an observer can, even in principle, determine which past actions occurred.

Phase–Echo Theory (PET) addresses this gap by treating irreversibility as an operational phenomenon: a consequence of restricted access rather than fundamental non–invertibility. In PET, actions persist as correlations in the global physical state, while observers experience irreversibility when those correlations no longer influence their accessible degrees of freedom.

The goal of this paper is to formalize this perspective in a conservative, mathematically precise way, without introducing new physical postulates or speculative mechanisms.

2 Global dynamics and actions

2.1 Global state

Let $\mathcal{H}$ be the Hilbert space of a closed physical system, and let

$$\rho(t) \in \mathcal{D}(\mathcal{H})$$

denote the global density operator at time t.

2.2 Reversible microscopic evolution

We assume reversible microscopic dynamics:

$$\rho(t) = U(t)\rho(0)U(t)^\dagger, \qquad U(t) = e^{-iHt}, \tag{1}$$

where H is the system Hamiltonian. Open systems may be treated by embedding them in a larger closed system.

2.3 Actions

Definition 1 (Action)**.** *An* action *a is a physically implementable intervention represented by a unitary operator V_a acting on a controllable subsystem. The state immediately after the action is*

$$\rho \mapsto \rho_a := V_a \rho V_a^\dagger.$$

At the microscopic level, $V_a^\dagger$ exists, so actions are invertible in principle.

3 Embedded observers and coarse–graining

Definition 2 (Observer access map)**.** *An observer O is characterized by a completely positive trace–preserving (CPTP) map*

$$\Gamma_O : \mathcal{D}(\mathcal{H}) \to \mathcal{D}(\mathcal{H}_O),$$

which extracts the observer–accessible state $\bar{\rho}_O = \Gamma_O(\rho)$. A canonical example is partial trace over inaccessible degrees of freedom.

The observer is a physical subsystem of the global system; no external vantage point is assumed.

4 Operational reality and equivalence classes

Definition 3 (Operational equivalence)**.** *Define an equivalence relation $\sim_O$ on $\mathcal{D}(\mathcal{H})$ by*

$$\rho \sim_O \sigma \quad \iff \quad \Gamma_O(\rho) = \Gamma_O(\sigma).$$

Definition 4 (Operational reality)**.** *The operational reality experienced by observer O at time t is the equivalence class*

$$[\rho(t)]_{\sim_O} := \{\sigma \in \mathcal{D}(\mathcal{H}) : \Gamma_O(\sigma) = \Gamma_O(\rho(t))\}.$$

Proposition 1 (Indistinguishability)**.** *If $\rho \sim_O \sigma$, then no measurement accessible to observer O can distinguish ρ from σ.*

Proof. All measurement statistics available to O are computed from $\Gamma_O(\rho)$; hence identical outputs imply identical statistics. □

5 Echo and recoverability of actions

Let A be a random variable labeling which action $a \in \mathcal{A}$ occurred at time t_0.

Definition 5 (Echo strength)**.** *Let Z denote classical data obtained by measurements on $\Gamma_O(\rho_A(t))$. The echo strength at time t is*

$$\mathsf{Echo}_O(t) := I(A; Z),$$

the mutual information between action label and accessible data.

Definition 6 (Echo capacity)**.** *Define the echo capacity as*

$$C_{\text{echo}}(O, t; \mathcal{A}) := \sup I(A; Z),$$

where the supremum ranges over all measurements and estimators accessible to observer O.

Proposition 2 (Data–processing bound)**.** *For any observer O and any measurement pipeline,*

$$I(A; Z) \le I(A; \Gamma_O(\rho_A(t))).$$

6 Action significance: nodes and antinodes

Definition 7 (Distinguishability functional). *Let h, h' be histories differing only by an action at time t_0. Define*

$$\Delta_O(t; t_0) := \|\Gamma_O(\rho_h(t)) - \Gamma_O(\rho_{h'}(t))\|_1 .$$

Definition 8 (Node index). *For a window $W > 0$, define*

$$\mathcal{N}_O(t_0; W) := \int_{t_0}^{t_0+W} \Delta_O(t; t_0)\, dt.$$

Large $\mathcal{N}_O$ indicates actions whose effects remain operationally distinguishable; small $\mathcal{N}_O$ indicates rapid wash–out.

7 Persistence without accessibility

Theorem 1 (Persistence of action information). *Let a be an action performed at time t_0. Under reversible dynamics, information about a remains encoded in the global state $\rho(t)$ for all $t > t_0$.*

Proof. Reversible evolution preserves the full state history as correlations within $\rho(t)$. □

Theorem 2 (Operational loss of the past). *For any embedded observer O with restricted access Γ_O, there exists $t_* > t_0$ such that*

$$\Gamma_O(\rho_h(t)) = \Gamma_O(\rho_{h'}(t)) \quad \forall t > t_*,$$

for histories h, h' differing only by the action at t_0, under generic entangling or chaotic dynamics.

8 Quantum example: qubit plus bath

Let $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_E$ with $\mathcal{H}_S \cong \mathbb{C}^2$ and $\mathcal{H}_E \cong (\mathbb{C}^2)^{\otimes N}$. Take initial state $\rho_0 = |+\rangle\langle+| \otimes |0\rangle\langle 0|^{\otimes N}$. Let $V_0 = \mathbb{I}$ and $V_1 = Z_S$. Let $H = \sum_{k=1}^{N} g_k Z_S \otimes Z_k$.

With $\Gamma(\rho) = \mathrm{Tr}_E(\rho)$, the reduced states satisfy

$$\bar{\rho}^{(A)}(t) = \begin{pmatrix} \frac{1}{2} & \frac{1}{2}\gamma(t)(-1)^A \\ \frac{1}{2}\gamma(t)(-1)^A & \frac{1}{2} \end{pmatrix},$$

where $\gamma(t) \to 0$ under generic coupling. Thus global action information persists, while local distinguishability vanishes.

9 Classical example: chaotic dynamics

Let (Ω, μ) be phase space with measure–preserving dynamics F_t. Let Γ be a coarse–graining defined by a finite partition $\{C_i\}$. For two histories differing by a small perturbation at time t_0, chaotic dynamics with Lyapunov exponent $\lambda > 0$ amplify microscopic differences while coarse–graining causes rapid convergence of macroscopic distributions, eliminating operational distinguishability.

10 Discussion

PET explains irreversibility without invoking fundamental information loss. The past persists globally but becomes operationally inaccessible. The theory does not claim retrocausality, time loops, or predictive oracles; such extensions would require additional axioms beyond PET.

11 Conclusion

Phase–Echo Theory provides a mathematically precise account of why actions feel final and time appears to flow forward, despite reversible microscopic laws. Irreversibility emerges from the collapse of distinguishability under restricted access, not from destruction of information. This framework clarifies the relationship between dynamics, memory, and agency, and provides a foundation for future work on observer–relative time and information accessibility.

Related Work (Contextual)

This work is related in spirit to studies of decoherence, coarse-graining, and information-theoretic approaches to irreversibility. However, Phase–Echo Theory focuses specifically on the recoverability of action histories by embedded observers, rather than on state evolution alone. The present paper is intended as a self-contained foundational framework.