A Timeless Universe

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Abstract

Time is conventionally treated as a fundamental parameter of physical reality. We propose an alternative axiomatic framework in which the universe is postulated as a closed, maximally entangled quantum many-body system with no fundamental notion of time. In this framework, observers are finite quantum subsystems with limited information-processing capacity, preventing access to the complete universal state. We argue that the perceived flow of time emerges from observer-dependent reconstruction of incomplete information rather than from an intrinsic temporal dimension. This perspective establishes a timeless information-theoretic description of the universe and provides a mathematical foundation for investigating the emergence of temporal order, observation, and classical reality within a unified quantum framework.

Keywords: Timeless universe, Emergent time, Quantum many body systems, Quantum information theory

1 Introduction

Time occupies a central position in modern physics. In classical mechanics, it serves as an independent parameter governing the evolution of physical systems, while in quantum mechanics it appears as an external parameter in the Schrödinger equation rather than as a quantum observable. General relativity further intertwines time with space through the geometry of spacetime, allowing its flow to depend on gravitational fields and relative motion. Despite these successful descriptions, the fundamental nature of time remains unresolved, particularly in attempts to reconcile quantum mechanics with general relativity. The incompatibility between the fixed temporal background of quantum theory and the dynamical spacetime of gravitation has motivated extensive investigations into whether time is truly fundamental or instead emerges from deeper physical principles.

Several approaches have explored the possibility that time is not a primitive concept [1]. The Wheeler–DeWitt equation [2] eliminates explicit temporal evolution from canonical quantum gravity, leading to the so-called "problem of time." [3] Relational formulations [4, 5] propose that temporal evolution is meaningful only through correlations between physical systems rather than with respect to an external clock. The Page–Wootters mechanism [6] demonstrates that an observer can recover an effective notion of time by conditioning on an internal quantum clock, while thermal and information-theoretic approaches [7, 8] relate the arrow of time to entropy production, coarse graining, and irreversible information loss. Although these frameworks differ substantially in their mathematical formulation, they collectively suggest that the observed flow of time may arise from properties of observers or correlations within the universe rather than from a fundamental temporal dimension.

Quantum information theory [9] has further strengthened this perspective by emphasizing information as a fundamental physical resource. Entanglement has emerged as a central concept connecting quantum computation, condensed matter physics, quantum gravity, and holography [10]. Recent developments indicate that quantum correlations may underlie the emergence of geometric and spacetime structures [11], motivating the broader question of whether temporal order itself could also originate from information-theoretic principles. Existing proposals, however, generally retain an underlying ordering parameter, employ an explicit internal clock, or assume a dynamical process from which effective time is reconstructed.

In this work, we propose an alternative axiomatic framework in which the universe is described as a closed quantum many-body system possessing no fundamental temporal parameter. Rather than treating time as an intrinsic property of reality, we postulate that temporal order emerges from the finite information-processing capabilities of observers embedded within the universal quantum state. Observers are modeled as subsystems with limited access to the complete information encoded in the universe. Because no observer can reconstruct the global quantum state exactly, physical reality is perceived through coarse-grained information that groups microscopically distinct configurations into indistinguishable observational classes. Within this framework, the apparent flow of time is interpreted as the sequential reconstruction of information by finite observers rather than as evolution with respect to an objective universal clock.

The proposed framework differs from conventional emergent-time models by removing the assumption of an underlying temporal ordering at the fundamental level. Instead, temporal structure is regarded as an observer-dependent consequence of finite information resolution. Consequently, the universe is fundamentally timeless, while causality, temporal succession, and classical experience arise as emergent phenomena associated with incomplete access to the universal quantum state. This perspective shifts the role of time from a basic physical entity to a derived informational construct.

The principal contribution of this work is the formulation of a mathematically consistent axiomatic framework in which temporal order emerges from finite observer-dependent informational reconstruction. Unlike existing timeless approaches based on relational clocks, the proposed formulation introduces the Temporal Information Functional as the fundamental quantity governing emergent temporal experience.

2 Foundational Postulates

The proposed framework is developed from a set of fundamental postulates that describe the universe independently of any predefined notion of time. These postulates are not derived from existing physical theories but are assumed as the foundational principles upon which the subsequent mathematical framework is constructed.

Postulate 1 (Timeless Universe) *The universe is assumed to exist as a single closed physical system with no fundamental temporal parameter. Consequently, there is no universal clock, external time coordinate, or intrinsic ordering of physical configurations. The complete description of reality is therefore represented by a timeless quantum state*

$$|\Psi_U\rangle \in \mathcal{H}_U$$

where $\mathcal{H}_U$ denotes the Hilbert space of the entire universe. Since the universe is closed, no external observer or external reference frame exists.

Postulate 2 (Universal Quantum State) *The universal state is postulated to be a pure many-body quantum state*

$$|\Psi_U\rangle = \sum_i c_i |i\rangle$$

where $\{|i\rangle\}$ forms an orthonormal basis of $\mathcal{H}_U$ and $\sum_i |c_i|^2 = 1$. The universal state completely specifies all physical information contained within the universe. No information exists outside this state.

Postulate 3 (Observer as a Quantum Subsystem) *An observer is not external to the universe but is itself a finite quantum subsystem defined as*

$$\mathcal{H}_U = \mathcal{H}_O \otimes \mathcal{H}_E$$

where $\mathcal{H}_O$ represents the observer and $\mathcal{H}_E$ denotes the remainder of the universe. The observer has access only to information contained within $\mathcal{H}_O$ together with interactions between $\mathcal{H}_O$ and $\mathcal{H}_E$. Consequently, no observer can directly reconstruct the complete universal state $|\Psi_U\rangle$.

Postulate 4 (Finite Information Processing) *Every observer possesses finite information-processing capacity. Let $\mathcal{I}_O \subset \mathcal{I}_U$ denote the information accessible to the observer, where $\mathcal{I}_U$ represents the complete information contained in the universal state. Since $\mathcal{I}_O \neq \mathcal{I}_U$, the observer necessarily reconstructs only an approximation of physical reality. Multiple microscopic configurations of the universal state may therefore become indistinguishable from the observer's perspective.*

Postulate 5 (Emergence of Temporal Order) *Temporal order is not a fundamental property of the universe. Instead, it arises from the observer's reconstruction of incomplete information. Let $\mathcal{R} : |\Psi_U\rangle \longrightarrow \mathcal{S}_O$ denote the observer-dependent reconstruction map, where $\mathcal{S}_O$ represents the observer's perceived reality.*

The sequence perceived by the observer is therefore generated by repeated applications of $\mathcal{R}$ rather than by evolution with respect to an objective temporal parameter. Consequently, the apparent flow of time is an emergent informational phenomenon associated with finite observation.

These postulates establish a framework in which the universe is fundamentally timeless while observers experience an ordered reality through incomplete access to the universal quantum state. The subsequent sections develop the mathematical structures required to formalize the reconstruction map, characterize observer-dependent distinguishability, and derive the emergence of temporal order from finite information processing.

3 Mathematical Framework

The postulates introduced in the previous section establish a timeless ontology for the universe. This section formalizes the mathematical structures required to describe finite observers, accessible information, and the reconstruction of physical reality. Throughout this work, no temporal parameter is assumed. All mathematical objects are therefore defined on the universal quantum state itself.

Let the universe be represented by a finite-dimensional Hilbert space

$$\mathcal{H}_U = \bigotimes_{i=1}^{N} \mathcal{H}_i,$$

where $\mathcal{H}_i$ denotes the Hilbert space associated with the i-th elementary subsystem and N is the total number of subsystems. The universal quantum state is given by

$$|\Psi_U\rangle \in \mathcal{H}_U, \qquad \langle \Psi_U | \Psi_U \rangle = 1.$$

Since the universe is assumed to be closed, no external Hilbert space exists. An observer is modeled as a finite subsystem occupying a proper subspace

$$\mathcal{H}_O = \bigotimes_{i \in O} \mathcal{H}_i,$$

where $O \subset \{1, \ldots, N\}$. The remaining degrees of freedom constitute the observer's environment

$$\mathcal{H}_E = \bigotimes_{i \notin O} \mathcal{H}_i,$$

such that $\mathcal{H}_U = \mathcal{H}_O \otimes \mathcal{H}_E$. The observer is therefore embedded within the universe rather than external to it. The observer cannot directly access the universal state. Instead, its physical description is completely determined by the reduced density operator [9, 12]

$$\rho_O = \mathrm{Tr}_E \left(|\Psi_U\rangle\langle\Psi_U| \right),$$

obtained by tracing over all inaccessible degrees of freedom. The observer's accessible information is quantified by the von Neumann entropy [12]

$$S(\rho_O) = -\mathrm{Tr}(\rho_O \log \rho_O),$$

which characterizes the uncertainty resulting from entanglement with the remainder of the universe. Since only ρ_O is observable, the observer reconstructs reality through a mapping

$$\mathcal{R} : \rho_O \to \Omega_O,$$

where Ω_O denotes the observer's perceived description of reality. The map $\mathcal{R}$ represents all physical processes involved in measurement, information processing, memory formation, and inference. Consequently, Ω_O is generally an approximation of the universal quantum state. The observer possesses finite resolution and cannot distinguish arbitrarily similar physical descriptions. Let $D(\rho_1, \rho_2)$ be a distinguishability measure between two reduced density operators. Examples include the trace distance or the Bures distance [9]. For a finite resolution threshold $\varepsilon > 0$, two observer states are considered indistinguishable whenever $D(\rho_1, \rho_2) < \varepsilon$. This induces an equivalence relation

$$\rho_1 \sim \rho_2 \iff D(\rho_1, \rho_2) < \varepsilon,$$

partitioning the observer's state space into equivalence classes. Each equivalence class corresponds to a single perceived physical configuration despite containing multiple microscopic quantum states. The observer therefore perceives not individual quantum states but the quotient space

$$\mathcal{Q} = \mathcal{H}_O / \sim,$$

whose elements are equivalence classes determined by finite distinguishability.

Within the proposed framework, the emergence of temporal order is attributed to transitions between these perceived configurations rather than to evolution with respect to an external temporal parameter. The formal construction of observer-dependent temporal order is developed in the following section.

4 Emergence of Temporal Order

The preceding sections established a timeless description of the universe and introduced finite observers as subsystems with limited information-processing capabilities. We now formalize the emergence of temporal order without assuming an underlying temporal parameter or an objective sequence of universal states.

An observer does not perceive the universal quantum state directly. Instead, its knowledge is represented by an internal informational state, $\omega \in \Omega$, where Ω denotes the observer's information space. The state ω is obtained through the reconstruction [5] map

$$\mathcal{R} : \rho_O \to \omega,$$

where ρ_O is the reduced density operator of the observer subsystem. At any instant of perception, the observer possesses only a single informational state ω. No global ordering of such states is assumed.

Suppose the observer reconstructs another informational state ω', from newly accessible information. To compare the two informational descriptions, we define a distinguishability measure $D(\omega, \omega')$, where D satisfies

$$D(\omega, \omega) = 0, \tag{1}$$

$$D(\omega, \omega') \geq 0, \tag{2}$$

$$D(\omega, \omega') = D(\omega', \omega). \tag{3}$$

The observer possesses a finite resolution threshold $\varepsilon > 0$. Whenever

$$D(\omega, \omega') < \varepsilon,$$

the two informational descriptions are operationally indistinguishable and are therefore identified as representing the same perceived reality. Conversely,

$$D(\omega, \omega') \geq \varepsilon$$

indicates that the observer can distinguish the two informational descriptions.

The observer updates its internal representation only when distinguishable information becomes available.

Definition 1 (Observer Update) *An observer update is the mapping $\omega \longrightarrow \omega'$, such that*

$$D(\omega, \omega') \geq \varepsilon.$$

No update occurs whenever the distinguishability remains below the observer's resolution threshold ε. Consequently, observer updates are entirely determined by accessible information and not by an external temporal parameter.

Temporal order is now defined as an ordering of observer updates rather than an ordering of universal states.

Definition 2 (Emergent Temporal Order) *Let $\mathcal{U} = \{\omega_1 \to \omega_2, \omega_2 \to \omega_3, \ldots\}$ denote the collection of observer updates satisfying the distinguishability criterion. The observer-dependent temporal structure is defined by*

$$\mathcal{T}_O = (\Omega, \mathcal{U}),$$

where each element of $\mathcal{U}$ represents a distinguishable informational update.

Thus, temporal order is a property of the observer's reconstruction process and not of the universal quantum state.

Theorem 1 (Observer Dependence of Temporal Order) *Suppose the universe satisfies the postulates introduced in Section II. Then every temporal ordering perceived by an observer is observer dependent.*

Proof By Postulate 1, the universal quantum state contains no fundamental temporal parameter and by Postulate 3, every observer has access only to its reduced density operator,

$$\rho_O = \mathrm{Tr}_E \left(|\Psi_U\rangle\langle\Psi_U| \right).$$

The observer reconstructs an informational state $\omega = \mathcal{R}(\rho_O)$, and modifies this description only when another informational state ω' satisfies

$$D(\omega, \omega') \geq \varepsilon.$$

Therefore, the ordering of observer updates depends entirely upon the observer's finite information-processing capability. Since no ordering exists within the universal quantum state itself, temporal order cannot be regarded as a fundamental property of the universe. □

The proposed framework distinguishes the timeless ontology of the universe from the temporal experience of observers. The universal quantum state exists independently of temporal order, while finite observers construct an ordered description of reality through distinguishable informational updates. Consequently, time is interpreted as an emergent property of information processing rather than a fundamental dimension of the universe.

5 Temporal Information Functional

The previous sections established that temporal order does not exist as a fundamental property of the universe but emerges through observer-dependent informational updates. Rather than introducing time as a primitive quantity, we define a new functional that quantifies the cumulative distinguishable information reconstructed by a finite observer. Conventional time is subsequently interpreted as an emergent approximation of this functional.

Let $\omega_i, \omega_j \in \Omega$ be two informational states reconstructed by an observer. The distinguishable information gained during an observer update is measured by

$$\Delta I(\omega_i, \omega_j) = D(\omega_i, \omega_j),$$

where $D(\cdot, \cdot)$ denotes the distinguishability measure introduced previously. An informational update is registered only if

$$\Delta I(\omega_i, \omega_j) \geq \varepsilon,$$

where $\varepsilon > 0$ is the observer's finite information resolution. The observer's accumulated distinguishable information is represented by a non-negative information measure [7]

$$I : \Omega \to \mathbb{R}^+,$$

defined on the reconstruction space Ω. Assuming that I is absolutely continuous with respect to the natural measure μ on Ω, the *distinguishable information density* [13] is defined by

$$\rho_I(\omega) = \frac{dI}{d\mu}(\omega),$$

where $\rho_I(\omega) \geq 0$.

Let Γ denote the observer's reconstruction trajectory in the information space Ω. Define $\rho_I : \Omega \to \mathbb{R}^+$ to be the distinguishable information density perceived by the observer. The Temporal Information Functional is defined by

$$\Theta(\Gamma) = \int_\Gamma \rho_I(\omega)\, d\mu(\omega),$$

where $d\mu$ denotes the natural measure on the observer's reconstruction space. The functional Θ represents the cumulative distinguishable information reconstructed by the observer. Unlike conventional time, Θ is not an external evolution parameter but an intrinsic property of the observer's informational reconstruction.

The Temporal Information Functional satisfies following fundamental mathematical properties:

1. **Non-negativity** Since the distinguishable information density is non-negative,

   $$\rho_I(\omega) \geq 0,$$

   it follows immediately that

   $$\Theta(\Gamma) = \int_\Gamma \rho_I(\omega)\, d\mu(\omega) \geq 0.$$

2. **Null Reconstruction** If $\rho_I(\omega) = 0$ almost everywhere on Γ, then $\Theta(\Gamma) = 0$. Hence, an observer that reconstructs no distinguishable information accumulates no temporal information.
3. **Monotonicity** Let $\Gamma \subseteq \Gamma'$ denote two reconstruction trajectories, where Γ' extends Γ by additional distinguishable informational configurations. Then

   $$\Theta(\Gamma') = \Theta(\Gamma) + \int_{\Gamma' \setminus \Gamma} \rho_I(\omega)\, d\mu(\omega).$$

   Since $\rho_I(\omega) \geq 0$, we obtain $\Theta(\Gamma') \geq \Theta(\Gamma)$. Therefore, the Temporal Information Functional is monotonic with respect to distinguishable informational reconstruction.

Different observers generally reconstruct different informational states from the same universal quantum state. Let Θ_A and Θ_B denote the Temporal Information Functionals corresponding to observers A and B. Since $\mathcal{R}_A \neq \mathcal{R}_B$ in general,

$$\Theta_A \neq \Theta_B.$$

Therefore, temporal information is fundamentally observer dependent.

Theorem 2 (Observer Invariance) *Let $T : \Omega \to \Omega$ be a transformation of the observer's reconstruction space that preserves the distinguishable information density, i.e.,*

$$\rho_I(T(\omega)) = \rho_I(\omega),$$

and preserves the measure $d\mu$. Then the Temporal Information Functional is invariant under T: $\Theta(T(\Gamma)) = \Theta(\Gamma)$.

Proof The Temporal Information Functional is defined as

$$\Theta(\Gamma) = \int_\Gamma \rho_I(\omega)\, d\mu(\omega).$$

Applying the transformation T yields

$$\Theta(T(\Gamma)) = \int_{T(\Gamma)} \rho_I(\omega)\, d\mu(\omega).$$

Since T preserves both the distinguishable information density and the measure,

$$\rho_I(T(\omega)) = \rho_I(\omega), \qquad d\mu(T(\omega)) = d\mu(\omega),$$

it follows that

$$\int_{T(\Gamma)} \rho_I(\omega)\, d\mu(\omega) = \int_\Gamma \rho_I(\omega)\, d\mu(\omega).$$

Therefore, $\Theta(T(\Gamma)) = \Theta(\Gamma)$. □

Emergence of Physical Time

The quantity Θ is proposed as the fundamental observable of temporal experience. Conventional physical time is interpreted as an emergent macroscopic approximation obtained from Θ under suitable coarse-graining conditions, $t \approx \alpha\Theta$, where α is an observer-dependent calibration constant relating accumulated distinguishable information to measured clock time.

Accordingly, clocks do not measure a fundamental temporal dimension; rather, they measure physical processes whose accumulated informational reconstruction is proportional to Θ.

6 Illustrative Example

To illustrate the proposed framework, we consider a simple two-qubit system prepared in the Bell state [9]

$$|\Psi_U\rangle = \frac{1}{\sqrt{2}} \left(|00\rangle + |11\rangle\right).$$

Suppose the first qubit represents the observer subsystem $\mathcal{H}_O$ and the second qubit represents the environment $\mathcal{H}_E$. The observer therefore has access only to the reduced density operator [9, 12]

$$\rho_O = \mathrm{Tr}_E \left(|\Psi_U\rangle \langle\Psi_U|\right) = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

Although the universal quantum state is pure, the observer reconstructs only the maximally mixed state because information about the environment is inaccessible.

Assume that, following additional interactions with the environment, the observer reconstructs another informational state

$$\rho'_O = \begin{pmatrix} 0.7 & 0 \\ 0 & 0.3 \end{pmatrix}.$$

The distinguishability between the two reconstructed states is quantified using the trace distance

$$D(\rho_O, \rho'_O) = \frac{1}{2} \|\rho_O - \rho'_O\|_1 .$$

Substituting the above matrices yields

$$D(\rho_O, \rho'_O) = 0.2.$$

Let the observer possess a distinguishability threshold $\varepsilon = 0.1$. Since $D(\rho_O, \rho'_O) = 0.2 > \varepsilon$, the observer registers an informational update according to Definition 1. For this single update, the distinguishable information accumulated by the observer is $\Delta I = D(\rho_O, \rho'_O) = 0.2$.

Consequently, the Temporal Information Functional associated with this reconstruction trajectory is

$$\Theta(\Gamma) = \int_\Gamma \rho_I(\omega)\, d\mu(\omega) = 0.2,$$

where the integral reduces to the accumulated distinguishable information corresponding to a single observer update.

This example illustrates the central principle of the proposed framework. Although the global Bell state $|\Psi_U\rangle$ is fundamentally timeless, the observer reconstructs only reduced informational states and registers updates whenever distinguishable information exceeds the threshold ε. The resulting value of Θ therefore quantifies accumulated informational reconstruction rather than evolution with respect to an external temporal parameter.

7 Properties of the Emergent Temporal Framework

The preceding sections introduced the Temporal Information Functional as the fundamental quantity describing observer-dependent temporal experience. We now derive several consequences that follow directly from the proposed framework. These results characterize the relationship between observer resolution, information reconstruction, and emergent temporal order.

Theorem 3 (Absence of Universal Time) *There exists no observer-independent temporal parameter associated with the universal quantum state.*

Proof By Postulate 1, the universal quantum state $|\Psi_U\rangle \in \mathcal{H}_U$ is timeless and is not parameterized by any external temporal variable. The Temporal Information Functional is defined by

$$\Theta(\Gamma) = \int_\Gamma \rho_I(\omega)\, d\mu(\omega),$$

where Γ denotes the observer's reconstruction trajectory in the informational reconstruction space Ω.

Since both Γ and ρ_I are determined entirely by the observer's reconstruction process, the functional Θ is observer dependent and is not a property of the universal state itself. Therefore, no observer-independent temporal parameter can be associated with $|\Psi_U\rangle$. Temporal order arises only through observer-dependent informational reconstruction. □

Theorem 4 (Observer Dependence) *Let two observers O_A and O_B possess distinct reconstruction maps $\mathcal{R}_A \neq \mathcal{R}_B$. If these reconstruction maps induce different distinguishable information densities, $\rho_I^{(A)}(\omega) \neq \rho_I^{(B)}(\omega)$, or different reconstruction trajectories, $\Gamma_A \neq \Gamma_B$, then, in general, $\Theta_A \neq \Theta_B$.*

Proof The Temporal Information Functional for observer O_i is

$$\Theta_i = \int_{\Gamma_i} \rho_I^{(i)}(\omega)\, d\mu(\omega), \qquad i \in \{A, B\}.$$

Since the reconstruction maps are distinct, they generally produce either different reconstruction trajectories or different distinguishable information densities. Therefore,

$$\int_{\Gamma_A} \rho_I^{(A)}(\omega)\, d\mu(\omega) \neq \int_{\Gamma_B} \rho_I^{(B)}(\omega)\, d\mu(\omega),$$

which implies $\Theta_A \neq \Theta_B$. Hence, temporal information is observer dependent. □

The observer's distinguishability threshold determines which informational changes contribute to the Temporal Information Functional. Let $\Gamma_\varepsilon = \{\omega \in \Gamma : \rho_I(\omega) \geq \varepsilon\}$ denote the subset of informational configurations distinguishable by an observer with threshold ε. The corresponding Temporal Information Functional is

$$\Theta_\varepsilon = \int_{\Gamma_\varepsilon} \rho_I(\omega)\, d\mu(\omega).$$

Theorem 5 (Resolution Dependence) *Let $\varepsilon_1 < \varepsilon_2$. Then $\Theta_{\varepsilon_1} \geq \Theta_{\varepsilon_2}$.*

Proof Since $\varepsilon_1 < \varepsilon_2$, every informational configuration distinguishable by the observer with threshold ε_2 is also distinguishable by the observer with threshold ε_1. Hence, $\Gamma_{\varepsilon_2} \subseteq \Gamma_{\varepsilon_1}$. Because $\rho_I(\omega) \geq 0$, integration over the larger domain cannot decrease the value of the integral. Therefore,

$$\Theta_{\varepsilon_1} = \int_{\Gamma_{\varepsilon_1}} \rho_I(\omega)\, d\mu \geq \int_{\Gamma_{\varepsilon_2}} \rho_I(\omega)\, d\mu = \Theta_{\varepsilon_2}.$$

□

The limiting behaviour of the proposed framework provides an important conceptual consequence.

Theorem 6 (Infinite Resolution Limit) *Suppose the observer's distinguishability threshold satisfies $\varepsilon \to 0$. Then every nonzero informational difference is distinguishable, and the observer's reconstruction becomes complete. Consequently, no distinguishable informational changes remain to generate an emergent temporal ordering.*

Proof By Definition 1, an informational update is registered only if $D(\omega_i, \omega_j) \geq \varepsilon$, where D is the distinguishability measure. Taking the limit $\varepsilon \to 0$, every pair of informational states satisfying $D(\omega_i, \omega_j) > 0$ becomes distinguishable. Hence the observer can reconstruct all distinguishable informational differences contained in the reconstruction space. Since the Temporal Information Functional

$$\Theta(\Gamma) = \int_{\Gamma} \rho_I(\omega)\, d\mu(\omega)$$

quantifies temporal order through accumulated distinguishable informational reconstruction, complete reconstruction leaves no unresolved informational changes from which additional temporal ordering can emerge.

Therefore, in the infinite-resolution limit, emergent temporal ordering vanishes because no additional observer-dependent informational distinctions remain to be generated. □

Classical Limit

Macroscopic observers possess finite and approximately stable information-processing capabilities. Consequently, the Temporal Information Functional evolves smoothly over successive informational updates. Under these conditions, conventional clock time is recovered as an effective macroscopic approximation, $t \approx \alpha\Theta$, where α is a calibration constant relating accumulated informational reconstruction to physical clock measurements.

Therefore, clocks [14, 15] do not measure fundamental time but rather physical processes whose informational reconstruction is proportional to the Temporal Information Functional.

Corollary 1 *The proposed framework predicts that observers possessing different information-processing capabilities generally reconstruct different temporal descriptions even while observing the same underlying universal quantum state. Accordingly, temporal experience is not an intrinsic property of reality but an emergent consequence of finite observation.*

8 Relationship with Existing Physical Theories

The proposed framework does not seek to replace quantum mechanics or general relativity. Instead, it introduces an alternative ontological perspective in which time is not regarded as a fundamental component of physical reality. The established dynamical laws of physics are interpreted as effective descriptions reconstructed by finite observers through distinguishable information. This section discusses the relationship between the proposed framework and existing physical theories.

Quantum Mechanics

In conventional quantum mechanics, the evolution of a closed quantum system is governed by the Schrödinger equation [16]

$$i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = \hat{H} |\psi(t)\rangle ,$$

where t is treated as an external classical parameter rather than a quantum observable.

Within the proposed framework, the universal quantum state $|\Psi_U\rangle$ is fundamentally timeless and therefore is not parameterized by an external temporal variable. The Schrödinger equation is interpreted as an effective dynamical description applicable to observer-reconstructed subsystems rather than to the universe as a whole.

Consequently, quantum mechanics remains valid as an effective theory describing observer-reconstructed dynamics. The proposed framework does not modify the Schrödinger equation but instead interprets its temporal parameter as an emergent quantity arising from observer-dependent informational reconstruction.

Comparison with the Page–Wootters Mechanism

The Page–Wootters mechanism [6] demonstrates that temporal evolution can emerge from correlations between a timeless global quantum state and an internal quantum clock. In this formulation, the universe remains globally timeless while subsystems evolve relative to a designated clock degree of freedom.

The present framework shares the assumption of a fundamentally timeless universal quantum state but differs in the mechanism responsible for temporal emergence. Rather than introducing an internal quantum clock, temporal order is reconstructed through the finite informational capacity of observers. Accordingly, the Temporal Information Functional

$$\Theta(\Gamma) = \int_\Gamma \rho_I(\omega)\, d\mu(\omega)$$

replaces the role of an internal clock by quantifying the cumulative distinguishable information reconstructed along the observer's informational trajectory.

General Relativity

General relativity [14, 15] models spacetime as a four-dimensional differentiable manifold equipped with the metric tensor $g_{\mu\nu}$, whose curvature is determined by the Einstein field equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}.$$

Time is incorporated as one coordinate of spacetime and possesses no universal flow.

The proposed framework is compatible with this viewpoint in the sense that no preferred universal clock exists. However, it differs fundamentally by assuming that temporal ordering itself is not an intrinsic property of spacetime but is reconstructed by finite observers through distinguishable informational updates.

Accordingly, spacetime is interpreted as an emergent geometric description reconstructed by finite observers rather than as the fundamental arena of physical reality.

Observer-Dependent Time

Consider two observers possessing distinct reconstruction maps $\mathcal{R}_A \neq \mathcal{R}_B$. The corresponding Temporal Information Functionals are

$$\Theta_A = \int_{\Gamma_A} \rho_I^{(A)}(\omega)\, d\mu(\omega),$$

and

$$\Theta_B = \int_{\Gamma_B} \rho_I^{(B)}(\omega)\, d\mu(\omega).$$

In general,

$$\Theta_A \neq \Theta_B.$$

Therefore, different observers may reconstruct different temporal descriptions while remaining consistent with the same underlying universal quantum state.

This observer dependence resembles the relativity of simultaneity [14] in special relativity, although it originates from differences in accessible information rather than from relative inertial motion.

Comparison with the Wheeler–DeWitt Equation

Canonical quantum gravity leads to the Wheeler–DeWitt equation [2] $\hat{H}\,|\Psi_U\rangle = 0$, which contains no explicit temporal parameter and is commonly associated with the problem of time.

The present framework shares the assumption of a fundamentally timeless universe but differs in its interpretation. Rather than recovering time through an internal physical clock or relational degree of freedom, temporal experience is attributed to finite observer-dependent informational reconstruction.

The timeless nature of the universal quantum state is therefore adopted as a foundational ontological postulate, while temporal order emerges through the accumulation of distinguishable information quantified by the Temporal Information Functional.

Summary

The proposed framework preserves the predictive success of existing physical theories while assigning them a different conceptual foundation. Quantum mechanics and general relativity remain valid as effective descriptions reconstructed by finite observers, whereas the universal quantum state itself is fundamentally timeless.

Temporal experience emerges through observer-dependent informational reconstruction quantified by the Temporal Information Functional

$$\Theta(\Gamma) = \int_{\Gamma} \rho_I(\omega)\, d\mu(\omega),$$

providing an information-theoretic interpretation of temporal order that is compatible with, yet conceptually distinct from, existing formulations of quantum mechanics, relativity, and canonical quantum gravity.

9 Discussion

The framework developed in this work proposes that time is not a fundamental property of the universe but an emergent consequence of finite observer-dependent informational reconstruction. Within this perspective, the universal quantum state remains timeless, while temporal experience arises from the accumulation of distinguishable information quantified by the Temporal Information Functional.

Unlike conventional approaches that assume time as a primitive parameter, the proposed framework attributes temporal order to the finite information-processing capability [8] of observers. Finite distinguishability prevents an observer from accessing the complete universal state, requiring reality to be reconstructed through successive informational updates. Consequently, the perceived flow of time reflects the observer's reconstruction process rather than an objective evolution of the universe.

A notable feature of the framework is that temporal descriptions are inherently observer dependent. Different observers possessing distinct reconstruction maps or information-processing capabilities generally reconstruct different informational trajectories and therefore different values of the Temporal Information Functional. Nevertheless, these descriptions remain compatible with the same underlying timeless universal state. This observer dependence [5] extends the relational viewpoint already present in modern physics while providing an information-theoretic mechanism for temporal emergence.

The framework is intentionally formulated independently of any particular distinguishability metric. The distinguishability measure [17] D and the corresponding information density ρ_I may be instantiated using different quantum information measures depending on the physical context. This generality allows the framework to remain compatible with a wide range of quantum information-theoretic models while preserving its central conceptual structure.

Several directions for future investigation remain open. First, explicit choices for the distinguishability measure may lead to quantitative predictions that can be compared with existing physical theories. Second, the relationship between informational reconstruction and quantum measurement warrants further investigation. Third, extending the framework to relativistic quantum field theories and quantum gravity may provide additional insight into the long-standing problem of time. Finally, numerical simulations of finite observer models may clarify how classical temporal behavior emerges from informational reconstruction.

The present framework is intentionally formulated at an axiomatic level and therefore adopts several simplifying assumptions. Throughout this work, the universal Hilbert space is assumed to be finite-dimensional, allowing the mathematical development to remain conceptually transparent while avoiding technical complications associated with infinite-dimensional quantum systems and quantum field theory. Furthermore, the observer reconstruction map R is introduced as an abstract mathematical mapping without specifying the physical dynamics by which informational reconstruction is realized. Likewise, the distinguishability measure D is left deliberately general so that the framework remains compatible with different operational notions of distinguishability, such as trace distance, fidelity-based measures, or quantum relative entropy. Although these abstractions preserve the generality of the proposed theory, future work should investigate concrete realizations of the reconstruction process, explicit choices of distinguishability measures, and extensions to relativistic quantum systems.

The present work should therefore be regarded as a foundational framework rather than a complete physical theory. Its principal contribution is the introduction of an information-theoretic formulation in which temporal order emerges naturally from finite observation without requiring time to be postulated as a fundamental component of reality.

10 Conclusion

This paper introduced a theoretical framework in which the universe is modeled as a fundamentally timeless quantum system and temporal order emerges from finite observer-dependent informational reconstruction. The framework formalizes this idea through the Temporal Information Functional, which quantifies the accumulation of distinguishable information along an observer's reconstruction trajectory.

By separating the timeless universal state from the observer's informational reconstruction, the proposed framework provides an alternative ontological interpretation of time that remains compatible with established physical theories while avoiding the assumption of a fundamental temporal parameter.

The resulting perspective suggests that the passage of time is not an intrinsic property of the universe but an emergent feature of finite observation. Future work will investigate concrete realizations of the distinguishability measure, connections with quantum information theory, and possible implications for quantum gravity and the foundations of physics.

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