Spacetime as an Emergent Cognitive Structure: A Hypothesis of Local Causality

A. N. Smirnov
Independent researcher
andreysxxxx@gmail.com

2025

Abstract

A hypothesis of local causality is proposed, according to which the causal structure is formed independently within each inertial frame of reference (IFR), and the notion of an event is defined only within the bounds of the observer's cognitive accessibility. Space and time are not treated as fundamental entities, but rather as emergent cognitive constructs arising from the consistent reconstruction of causal relations. A distinction is introduced between direct (external) and observable (cognitive) transformations, corresponding respectively to formal mappings of causal structures and internally consistent modifications of the observer's memory. It is shown that cognitive structures may differ even between observers within the same IFR, and their reconciliation requires admissible cognitive interaction. Using a scalar field model on $\mathbb{R}^2$, it is illustrated how multiple spacetimes can emergently arise from a single underlying superstructure. Conditions are established under which observable transformations take the form of Lorentz transformations as cognitively coherent transitions between IFRs. Physical implications and future directions are discussed, including the cognitive nature of matter and time, and the possibility of describing interactions without reference to global spacetime.

keywords: Emergent spacetime, Local causality, Observable transformations, Cognitive structure

PACS: 03.30.+p, 04.20.Cv, 03.65.Ta

1 Introduction: From Global Events to Local Causality

Modern physical theories—from special and general relativity to quantum field theory—presuppose the existence of a global spacetime. In this framework, each *global event* is interpreted as a point on a smooth four-dimensional manifold with fixed coordinates, objectively existing independently of any observer [1, 2].

However, such an approach contradicts the operational limitations of observation. Even in formalized theories of causality, such as the theory of causal networks [3], causality remains a global concept, defined relative to a fixed structure. In real conditions, an observer always operates within a finite inertial frame of reference (IFR) and can only register events that are causally accessible from within that frame [4, 5, 6]. Events outside the accessible causal structure are not only empirically inaccessible but also lack unambiguous definitions in terms of observable quantities.

This work proposes the *hypothesis of local causality*, according to which causality is realized *locally and independently* within each IFR, and the very notion of an event is defined not globally but only within the observable causal structure of a given observer. Space and time, in this view, are not treated as fundamental entities, but as cognitively determined constructs arising from the consistent reconstruction of causal relations [6, 7].

Let $\mathcal{M}$ denote the formal set of all potential events, without any ontological status. Each observer operates only within their own *causal section*[1] $\mathcal{C}_{\mathcal{O}} \subset \mathcal{M}$, defined by the physical and cognitive limitations of their IFR. Formally,

$$\mathcal{C}_{\mathcal{O}} = \left\{ p \in \mathcal{M} \mid \exists q \in \gamma_{\mathcal{O}} : p \in J^{-}(q) \cup J^{+}(q) \right\},$$

where $\gamma_{\mathcal{O}}$ is the locally stable cognitive-physical structure of the observer in the IFR $\mathcal{O}$, including their body, sensory mechanisms, memory, and internal states responsible for registering and interpreting events. Here, $J^{-}(q)$ and $J^{+}(q)$ denote the allowed causal past and future relative to the state $q \in \gamma_{\mathcal{O}}$.

It is important to emphasize that both the structure $\gamma_{\mathcal{O}}$ and its internal components also belong to $\mathcal{C}_{\mathcal{O}}$, as they are defined within the accessible causal domain. This structure is internal to the observer and does not presuppose external observability.

This formulation yields an important consequence: when the observer transitions between IFRs—that is, undergoes a change of state, including

[1] The term *causal section* is used here as an author-defined concept. It denotes the region of the causal structure accessible to the observer, but does not coincide with the notions of Cauchy slices or hypersurfaces in general relativity.

velocity—all internal states, including memory, must remain cognitively consistent with the causal structure of the new IFR. This may require admissible information modification: the observer may perceive as part of their past events that had no admissible cause in the previous IFR, but become causally admissible in the new one—provided that a consistent reconstruction of the event structure is maintained.

In this context, it is essential to distinguish between two aspects of the past:

- the *real causal structure*, defined in the formalism of external description, including the admissibility conditions of direct transformations between IFRs;
- the *cognitively reconstructed past*, represented in the observer's memory and determined by the accessible event structure.

It is the latter that ensures the observer's internally coherent representation of the world and serves as the basis for the emergence of observable spacetime.

To describe transitions between IFRs, we distinguish two types of transformations:

- *Direct transformations*—formal mappings between the causal structures of different IFRs. These are defined externally and determine the admissibility of events and states;
- *Observable transformations*—reconstructions performed by the observer, based on memory and available causal connections. These transformations reflect not what *actually happened*, but what is cognitively consistent with the internal dynamics of the subject.

This distinction is fundamental: even in the presence of significant differences in the direct causal structure, the observer does not register contradictions as long as their cognitive system remains internally coherent.

Such an approach is consistent with relational and operational interpretations of quantum mechanics, as well as with developments in quantum gravity based on non-fixed causal structure [5, 6, 7, 8]. In the following sections, we show how coherence of observable structures can give rise to emergent spacetime without invoking a global metric or background structure.

It should also be noted that the cognitive structure of the observer is formed individually. Even within the same IFR, different observers may have distinct trajectories of perception, accessible causal links, and contents of memory. Therefore, an event accessible to one observer does not necessarily belong to another's cognitive structure without additional reconciliation. The coordination of events between observers requires cognitive compatibility and admissible memory reconstruction, rather than being derivable from global geometry. This allows one to abandon the idea of a universal space of events in favor of local eventhood, coordinated through internal cognitive dynamics.

2 Formulation of the Hypothesis and Core Postulates

Formally, the hypothesis is introduced through two postulates that define the structure of causality as cognitively constrained and dependent on the observer's frame of reference.

The proposed hypothesis of local causality is formulated as an alternative to the global approach to spacetime. Its foundation lies in abandoning the assumption of a single global causal structure and transitioning to operationally defined local structures accessible to individual observers. Two postulates play a central role:

- **Postulate 1 (Local Causality):** *The principle of causality applies separately and independently within each distinct inertial frame of reference (IFR).* [2]

  Commentary: This means that the causal structure available within one IFR cannot be directly transferred to another; each IFR possesses its own admissible system of events, determined by the available interactions.

- **Postulate 2 (Coherence in the Limit):** *If the cognitive structures of two observers in different IFRs become sufficiently close such that their accessible causal connections nearly coincide, then applying the principle of causality in each IFR becomes approximately equivalent to applying it to the combined structure.*

  Commentary: This cognitive convergence corresponds to a situation analogous to the vanishing of relative velocity between IFRs in the

[2] In classical theories, distinct IFRs are defined by differences in velocity. Here, due to the absence of fundamental space and time, the distinction between IFRs is defined cognitively—by the inconsistency of their causal sections. Nevertheless, in the limit of cognitive coherence, this distinction approximately corresponds to the notion of relative velocity between IFRs.

classical picture, even though space and time are not treated as fundamental entities in this hypothesis. It expresses the requirement of consistency in descriptions under infinitesimal differences between frames of reference, ensuring the cognitive and physical coherence of the observable dynamics.

These postulates reflect a minimally sufficient structure: they do not assume global time, absolute space, or any predefined metric. Causality here is not an a priori global relation, but an empirically defined and operationally localized structure.

This approach continues the logical line of relational and operational interpretations of quantum theory and quantum gravity, in which fundamental concepts are defined through measurements and interactions accessible to the observer [5, 6, 7, 8].

The above postulates immediately imply several important conceptual consequences, which are formalized in subsequent sections:

1. For each observer, there exists a distinct *causal section* $\mathcal{C}_{\mathcal{O}} \subset \mathcal{M}$, consisting of events accessible to perception and influence within their IFR. This set is determined by the physically realizable cognitive structure of the observer.

2. Transitions between IFRs may lead to admissible changes in the causal structure and, consequently, to cognitively coherent reconstructions of the observer's memory.

3. Space and time are not introduced as fundamental entities, but are considered emergent, cognitively derived from coherent transitions between IFRs.

4. It is essential to distinguish two types of transformations between IFRs: *direct transformations*, which describe how the structure of admissible events changes, and *observable transformations*, which describe how the observer cognitively interprets the change of frame, based on their memory and current observations.

The entire subsequent structure of the article is built solely on these two postulates. Their rigor and minimalism allow a broad range of phenomena to be derived—from emergent spacetime to the recoverable correspondence with Lorentz transformations—as consequences of cognitive coherence between local causal structures.

These two postulates replace the traditional axioms of spacetime and define a new cognitive-operational ontology of causality.

3 Minimal Cognitive Structure of the Observer

Within the proposed hypothesis, the observer is not treated as an external abstraction with full access to a global structure of events, but as a physically realizable system localized within a specific inertial frame of reference (IFR) and constrained by its causal domain. This approach aligns with relational and operational interpretations of quantum theory, in which fundamental concepts are defined solely through accessible measurements and interactions [4, 6, 7].

To construct the necessary framework formally, we introduce the notion of the *minimal cognitive structure of the observer*, which ensures the ability to register, distinguish, and reconcile events within the observer's causal section.

3.1 Definition

The minimal cognitive structure of the observer in an IFR $\mathcal{O}$ is a locally stable subsystem, denoted $\gamma_{\mathcal{O}}$, which:

1. is physically realized within the observer's body and embedded in the causal structure $\mathcal{C}_{\mathcal{O}}$;
2. is capable of retaining and processing information about previously perceived events;
3. permits locally coherent differentiation of the sequence of events;
4. maintains cognitive consistency under admissible transitions between IFRs.

This structure enables the observer to order events, distinguish past from future, and construct a cognitively coherent representation of the observed world.

3.2 Physical Content

Physically, $\gamma_{\mathcal{O}}$ may be implemented, for example, as a physical body with stable internal degrees of freedom capable of registration and interpretation [9]. Examples include:

- material memory substrates (e.g., neural configurations or equivalent structures);
- sensory channels of perception;
- internal mechanisms for filtering and distinguishing causal connections.

3.3 Formal Stability Condition

Let $\gamma_{\mathcal{O}}$ be the cognitive structure in the IFR $\mathcal{O}$, and $\mathcal{C}_{\mathcal{O}}$ the corresponding causal section. Then the stability of $\gamma_{\mathcal{O}}$ implies that for a small deformation $\gamma_{\mathcal{O}} \to \gamma'_{\mathcal{O}}$, inducing a transformation $\mathcal{C}_{\mathcal{O}} \to \mathcal{C}'_{\mathcal{O}}$, the following holds:

$$\forall p \in \mathcal{C}_{\mathcal{O}} \cap \mathcal{C}'_{\mathcal{O}} : \quad \text{the cognitive interpretation of event } p \text{ is preserved.}$$

In other words, the observer continues to interpret all shared events p coherently in both structures, despite possible reconstruction of memory. This is consistent with **Postulate 2** concerning coherence in the limit.

3.4 Role in the Causal Structure

The structure $\gamma_{\mathcal{O}}$ is an integral part of the observer's causal section. It participates in defining the set of events $\mathcal{C}_{\mathcal{O}}$ via the condition:

$$\mathcal{C}_{\mathcal{O}} = \left\{ p \in \mathcal{M} \mid \exists q \in \gamma_{\mathcal{O}} : p \in J^{-}(q) \cup J^{+}(q) \right\}.$$

Thus, the cognitive structure not only conforms to causality but also defines the observable world itself.

3.5 Transitions Between IFRs and Coherence

Transitions between IFRs may involve transformations that alter the causal structure. However, the cognitive structure $\gamma_{\mathcal{O}}$ must retain internal coherence. This may require admissible modifications of memory and perception, but not a breakdown of the ability to interpret events in the new IFR. The stability of $\gamma_{\mathcal{O}}$ guarantees that the observer can continue to identify themselves and their observations after the transition.

3.6 Implications

Hence, the minimal cognitive structure of the observer:

- provides the basis for constructing the causal structure within a given IFR;
- defines the domain of admissible observable transformations;
- serves as a physically realizable and informationally stable anchor for emergent space and time.

The stability of the cognitive structure requires not a global identity of eventhood, but consistency of memory and admissibility of causal reconstruction in the new IFR. Even if two observers are situated within the same physical IFR from the perspective of an external formalism, their cognitive structures $\mathcal{C}_{\mathcal{O}}$ may differ. This difference arises from individual trajectories of perception $\gamma_{\mathcal{O}}$, differing access to causal connections, and differing memory contents. Consequently, an event belonging to one cognitive structure is not required to belong to the other until cognitive interaction occurs, accompanied by memory reconstruction within the framework of new causal admissibility.

4 Two Types of Transformations

In the proposed approach, two fundamentally distinct types of transformations between inertial frames of reference (IFRs) play a central role: *direct transformations* and *observable transformations*. These describe, respectively, the external (formal) and internal (cognitive) mappings of the event structure during transitions between IFRs. Similar distinctions between external (global) and internal (local or agent-based) descriptions of eventhood are discussed in [6, 7, 8], as well as within reconstructions of quantum theory from information-theoretic principles [10].

4.1 Direct Transformations

Direct transformations represent formal correspondences between the causal structures of different IFRs. They express the relation between $\mathcal{C}_{\mathcal{O}}$ and $\mathcal{C}_{\mathcal{O}'}$, where events, states, and processes from one IFR are mapped onto another in accordance with the postulate of local causality. These do not assume a global spacetime but logically require some more fundamental structure (e.g., a Euclidean superstructural space), within which such mappings become definable.

Thus, direct transformations:

- determine which events in one IFR can be interpreted as admissible from the viewpoint of another IFR's causal structure;
- imply an external perspective: they are not directly accessible to the observer and function as a mathematical tool for describing coherent transitions between causal sections;
- are only defined if there exists a mapping between cognitive structures $\gamma_{\mathcal{O}} \to \gamma_{\mathcal{O}'}$ compatible with causality.

If such a mapping is absent (e.g., due to excessive disparity between IFRs), direct transformations become undefined. This means that from a formal standpoint, event correspondence between these IFRs is indeterminate.

4.2 Observable Transformations

Observable transformations describe how the observer themselves interpret the transition between IFRs based on accessible data: memory, sensations, and current observations. They are formed internally within the cognitive system and define how the observer reconstructs the structure of space and time after the transition.

Observable transformations:

- are defined solely by events accessible to the observer, belonging to $\mathcal{C}_\mathcal{O}$;
- ensure cognitive consistency: the observer must not register conflicts between past and present;
- may differ from direct transformations, especially when the causal structure changes during the IFR transition;
- approach identity in the limit of vanishing relative velocity between IFRs (by Postulate$\tilde{2}$).

Cognitive reconstruction here refers to the process of aligning the internal causal structure of the observer in the new IFR with the structure they possessed prior to the transition. The observer aims to interpret incoming information such that a coherent history is restored—where memory, perception, and the logical consistency of events do not conflict. This does not require full physical equivalence between IFRs but does demand that the new cognitive picture preserve the identity and continuity of subjective experience.

This interpretation is in line with operational approaches in quantum mechanics and theoretical frameworks with undefined causal structure [11, 12], which prioritize descriptions realizable from within local observers.

Under the hypothesis of local causality, no global real causal structure exists. Nevertheless, for formal analysis, the *real causal structure* can be interpreted as one derived from *direct transformations*, i.e., a mathematically constructed configuration of admissible events stemming from an underlying structure not directly observable. In contrast, the *observable structure* is determined solely by the cognitively accessible events in a given IFR.

4.3 Constraints on Observable Transformations

Observable transformations are possible only under the condition of cognitive stability. This means that the observer's memory, body, and perception ($\gamma_{\mathcal{O}}$) must be reconstructible in the new IFR in a way that avoids internal contradictions.

Formally, observable transformations are admissible if there exists a causally coherent mapping

$$\gamma_{\mathcal{O}} \longrightarrow \gamma_{\mathcal{O}'},$$

where both structures belong to their respective $\mathcal{C}_{\mathcal{O}}$ and $\mathcal{C}_{\mathcal{O}'}$ and are consistent with local cognitive dynamics. Here, $\gamma_{\mathcal{O}}$ denotes the observer's cognitive configuration, including memory, bodily state, and perceptual parameters.

If causal reachability between events is entirely absent and no cognitively coherent continuation of the observer's history exists in the new IFR, then observable transformations become meaningless: such a transition is deemed physically and cognitively impossible. This agrees with the operational interpretation of IFR transitions: only those allowing consistent memory and identity reconstruction are considered realizable.

Thus, while direct transformations may be mathematically definable over a broader domain, only those allowing cognitive realization hold physical meaning within the hypothesis of local causality.

Observable transformations are formed individually for each observer. Even if two observers share the same IFR, their cognitive structures $\mathcal{C}_{\mathcal{O}}$ may differ, as they depend on individual perceptual trajectories, memory contents, and accessible causal links. Hence, event coordination between observers is not guaranteed by sharing an IFR, but requires cognitive interaction and admissible memory reconstruction. This highlights that the physical meaning of observable transformations lies not in global objective universality, but in the individual coherent reconstruction of the causal world.

It should be emphasized that even when the equations for observable transformations formally coincide with Lorentz transformations, this coincidence should not be interpreted as evidence of a fundamental spacetime symmetry. Rather, it reflects the cognitive limit of coherence between IFRs and indicates operational consistency of eventhood, not a global geometric structure.

4.4 Interpretation of the Distinction

The distinction between direct and observable transformations reflects a fundamental divide between objectively possible structures and those cognitively reconstructible by an observer within limited causal accessibility. Direct transformations define ontologically admissible correspondences, while observable transformations define epistemically admissible cognitive projections.

4.5 Transformational Function in the Hypothesis

In the generalized causality hypothesis:

- Direct transformations define which events are compatible with external descriptions within some fundamental structure $\mathfrak{B}$ [3];
- Observable transformations ensure the coherent reconstruction of the observer's internal world;
- Space and time emerge as cognitively coherent constructions formed through observable transformations.

More formally, the observed event structure $\mathcal{C}_{\mathcal{O}}(t)$ experienced by observer $\mathcal{O}$ at cognitive time t can be represented as the result of applying a cognitive projection operator $A_{y(\mathcal{O},t)}$ to a more fundamental structure $\mathfrak{B}$:

$$\mathcal{C}_{\mathcal{O}}(t) = A_{y(\mathcal{O},t)}(\mathfrak{B}).$$

Here, the anchor $y(\mathcal{O}, t)$ specifies the observer's cognitive configuration at time t, including memory, bodily state, and perceptual parameters. This scheme does not play a central role in the present article but conceptually supports the idea that the causal picture of the world can emerge as a coherent reconstruction of a limited portion of a deeper configuration. Further exploration of such projections will be presented in future work.

This distinction between the physical and cognitive levels explains how an observer can interpret a continuous experience even during transitions between causally distinct IFRs, while maintaining internal coherence and cognitive stability.

[3] $\mathfrak{B}$ denotes some fundamental, not directly observable structure that allows formal event mappings between IFRs. Its precise nature is not specified in this paper, though future work is planned.

4.6 Cognitive Coherence of Events

Since observable transformations are based on a consistent reconstruction of the observable past, they must ensure cognitive consistency: events already present in the observer's memory and still admissible in the new IFR must be interpreted so as to preserve a coherent history.

Formally, observable transformations satisfy the condition of cognitive coherence:

$$p \in \gamma_{\mathcal{O}} \cap \mathcal{C}_{\mathcal{O}'} \;\Rightarrow\; f_{\text{obs}}(p) \in \gamma_{\mathcal{O}'}.$$

This condition does not require full identity of event structures but guarantees that admissible memory elements can be cognitively reconstructed without contradictions. Events inadmissible in the new IFR may be forgotten or replaced by cognitively equivalent ones, while the observable world remains consistent. In other words, observable transformations aim at cognitive coherence, not exact physical correspondence.

4.7 Compatibility with Lorentz Transformations

In classical special relativity, Lorentz transformations play the role of fundamental symmetry transitions between IFRs. Under the hypothesis of local causality, however, they are regarded as emergent forms arising under two conditions:

1. **Strict Event Preservation:** Observable transformations must map events from $\mathcal{C}_{\mathcal{O}}$ to $\mathcal{C}_{\mathcal{O}'}$ such that memory reconstruction preserves causal admissibility and internal consistency.

2. **Coherence in the Limit:** In the limit where relative acceleration or velocity between IFRs vanishes, observable transformations must approach the identity map. This corresponds to *Postulate 2* and ensures continuity of the cognitive structure.

Here, *strict event preservation* does not mean absolute invariance, but cognitive coherence: events stored in memory and admissible in the new causal structure must be reconstructed so as to preserve a consistent history. This aligns with Postulate$\tilde{1}$ and underscores that observable transformations operate within cognitive admissibility, not global physical symmetry.

Since Lorentz transformations minimally deform causal structure while preserving events, they satisfy these conditions. Therefore, we may state:

> **Claim:** Lorentz transformations are admissible observable transformations for transitions between IFRs that allow cognitively coherent reconstruction of event structure.

This claim does not assert that Lorentz transformations are fundamental. On the contrary, it shows that such transformations can emerge as a result of cognitive optimality: Lorentz-invariant transformations minimize the discrepancy between reconstructed memory and admissible direct structure, thereby preserving consistency in the observed spacetime.

Hence, within the hypothesis of local causality, Lorentz transformations acquire not a fundamental, but a *cognitively coherent* status—they are realized as admissible observable transformations that maintain descriptive stability during frame transitions.

A similar logic appears in [13, 14], where Lorentz symmetry is derived as a consistency requirement among local viewpoints in agent-based theories.

Importantly, the equations of Lorentz transformations can be exactly realized as a form of observable transformations in cases where the observer's excitations are cognitively reconstructed into a coherent and consistent event structure. This permits the use of Lorentz transformations as an exact description of cognitive reconstruction, without assuming global symmetry or universal invariance. Thus, exact Lorentz invariance is permissible within the hypothesis but not required as a universal principle.

Although a rigorous definition of minimality in cognitive reconstruction requires further formalization (e.g., a metric or functional on the space of causal structures), it is already evident that Lorentz transformations possess properties that make them particularly suitable: they implement smooth, invertible transitions between IFRs while preserving consistency of event descriptions with minimal memory modification. This renders them cognitively optimal among admissible observable transformations—in the sense that they minimize the need to reconstruct causal connections and preserve the coherence of observable experience.

5 A New Definition of an Event

Within the framework of the local causality hypothesis, the classical definition of an event as a global point in spacetime loses its universal status. Since space and time are not treated as fundamental entities, and the observer is restricted to their causal section $\mathcal{C}_{\mathcal{O}}$, the very notion of an event must be redefined in operational and cognitive terms.

The classical conception of an event as a point in spacetime has been challenged in relational and operational interpretations of quantum theory, as well as in reconstruction programs based on informational principles [7, 8, 10].

5.1 Limitations of the Traditional Definition

In standard formulations, events are identified with points on a global manifold equipped with a metric and causal structure. This definition:

- presupposes the objective existence of all events independently of any observer;
- requires a globally accessible spacetime "in its entirety";
- ignores the limited accessibility of an observer confined to a particular inertial frame (IFO).

However, as shown in the previous sections, the observer only has access to events within their own causal section $\mathcal{C}_{\mathcal{O}}$, and transitions between IFOs involve cognitively admissible reconstructions of accessible past information. Therefore, the notion of an event must be redefined *within the local cognitive structure*.

5.2 Operational Definition of an Event

Definition: An *event* is an element $p \in \mathcal{C}_{\mathcal{O}}$, cognitively registered by an observer in IFO $\mathcal{O}$ as a causally accessible interaction that leaves a stable trace in perception or memory.

This definition rests on three key criteria:

1. **Accessibility:** The event p must lie within $J^-(q) \cup J^+(q)$ for some $q \in \gamma_{\mathcal{O}}$;
2. **Cognitive registration:** The event must be registered or mediated through perception, measurement, or causal influence;
3. **Coherence:** The interpretation of the event must be consistent within the current cognitive structure.

This definition of events as functional interactions aligns with agent-based approaches in quantum gravity [11, 14], in which causality is defined from within the observer.

5.3 Observability and Eventhood

Not all potential elements of the set $\mathcal{M}$ qualify as events. Eventhood is not ontological but cognitive: it depends on accessibility and registrability within the context of a given IFO. Accordingly, an event does not "exist by itself" but is defined through its operational function in the observer's cognitive structure.

This approach avoids logical inconsistencies inherent in globalist formulations and is consistent with relational and operational interpretations of physical quantities [4, 6].

5.4 Events and Observable Transformations

Since observable transformations provide a cognitively coherent reconstruction of experience when transitioning between IFOs, they also determine the admissible rewriting of eventhood. An event $p \in \mathcal{C}_{\mathcal{O}}$ preserved in memory continues to exist in $\mathcal{C}_{\mathcal{O}'}$ only if its reconstruction remains cognitively consistent.

In other words, eventhood is *dynamic and contextual*, and the event structure arises as a cognitively coherent interaction between the observer and the underlying structure.

This reflects the fundamental divergence between ontological and epistemic approaches to physical reality, emphasized in frameworks with indefinite causal order [12].

5.5 Formal Reduction

Given the above, the set of events for an observer in IFO $\mathcal{O}$ can be formally defined as:

$$\mathcal{E}_{\mathcal{O}} = \{p \in \mathcal{C}_{\mathcal{O}} \mid \text{there exists a registration or influence consistent with } \gamma_{\mathcal{O}}\}\,.$$

This set is dynamic and may be modified upon transition to another IFO, provided cognitive stability is maintained. Thus, an *event* is not a point in a global space but a *cognitively defined and operationally registered interaction* that is admissible within the current causal structure.

6 Toy Model: Events as Cognitive Minima in a Scalar Field on $\mathbb{R}^2$

To illustrate the key aspects formulated in the preceding sections—particularly the dependence of eventhood on the observer's cognitive structure and the absence of a global spacetime—we consider a simple model in the two-dimensional Euclidean space $\mathbb{R}^2$, where the fundamental entity is a real scalar field $\phi(x, y)$. This field possesses no internal symmetries or dynamics; it is given as a static distribution of values over the plane. Neither the x- nor the y-axis is distinguished, reflecting the absence of any fundamental difference between space and time in the underlying structure.

Abstract models of this kind, in which temporal structure emerges from the observer's choice, appear in agent-based reconstructions of quantum theory and in theories of emergent time [9, 7, 14].

In this model, space and time are not predefined but emerge as cognitive constructions of the observer, shaped by the choice of causal interpretation direction.

6.1 Cognitive Time and the Observation Direction

Let an observer $\mathcal{O}$ choose a direction $v_{\mathcal{O}}$ in $\mathbb{R}^2$, to be interpreted as the "time" direction in their IFO. Assume that $v_{\mathcal{O}}$ is normalized: $\|v_{\mathcal{O}}\| = 1$. The direction orthogonal to it, $v_{\mathcal{O}}^{\perp}$, is interpreted as "space." This choice defines the observer's cognitive structure: events are defined as local minima of the scalar field ϕ along the temporal direction $v_{\mathcal{O}}$.

That is, a point $p \in \mathbb{R}^2$ is considered an event for observer $\mathcal{O}$ if it satisfies the condition:

$$\frac{d^2}{d\lambda^2}\phi(p + \lambda v_{\mathcal{O}}) > 0, \quad \text{and} \quad \frac{d}{d\lambda}\phi(p + \lambda v_{\mathcal{O}}) = 0 \quad \text{at } \lambda = 0,$$

where $\lambda \in \mathbb{R}$ is a parameter along the direction $v_{\mathcal{O}}$, and $\phi \in C^2(\mathbb{R}^2)$.

A *cognitive minimum* is a local minimum of the scalar field ϕ along the observer-defined time direction $v_{\mathcal{O}}$.

This condition means that ϕ attains a local minimum along the line through p in the direction $v_{\mathcal{O}}$.

This definition of events makes the direction $v_{\mathcal{O}}$ a functional analogue of a temporal orientation, chosen by the observer as a means of cognitively ordering perceived changes.

Thus, events depend on the chosen "time" direction, and different observers choosing different directions $v_{\mathcal{O}}$ will identify different sets of events.

6.2 Emergence of Spacetimes

Since the set of events depends on the direction $v_{\mathcal{O}}$, each observer's causal section $\mathcal{C}_{\mathcal{O}}$ defines a distinct spacetime. The pair $(v_{\mathcal{O}}, v_{\mathcal{O}}^{\perp})$ yields a decomposition of $\mathbb{R}^2$ into "space" and "time," and the ordered set of events (i.e., local minima along $v_{\mathcal{O}}$) forms the emergent temporal structure in the observer's IFO $\mathcal{O}$.

As $v_{\mathcal{O}}$ is arbitrary, the number of possible emergent spacetimes is unbounded: each direction yields a distinct cognitive space and time, interpreted from the scalar field. Spacetime is thus not given a priori, but emerges from recognizable patterns in the field relative to the observer's cognitive structure.

6.3 Relative Velocity Between IFOs

Suppose two observers, $\mathcal{O}$ and $\mathcal{O}'$, select time directions $v_{\mathcal{O}}$ and $v_{\mathcal{O}'}$ respectively. Their relative orientation is given by the angle θ between these directions. In the limit $\theta \to 0$, the observers become close: their event structures converge, and the observable transformations approach the identity map (in accordance with Postulate 2).

Thus, the relative velocity between IFOs is interpreted as the angle between their cognitive time directions. This definition is fully emergent and requires no preassigned metric: the angle arises as a relation between the observers' cognitive structures.

6.4 Implications of the Model

This toy model illustrates:

- how events may arise not a priori, but depending on the observer's cognitive structure;
- how different observers, by choosing different time directions, obtain distinct spacetimes;
- how a multiplicity of spacetimes can naturally emerge from a single underlying scalar field on $\mathbb{R}^2$;
- how the relative velocity between IFOs is interpreted as the angle between their cognitive time directions.

The model shows that space, time, events, and relativity can all be understood as cognitively conditioned emergent phenomena arising from a more fundamental causal structure, independent of the choice of IFO.

The toy model demonstrates the consistency of the local causality hypothesis with geometrically simple yet conceptually rich examples, suitable for further formalization in more general settings.

Remark 1. In this toy model, the observer is not represented as a physical system with internal dynamics or memory. Their causal structure is modeled abstractly—via the orientation of the direction $v_{\mathcal{O}}$, which defines the ordering of interpreted events. While this simplification does not capture the observer as part of a self-consistent causal structure, it suffices to illustrate the key aspect of the hypothesis—namely, the dependence of eventhood on the choice of IFO. A complete description of the observer requires a richer model, including at least a locally stable structure capable of retaining and transmitting information, which lies beyond the scope of this example and will be addressed separately.

Remark 2. Although in this model the cognitive ordering is imposed externally via the direction $v_{\mathcal{O}}$, its structure may be connected to intrinsic features of the field and stable configurations. Future work will address the mechanism by which the observer selects a local temporal orientation as a functional of the field. Such approaches resonate with attempts to derive the arrow of time from internal correlations or robust configurations [6, 15].

Remark 3. In this model, the space is Euclidean and timeless. Nevertheless, the distinction between IFOs can be formalized by the angle between their causal orientations $v_{\mathcal{O}}$ and $v_{\mathcal{O}'}$, which effectively plays the role of relative velocity. In the small-angle limit, the causal structures become nearly indistinguishable, corresponding to the postulate of coherence under small relative velocities.

Remark 4. Although memory is not explicitly modeled here, the change in event structure under variation of the cognitive time direction implicitly suggests the necessity of memory adaptation. This illustrates the cognitive basis of the editing mechanism discussed in detail in Appendix A.

7 Emergence of Space and Time

Within the framework of the local causality hypothesis, space and time are not regarded as fundamental entities (see also approaches to emergent geometry and metric [7]). Instead, they are interpreted as cognitively-empirical constructions that arise from the observer's consistent reconstruction of local causal structure. This contrasts with the classical paradigm in which space and time are globally given background parameters—e.g., a fixed manifold with a metric in general relativity.

7.1 Cognitive Time and Cognitive Space

An observer $\mathcal{O}$ interprets their traversal through causal structure as an ordered sequence of changes—this defines the direction of *cognitive time*, denoted $v_{\mathcal{O}}$. This direction is not fundamental but depends on the observer's internal processes: it reflects the order in which events are registered and interpreted.

Alongside this temporal direction, the observer may identify another direction, *independent* of $v_{\mathcal{O}}$ in the sense that local variations in observables along it do not alter the perceived causal ordering of events. This direction is interpreted as *cognitive space*. In specific cases—for instance, the toy model on $\mathbb{R}^2$—cognitive space may be formally defined as orthogonal to cognitive time (in the Euclidean sense). However, in the general case, such a definition does not presuppose a predefined metric and must be derived operationally—via distinguishability and local independence of event correlations as perceived by the observer.

Thus, the pair of directions $(v_{\mathcal{O}}, u_{\mathcal{O}})$, where $u_{\mathcal{O}}$ defines cognitive space, specifies a local decomposition of causal structure into time and space relative to the observer $\mathcal{O}$. These directions do not have a universal geometric status but play a crucial role in forming emergent spacetime as a cognitive construct.

7.2 Multiplicity of Spacetimes

Since the cognitive time direction $v_{\mathcal{O}}$ is arbitrary, the overall set of potential events $\mathcal{M}$ admits a multiplicity of cognitively distinct spacetimes. The set $\mathcal{M}$ is understood as the total set of points to which a causal interpretation may be applied by an observer—for instance, the set of all local configurations of a fundamental field that allow for cognitive reconstruction. This is consistent with the formalization introduced in the introduction, where $\mathcal{M}$ is treated as the formal set of potential events—not possessing ontological status, but permitting cognitively causal interpretation within a given IFO.

Each such interpretation is defined by its corresponding observer (see also the relational view of quantum states [6]) and cannot be reduced to a single global structure (cf. [8]). As a result:

- Spacetime emerges as a *local cognitive projection*—a functional selection of coordinate structure over a subset $\mathcal{C}_{\mathcal{O}} \subset \mathcal{M}$;
- No global metric is defined or observable on $\mathcal{M}$;

- Between different IFOs, only cognitively consistent interpretations of events are possible, not a shared global coordinate system.

Here, $\mathcal{C}_\mathcal{O}$ is interpreted as the cognitively accessible subset of $\mathcal{M}$, determined by the observer's internal and operational constraints (see Section 1).

7.3 Transformations Between IFOs and Cognitive Coherence

Transitions between the spacetime descriptions of different observers $\mathcal{O} \to \mathcal{O}'$ are realized via *observable transformations*, which enable consistent reconstruction of memory and events across changes in IFO (see also Appendix A, which discusses the cognitive mechanism of memory editing during such transitions). These are not physical coordinate transformations in the classical sense (cf. [6, 4, 5]) but describe cognitively permissible rearrangements of memory and interpretation of events under a new causal orientation.

In the general case, the difference between cognitive time directions $v_\mathcal{O}$ and $v_{\mathcal{O}'}$ operationally expresses the *relative cognitive velocity* between reference frames. By *cognitive velocity* we mean the degree of discrepancy in the interpretation of causal ordering between observers, defined by the deviation between their cognitive time directions. In specific models, this may be expressed as the angle between the directions; in the general case, it is defined operationally—through the divergence in the reconstruction of causal sequences.

Thus:

- The divergence between cognitive time directions reflects differences in event interpretation;
- When this divergence is small, observable transformations approximate the identity (Postulate 2);
- Cognitive coherence serves as the condition for emergent consistency between observers.

7.4 Spacetime as a Cognitive Construct

From the above, it follows that:

- Space and time are not ontological entities—they arise through cognitive processing of causal information;

- The emergent local coordinate system of an observer is formed as a functional projection of the consistent cognitive structure of events within $\mathcal{C}_{\mathcal{O}}$, with designated directions of cognitive time and cognitive space;

- Lorentz transformations may locally coincide with observable transformations in regions where the cognitive time directions of different IFOs are close, and where the causal structure allows for consistent linear reconstruction of events. In this sense, Lorentz transformations are compatible with the observable transformations arising under local cognitive coherence between IFOs.

Thus, in the proposed hypothesis, space and time do not belong to the fundamental ontology but are regarded as cognitively coordinated structures emerging from the observer's interpretation of causal information. Their form, transformations, and even number depend on the chosen causal orientation and the observer's cognitive structure.

8 Discussion

The proposed hypothesis of local causality radically reconsiders the traditional understanding of space, time, and events as fundamental entities. In this section, we discuss the philosophical and physical implications of such an approach, including the interpretation of memory, the role of cognitive stability, and the distinction between determinism and coherence.

8.1 Memory, Cognitive Stability, and Reconstruction of the Past

Memory plays a central role in shaping the event structure of an observer [16, 11]. Within the framework of local causality, memory is not merely a repository of fixed data but part of the cognitive dynamics belonging to the observer's causal slice $\mathcal{C}_{\mathcal{O}}$. When switching to a different inertial frame $\mathcal{O}'$, the observer must align their state with the new causal structure $\mathcal{C}_{\mathcal{O}'}$.

This alignment may require a *reconstruction of memory* — a cognitive adaptation in which past events that are no longer admissible in the new structure are removed or replaced by causally admissible ones. This does not imply a distortion of truth, since in this approach, truth is defined locally within each frame. Cognitive stability demands that memory does not contradict the accessible causal structure and the current observations.

This reconstruction is not arbitrary. It must satisfy the following conditions:

- consistency with the current state of the observer's body and cognitive processes;
- internal coherence within the new causal structure;
- preservation of the observer's identity as a continuous cognitive trajectory.

Thus, memory is not fixed in an absolute sense but revalidated in each new frame through admissible cognitive mechanisms.

8.2 Global Determinism and Local Coherence

In classical physics — especially in general relativity — it is assumed that a globally deterministic structure exists: a given initial hypersurface determines the evolution of the entire system [17, 2]. The hypothesis of local causality rejects this approach: causality is defined locally and independently within each inertial frame.

The absence of global determinism implies:

- the impossibility of constructing a universal spacetime consistent for all observers;
- the possibility of differences in event reconstruction between inertial frames;
- the rejection of a global world time or universal future.

However, this does not lead to arbitrariness or subjectivism. Instead, the hypothesis introduces a weaker but sufficient condition: *local coherence*. Transitions between frames are only possible under the condition of cognitive stability, and observable transformations approach consistency with direct transformations in the limit of small changes (see Postulate 2).

Thus, in place of global determinism, we have *cognitive coherence* — the observer preserves continuity of experience and event structure under admissible transitions between frames [6, 7].

It should be emphasized that local cognitive coherence applies not only to transitions between different frames but also to agreement between different observers within the same frame. Even in a shared geometric reference system, cognitive structures $\mathcal{C}_{\mathcal{O}}$ may differ, and reconciling events between observers requires cognitively admissible interaction. Cognitive coherence is therefore not global identity of descriptions, but a local condition of consistency and evolutionary compatibility of individual event structures.

Lorentz transformations may appear in the observable description as consistent forms of cognitive reconstruction between different frames in cases where the difference between frames is minimal and allows a consistent matching of events. However, they do not imply a global metric or objective symmetry, but merely express the possibility of coherent cognitive description within a limited causal accessibility.

8.3 Superdeterminism and Observable Freedom

Within the context of the hypothesis, one may ask: is superdeterminism allowed? That is, can the observer be entirely predetermined by the fundamental structure?

The answer depends on how the fundamental structure is interpreted. If it allows a complete reconstruction of all frames and observers' cognitive trajectories, then the hypothesis is compatible with superdeterminism. However, from the perspective of the observer, each transition between frames is experienced as free and locally coherent, without access to global information.

Thus, in the hypothesis:

- superdeterminism is possible as a global property of the fundamental structure;
- yet operationally, the observer always acts under conditions of *local freedom*, constrained only by cognitive stability;
- this allows one to reconcile predictability with the relative independence of local experience.

See also the discussion of superdeterminism in the context of quantum theory in [18, 19].

8.4 Relation to Other Theories

The proposed approach shares conceptual ground with:

- relational quantum mechanics (RQM) [6], where physical information is defined relative to the observer;
- quantum frameworks with dynamic causal structure [7];

- the philosophy of operationalism, where reality is defined through measurement procedures.

What distinguishes the hypothesis of local causality is its emphasis on the cognitive structure of the observer — their memory, perceptual coherence, and event reconstruction. It is precisely this cognitive coherence that replaces the role of a global background.

8.5 The Role of the Cognitive Superstructure

Although the hypothesis lacks a fundamental spacetime, it presupposes the existence of some underlying structure $\mathfrak{B}$ from which admissible causal slices and cognitive trajectories can be reconstructed. This structure need not be geometric; it may be described, for example, by a scalar field on $\mathbb{R}^2$, as in the toy model. This aligns with the idea of an "informational foundation" of physics [8, 20].

A key consequence: spacetime, causality, and events are not fundamental, but can be reconstructed as *cognitively emergent phenomena* from the coherent interpretation of a more fundamental structure.

> *Thus, the shift from a fundamental spacetime to cognitive coherence does not lead to a loss of predictive power, but instead opens the way to explaining observed symmetries, quantum uncertainty, and experiential consistency as natural consequences of local causal structure.*

9 Physical Realizations and Perspectives

Despite its abstract nature, the proposed hypothesis of local causality and cognitive coherence yields concrete physical consequences and prospects for both theoretical and experimental realization. This section outlines possible applications of the hypothesis, ways it might be tested, and its relation to existing fundamental theories.

The terms "cognitive structure," "cognitive reconstruction," and "cognitive coherence" are understood as defined in Sections 7 and 8.

9.1 Cognitive Reconstruction and Quantum Uncertainty

One of the central consequences of the hypothesis is a natural explanation of quantum uncertainty. Since events are cognitively defined and arise only within a coherent causal slice, their presence in the observer's memory is always subject to constraints on possible reconstructions in another inertial frame. This imposes fundamental limits on the simultaneous definiteness of events across different frames—analogous to the Heisenberg uncertainty principle [16, 11], and consistent with operational limitations in generalized probabilistic theories [21].

Thus, quantum uncertainty can be interpreted not as the result of stochastic dynamics, but as a consequence of constraints on cognitively admissible event reconstructions under causal structure transitions.

9.2 Origin of Lorentz Transformations

As shown earlier, Lorentz transformations can emerge as permissible forms of observable transformations between cognitively coherent frames $\mathcal{O} \to \mathcal{O}'$, each described by its own cognitive structure $\gamma_{\mathcal{O}}$ (see definition in Section 1). This offers a new perspective on their origin: they are not postulated, but derived from the requirement of cognitive consistency and minimal distortion of memory under transitions between frames. In this interpretation, Lorentz invariance is not a fundamental symmetry of nature, but a cognitively optimal form of event reconciliation between closely related frames.

This opens a path to deriving other symmetries as cognitively stable forms—possibly including the Standard Model symmetries $(\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1))$—as consequences of cognitive constraints on observers, realized through stable physical structures (see also approaches reconstructing symmetries from informational and cognitive principles [20, 22]).

9.3 Relation to General Relativity

Although the hypothesis discards global spacetime as fundamental, it still permits general relativity to emerge as an effective description of coherent observer dynamics, where the cognitive structures $\gamma_{\mathcal{O}}$ form a smooth manifold. In this approach, the metric is not fundamental, but arises as an effective tool for parametrizing transformations between cognitive structures in the limit of continuity.

This enables the construction of emergent geometry, where metric curvature expresses the deformation of mutually consistent cognitive structures among observers.

9.4 Experimental Consequences

Since the hypothesis allows for discrepancies between the observable and the direct (external) structure, one may consider scenarios in which cognitive coherence breaks down. Such effects could manifest:

- under extreme changes in frame—e.g., at high accelerations where memory reconstruction fails;
- in quantum entanglement, where coherence between observers may lead to discrepancies irreducible to classical causes, analogous to decoherence and pointer-state selection [23];
- in models involving multiple observers, where agreement of causal slices is ambiguous and cognitive paradoxes may arise.

Although these phenomena require more precise formalism, their predictability under the hypothesis makes it possible to identify experimentally observable consequences distinct from those of classical or standard quantum theory.

9.5 Future Directions

The proposed framework opens several promising research avenues:

- Formalization of the algebraic structure of cognitive transformations and construction of cognitively invariant dynamics.
- Development of field theory on a timeless fundamental structure (e.g., $\mathbb{R}^4$), where observable fields arise as projections onto cognitively selected causal slices.
- Investigation of the mechanism of emergent time based on the density of coherent cognitive projections.
- Analysis of interacting observers and consistent event structure under limited cognitive reconstruction.

In the longer term, a full reconstruction of the Standard Model and general relativity may be possible as cognitively optimal structures evolving under limited access to the fundamental substrate.

> *Thus, the hypothesis of local causality not only explains space and time as cognitively emergent phenomena, but also provides a path toward reinterpreting all of fundamental physics—from symmetries and quantization to gravitation—in terms of observable, coherent reconstructions.*

10 Conclusion

This work has proposed a new formulation of causality as a local and cognitively conditioned phenomenon. By abandoning the assumption of a global spacetime, we have redefined the fundamental concepts of events, time, and space as emergent constructs arising within observable causal structures. The introduced distinction between direct and observed transformations made it possible to resolve coordination paradoxes between different inertial frames, while preserving the internal cognitive consistency and experiential continuity of the observer.

The main results of this work include:

- The formulation of two postulates of local causality, providing an operational definition of admissible events within each inertial frame;
- The introduction of the observer's cognitive structure as a minimal carrier of causal reconstruction;
- The distinction between direct (external) and observed (internal) transformations between inertial frames;
- The construction of a toy model (see Section 6) illustrating the emergence of spacetimes and the multiplicity of cognitive descriptions based on a simple scalar field;
- The demonstration that relative velocity between inertial frames can be represented as the angle between their cognitive time directions;
- The demonstration that Lorentz transformations can emerge as observed cognitive transformations under certain conditions;
- The indication of a potential derivation of fundamental theories (quantum field theory, general relativity) from cognitively consistent reconstruction of events.

Importantly, Lorentz transformations in this framework are not treated as fundamental symmetries of physical spacetime. Their equations appear as forms of cognitively consistent transformations between observers under conditions of local non-contradiction and causal compatibility. Thus, Lorentz invariance is not postulated but arises as a cognitive limit structure in the presence of local agreement between inertial frames (see Section 7).

It is also important to emphasize that cognitive structures of events may differ not only between inertial frames but also between different observers within the same frame. These differences result from individual trajectories of perception, varying access to causal connections, and the contents of the observer's memory (see the discussion of cognitive structures in Section 8). As a result, coordination of events between observers requires admissible cognitive interaction and memory reconstruction within the new causal admissibility. This further reinforces the abandonment of a universal global ontology of events and emphasizes the operational character of physical reality.

Thus, the hypothesis of local causality opens a new path for rethinking the structure of physical reality. In this view, space and time are not fundamental elements of the universe, but rather the result of cognitive interpretation of accessible events. This perspective unifies relativistic, quantum, and operational approaches, removing the need for a predefined metric or global ontology.

Several open questions remain: how to formalize field dynamics, how to construct a theory of interacting observers, and how to reconcile multidimensional cognitive structures. These questions require further investigation, but it is already clear that the proposed framework provides conceptual and formal tools for a radical revision of the foundations of physics.

It should be emphasized that within this hypothesis, space and time are not regarded as fundamental entities. Their structure arises as the result of cognitive interpretation of causally admissible correlations within the accessible subset of events and experiences. This suggests the possibility of a deeper level of description, independent of any a priori notions of events or metric. One potential direction for further analysis is a model of a real scalar field without internal symmetries or preferred directions, defined on a four-dimensional Euclidean structure without time (see also [7, 8] for related approaches). While such a formulation lies beyond the formal scope of this paper, it sets a direction for future work on the formalization of the hypothesis and the emergence of physical structure.

> *The future description of nature may require abandoning the idea of a universal spacetime. Instead, we may find coherent islands of cognitive causality, within which events, laws, and symmetries emerge as manifestations of a deeper underlying structure.*

A Formal Note on Memory Modification under Direct Transformations

Within the framework of the local causality hypothesis, the observer's memory is considered part of their cognitive structure $\gamma_{\mathcal{O}}$, representing the internal model of causal relations and memory, and belonging to the causal section $\mathcal{C}_{\mathcal{O}}$. When transitioning between inertial frames, memory must be reconstructible within the new causal structure $\mathcal{C}_{\mathcal{O}'}$, requiring a consistent mapping (see also [7, 11] for operational analogies in quantum theory):

$$f_{\text{mem}} : \gamma_{\mathcal{O}} \cap \text{Memory} \longrightarrow \gamma_{\mathcal{O}'} \cap \text{Memory},$$

where Memory denotes the subset of the cognitive structure containing the observer's recollections of past events, including information stored in memory and reconstructible as part of the causally admissible experience.

Since direct transformations $F : \mathcal{C}_{\mathcal{O}} \to \mathcal{C}_{\mathcal{O}'}$ are defined at the level of the external formalism, they may map some memory elements to events that are not causally reachable from the current state in $\mathcal{O}'$. In this case, a cognitively admissible modification of memory is required to eliminate inconsistencies.

A.1 Condition for Admissible Modification

Let $\mathcal{M}_{\mathcal{O}}^{\text{mem}} \subset \gamma_{\mathcal{O}}$ denote the set of observer memories in frame $\mathcal{O}$, and $\mathcal{M}_{\mathcal{O}'}^{\text{mem}} \subset \gamma_{\mathcal{O}'}$ in frame $\mathcal{O}'$. A direct mapping $F : \mathcal{C}_{\mathcal{O}} \to \mathcal{C}_{\mathcal{O}'}$ may result in:

- Some memory elements $p \in \mathcal{M}_{\mathcal{O}}^{\text{mem}}$ being mapped to events $F(p) \notin \mathcal{C}_{\mathcal{O}'}$, i.e., they become inadmissible;
- New events $p' \in \mathcal{C}_{\mathcal{O}'}$, absent from $\mathcal{C}_{\mathcal{O}}$, becoming causally accessible and interpretable as "memories."

The modification of memory is admissible if:

- For each $p \in \mathcal{M}_{\mathcal{O}}^{\text{mem}}$, either $F(p) \in J^-(q) \cup J^+(q)$ for some $q \in \gamma_{\mathcal{O}'}$, i.e., the event remains admissible;
- Or there exists a valid substitution or removal of p according to functional equivalence;
- And memory extension is admissible if the new events $p' \in \mathcal{C}_{\mathcal{O}'}$ are cognitively compatible with the reconstructed structure and cause no logical contradictions.

Here, $J^{\pm}(q)$ denotes the causal past or future of event q. This condition ensures that memory in the new inertial frame remains cognitively admissible and functionally coherent, despite the absence of global event invariance.

A.2 Functional Criterion for Substitution and Extension

If for some memory $p \in \mathcal{M}_{\mathcal{O}}^{\text{mem}}$ the condition of cognitive admissibility is not satisfied, it must either be removed or — if possible — substituted with a functionally equivalent cognitive representation in the new frame. Such a substitution is possible if there exists a partial mapping

$$\mu : \mathcal{M}_{\mathcal{O}}^{\text{inadmiss}} \longrightarrow \gamma_{\mathcal{O}'} \cap \text{Memory},$$

where $\mathcal{M}_{\mathcal{O}}^{\text{inadmiss}} \subset \mathcal{M}_{\mathcal{O}}^{\text{mem}}$ is the subset of memories inadmissible in $\mathcal{C}_{\mathcal{O}'}$, and the target is cognitively reconstructible memories in $\gamma_{\mathcal{O}'}$.

This mapping does not require global correspondence of events between frames: it suffices that each $\mu(p)$ is cognitively perceived by the observer as an admissible memory, functionally equivalent to the original p, even if it arises from a different causal context.

Functional equivalence here means that for any internal dynamics $D_{\mathcal{O}}$ of the observer depending on memory, we have

$$D_{\mathcal{O}'}(\mu(p)) \approx D_{\mathcal{O}}(p),$$

where $\approx$ denotes the preservation of cognitive consistency: the observer continues to identify as the same subject, i.e., their reconstructed cognitive structure maintains subjective identity within a coherent experience.

Furthermore, new causally accessible events $p' \in \mathcal{C}_{\mathcal{O}'}$ not present in the previous structure may become available. In this case, it is cognitively admissible to *extend* memory with such events if they are consistent with the already reconstructed structure and do not violate cognitive coherence.

Elimination of memory is admissible if the event cannot be incorporated into the reconstructed cognitive structure without violating causal admissibility or consistency. That is, the event must not be allowed within the reconstructed cognitive cone and cannot be substituted or reinterpreted without losing perceptual integrity.

A.3 Stability of Memories under Event Coincidence

If an event $p \in \mathcal{M}_{\mathcal{O}}^{\text{mem}}$ remains present in both causal sections $\mathcal{C}_{\mathcal{O}}$ and $\mathcal{C}_{\mathcal{O}'}$, and the observer's cognitive stability holds, it should remain part of memory in the new frame. This follows from the fact that the event's information is realized as a causally connected chain within the cognitive structure $\gamma_{\mathcal{O}}$, and if this structure is preserved (or suitably modified), the chain persists within $\gamma_{\mathcal{O}'}$.

Therefore, even if other memory elements are altered, the recollection of p should be preserved or reconstructed in a functionally equivalent form compatible with the new causal structure.

A.4 Consequence for Observed Transformations

Memory modification is necessary only at the level of direct transformations. Observed transformations, by definition, operate solely within cognitively admissible structures. Therefore, they already include modified memory and require no further reconciliation. In other words, the observed history is always cognitively consistent — even if its physical correspondence with the previous frame was disrupted under a direct transition.

A.5 Interpretation

This behavior reflects a fundamental principle: *an observer cannot remember what could not have been observed*. If a transition to a new inertial frame renders an event inadmissible, its image in memory must be cognitively reinterpreted or eliminated. Such modification is not a flaw or failure, but a necessary part of cognitive adaptation to a new causal structure.

This behavior directly follows from Postulate 1 of the local causality hypothesis, according to which the entire observable structure of the world is determined by the internally coherent causality of the observer. In the absence of externally given time, cognitive reconstruction becomes essential to maintaining the continuity of subjective experience and coherence of the observed sequence of events.

This explains how consistency of perception is preserved in the absence of a global spacetime: the continuity of experience is ensured not by retaining all data, but by their cognitively consistent reconstruction.

References

[1] Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler. *Gravitation*. W. H. Freeman, 1973.

[2] Robert M. Wald. *General Relativity*. University of Chicago Press, 1984.

[3] Judea Pearl. *Causality: Models, Reasoning, and Inference*. Cambridge University Press, 2nd edition, 2009.

[4] Asher Peres. *Quantum Theory: Concepts and Methods*. Kluwer Academic, 1995.

[5] Niels Bohr. The quantum postulate and the recent development of atomic theory. *Nature*, 121:580–590, 1928.

[6] Carlo Rovelli. Relational quantum mechanics. *International Journal of Theoretical Physics*, 35:1637–1678, 1996.

[7] Lucien Hardy. Towards quantum gravity: A framework for probabilistic theories with non-fixed causal structure. *Journal of Physics A: Mathematical and Theoretical*, 40:3081–3099, 2007.

[8] Daniele Oriti, editor. *Approaches to Quantum Gravity*. Cambridge University Press, 2009.

[9] Don N. Page and William K. Wootters. Evolution without evolution: Dynamics described by stationary observables. *Physical Review D*, 27:2885, 1983.

[10] Giulio Chiribella, Giacomo Mauro D'Ariano, and Paolo Perinotti. Informational derivation of quantum theory. *Physical Review A*, 84:012311, 2011.

[11] Časlav Brukner. Quantum causality. *Nature Physics*, 10:259–263, 2014.

[12] Ognyan Oreshkov, Fabio Costa, and Časlav Brukner. Quantum correlations with no causal order. *Nature Communications*, 3:1092, 2012.

[13] Lucien Hardy. Reconstructing lorentz transformations from operational postulates, 2013. arXiv:1303.1538 [quant-ph].

[14] Flaminia Giacomini, Esteban Castro-Ruiz, and Časlav Brukner. Quantum mechanics and the covariance of physical laws in quantum reference frames. *Nature Communications*, 10:494, 2019.

[15] Rodolfo Gambini and Jorge Pullin. Relational physics with real rods and clocks and the measurement problem of quantum mechanics. *Foundations of Physics*, 37:1074–1092, 2007.

[16] Christopher A. Fuchs, N. David Mermin, and Rüdiger Schack. An introduction to qbism with an application to the locality of quantum mechanics. *American Journal of Physics*, 82:749–754, 2014.

[17] Stephen W. Hawking and George F. R. Ellis. The large scale structure of space-time. *Cambridge Monographs on Mathematical Physics*, 1973.

[18] Sabine Hossenfelder and Tim Palmer. Rethinking superdeterminism. *Frontiers in Physics*, 8:139, 2020.

[19] Nicolas Gisin. Free will and superdeterminism, 2010. arXiv:1002.1392 [quant-ph].

[20] Lucien Hardy. Quantum theory from five reasonable axioms, 2001.

[21] Jonathan Barrett. Information processing in generalized probabilistic theories. *Physical Review A*, 75:032304, 2007.

[22] Wojciech H. Zurek. Quantum darwinism, classical reality, and the randomness of quantum jumps. *Physics Today*, 44:36–44, 1991.

[23] Wojciech H. Zurek. Decoherence, einselection, and the quantum origins of the classical. *Reviews of Modern Physics*, 75:715–775, 2003.