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Relational Coexistence Theory (TCR): Foundational Ontology for Quantum and Cosmological Phenomena

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Abstract

The "Teoria della Coesistenza Relazionale" (TCR, Relational Coexistence Theory) proposes an ontological framework in which spacetime $\mathbf{R}$ is not the primary level of reality, but emerges from a more fundamental relational domain $\mathbf{R}'$. Within this perspective, quantum and cosmological phenomena commonly treated as independent such as entanglement, decoherence, cosmic expansion, and the arrow of time are reinterpreted as different manifestations of the same underlying relational dynamics. The present work is devoted to the definition of the ontological assumptions and axiomatic structure of the TCR. In particular, it introduces the concepts of relational coexistence and emergence as the foundational elements from which physical phenomena in spacetime are derived. The aim of this study is not to provide an empirical validation of the framework, but to establish its internal coherence, conceptual consistency, and explanatory scope at the level of fundamental ontology. This work does not aim at providing a complete physical model or immediate empirical validation, but at establishing a coherent ontological and axiomatic framework within the scope of foundational physics.

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1 Introduction

In the current framework of physics, the description of the universe rests on two distinct theoretical pillars: general relativity (GR), which governs gravitation and the large-scale structure of spacetime [1, 2], and quantum mechanics (QM), which accounts for interactions at the microscopic level [3–5]. Both theories have been subjected to rigorous experimental tests, and their successes represent one of the highest achievements of modern science.

Nevertheless, contemporary theoretical physics is marked by a profound conceptual discontinuity: these two major triumphs of scientific knowledge operate in separate domains and fail to integrate into a unified framework. This fracture becomes evident in the inability to provide a coherent and widely accepted explanation of complex phenomena such as the origin of the universe, cosmic inflation [6–9], the non-homogeneous distribution of expansion, or the very nature of quantum entanglement.

Over the past decades, the unification of QM and GR into a consistent theoretical framework has become one of the central challenges of fundamental physics. This objective has given rise to research programs of remarkable mathematical and conceptual sophistication. Among the most notable attempts are:

- string theory, which describes particles as vibrations of one-dimensional entities in higher-dimensional spaces (Green, Schwarz, Witten, and others);
- loop quantum gravity, which discretizes the geometry of spacetime (Rovelli and Smolin [10, 11]);
- emergent gravity, which interprets curvature as a thermodynamic phenomenon (Jacobson [12], Padmanabhan [13], Verlinde [14]);
- models of discrete or causal spacetime (Markopoulou [15]).

Recent theoretical developments have further explored the idea that spacetime geometry may admit an emergent or thermodynamic description. In particular, Padmanabhan’s later work [16] and Verlinde’s extended formulation of entropic gravity [17] investigate scenarios in which gravitational dynamics can be reformulated in terms of thermodynamic or informational principles.

In a complementary but conceptually distinct context, Van Raamsdonk [18] showed—within specific holographic toy models—that features of spacetime connectivity can be related to patterns of quantum entanglement. Taken together, these approaches suggest that spacetime geometry and gravitational dynamics may be compatible with descriptions grounded in relational, thermodynamic, or informational structures, without by themselves fixing a unique underlying ontology.

While offering valuable insights and formal developments, none of these approaches has yet achieved direct experimental validation or a shared interpretative consensus. This leaves the central question unresolved: what ontological framework can accommodate, without contradiction, the descriptions provided by QM and GR.

The TCR proposes a conceptual shift to overcome the structural limits that separate QM and GR. Instead of quantizing spacetime directly or postulating its emergence from indeterminate entities, the TCR distinguishes itself from previous unification attempts through four fundamental features:

- Internal coherence: it is grounded on a primary relational ontology in which space and time are not assumed *a priori*, but emerge as derivative descriptions of coexistences among entities. This approach removes conceptual and interpretative contradictions, offering a unified language for both quantum and gravitational phenomena.
- GR–QM compatibility: starting from fundamental relations rather than a predefined spacetime structure, the TCR maintains compatibility with their experimental data.
- Current or potential experimental adherence: the model is designed to yield verifiable predictions, either indirectly, by confronting the formalism with existing cosmological and experimental data, or directly, through targeted experiments in quantum and astrophysical regimes, thus constituting an operationally feasible research program.

On these grounds, the TCR does not present itself as an antagonistic alternative to QM and GR, but rather as a unifying framework in which both find a natural place, without relinquishing their respective experimental achievements.

The TCR provides a unified framework in which apparently distinct phenomena are traced back to a single higher-level description grounded in primary relations. Within this perspective, cosmic inflation, large-scale inhomogeneities, and the current accelerated expansion of the universe emerge as manifestations of the same relational mechanism that lack direct observational confirmation. The theory also offers a new interpretation of entropy as an emergent property of coexistences, moving beyond purely statistical or geometric readings.

The present work follows the IMRaD structure (Introduction, Methods, Results, and Discussion):

- Section 1 (Introduction): defines the central problem, the theoretical context, and the limitations of existing theories, motivating the need for a new ontological framework.
- Section 2 (Methods): presents the conceptual and formal structure of the TCR, introducing the primary relational ontology R' , the function Ω , and the transformation Π , and specifies the criteria for derivation from observational data.
- Section 3 (Results): outlines the main unifications and reinterpretations provided by the TCR, including the connection between inflation, inhomogeneities, and cosmic acceleration, the new interpretation of entropy, and experimental predictions.
- Section 4 (Discussion): evaluates the theoretical and experimental significance of the results, explores the multidisciplinary implications of the proposed framework, lists supporting experiments for the theory, and proposes new ones for validation or falsification.

2 Method

2.1 Motivations and empirical context

The experimentally confirmed violations of Bell’s inequalities [19], particularly through loophole-free tests, rule out the possibility of accounting for quantum correlations by means of local hidden-variable theories. These violations were first systematically observed by Aspect et al. [20] and later confirmed with increasing experimental control by Hensen et al. [21], Giustina et al. [22].

As a consequence, any theoretical framework aiming to preserve realism must necessarily abandon locality in its classical formulation, or alternatively reconsider the conceptual foundations on which locality and causality are defined.

The most widespread interpretations of quantum mechanics are often grouped into two broad directions. On the one hand, epistemically oriented approaches—such as the Copenhagen interpretation—emphasize the limits of describing physical reality independently of the measurement context, refraining from committing to a fully observer-independent ontology [23, 24]. On the other hand, explicitly realist interpretations, such as Bohmian mechanics, retain an objective description of quantum systems at the price of introducing non-local structures whose compatibility with relativistic causality remains conceptually nontrivial [25, 26].

From a foundational perspective, both strategies present open difficulties. The former suspends ontological commitments at the fundamental level, while the latter preserves realism by postulating additional structures whose physical status is not directly accessible within spacetime. Importantly, the empirical violations of Bell’s inequalities do not by themselves mandate the abandonment of realism or locality in isolation, but rather indicate that the classical spatiotemporal framework underlying these notions may require revision.

2.2 Ontological assumptions

If we accept that two entangled particles cannot communicate through mechanisms internal to our spacetime, and we do not find a more ontologically satisfactory solution within the current spatiotemporal framework¹, the most logical and at the same time most parsimonious conclusion is that they are connected in another reality, here denoted as R' .

We are aware that positing an additional ontological domain R' is a strong assumption. However, this choice follows a standard scientific methodology: one formulates a hypothesis, even a controversial one; verifies its coherence with experimental data; and finally explores its practical and philosophical implications. Many realities that are now widely accepted, such as the relativity of time, were once regarded as implausible hypotheses.

From this perspective, two entangled particles behave like two “shadows,” that is, projections of the same entity in R' projected into R . Indeed, the two entities are

¹Other known options, such as retrocausal interpretations or models based on non-spatial algebraic structures, have been considered but discarded, as they require more complex ontologies or are less consistent with experimental evidence. Their inclusion in this context would introduce concepts that are not developed in the present theory, increasing the risk of confusion without providing interpretative benefits.

indistinguishable and unidentifiable in their properties as long as they remain in this state, and they may be situated at arbitrarily large distances while preserving the characteristics of projections, namely, changing simultaneously.

When, on the other hand, quantum correlation ceases, the particles behave as two projections of distinct entities. This analogy leads to two fundamental assumptions:

1. Entities in our reality R are projections of original entities in R' . Consequently, R' is the ontologically primary domain, while R is the emergent domain in which observable physical properties manifest.
2. In R' , entities may be at the same time perfectly united or completely separate, depending on their state of coexistence. To quantify this condition, we introduce the coexistence parameter Ω , defined as a measure of relational intensity in R' . Ω is a continuous and evolving parameter, with $\Omega = 1$ indicating that two entities in R' are, in fact, the same entity, and $\Omega = 0$ indicating a total absence of relation.

These assumptions allow entanglement to be interpreted as the direct manifestation of coexistence in R' , without requiring hypotheses of non-local interaction in spacetime.

If two entangled particles can be regarded as entities emerging from R' into our reality R , the logical next step is that all entities in our spacetime are nothing but emergences of entities from the original reality R' .

Here is a list of the only features of R' that we can deduce from experimental data:

1. R' is atemporal and aspatial, given the instantaneous emergence, at the quantum level, of changes in R' .
2. There exist entities in R' , which we denote as $\mathbf{e}'$, to distinguish them from entities in R , denoted as $\mathbf{e}$.
3. The entities $\mathbf{e}'$ in R' , inhabiting an atemporal and aspatial reality, cannot possess intrinsic state properties (such as mass, charge, or other physical attributes), but can only be described through their relations with other entities. This implies that R' is a purely relational reality.
4. Entities in R' possess a certain degree of coexistence with one another, ranging from $\Omega = 1$ (total fusion and indistinguishability) to $\Omega = 0$ (absence of any form of relation).

The last ontological novelty we introduce is the function Π , which acts as a bridge between R' and R , enabling and quantizing the emergence in R of entities from R' . Experimental observations are consistent with an instantaneous emergence of relations from R' to R in quantum phenomena, while the evolution of relations in R follows the laws of spacetime.

The two elements Π and Ω will constitute the foundation for formulating testable predictions in the following chapters.

Both the parameter Ω and the function Π are new concepts introduced in this theory. In this section their ontological description is provided, while a first quantitative treatment will be presented here in simplified terms. As with all new theoretical structures, a long process—likely years—will be required before arriving at a rigorous mathematical formulation.

At this stage, we focus on the analysis of limiting cases:

- Case $\Omega = 1$: two entities in R' coincide completely, making them indistinguishable and inseparable; in R , this manifests as perfect correlations, independent of distance and experimental conditions, analogous to an “ideal” entanglement not subject to degradation.
- Case $\Omega = 0$: two entities in R' are totally independent, and in R they exhibit no correlation whatsoever, not even statistical.
- Transitions of Ω : intermediate variations of Ω generate partial correlations.
- Discrete Π : if Π operates as a mapping into quantized events, the emergent phenomena in R display discrete jumps corresponding to changes in R' .
- Continuous Π : if Π operates as a fluid transformation, changes in R' are reflected in progressive and observable variations in R , since they operate within the temporal domain.

These limiting cases, though simplified, already allow for the formulation of novel and experimentally testable predictions, which will be outlined in the following sections.

As a final logical consideration, each entity e in R has a one-to-one correspondence with an entity e' in R' . Since the phenomenal reality R arises as a projection of R' , which is purely relational, it follows that R too, in its original structure, is a relational space. Properties that we commonly interpret as “intrinsic,” such as charge, may also emerge from deeper relational configurations. The theory proposed here assumes that every observable property in R ultimately derives from relations of coexistence in R' , while acknowledging that a quantitative and predictive formulation of this derivation will require further developments.

This ontological framework provides a natural explanation for correlations manifested within spacetime, by interpreting them as projections of a preexisting coexistence in R' . In this view, no fundamental “action” occurs between spatially separated points; rather, an underlying ontological unity is instantiated as multiple localized events in R .

The conflict between realism and locality, highlighted by Bell’s theorem, loses its traditional meaning. Realism is preserved by assuming the objective existence of R' , while “non-locality” is no longer an anomaly, since the fundamental relations are not subject to distance or propagation within spacetime during emergence in R .

This perspective suggests a different ontological reading of the apparent discontinuity between the microscopic and macroscopic worlds: the function Π ensures that the emergence of relations in R is instantaneous only in the transition from R' (as occurs in quantum phenomena), while their evolution within R remains constrained by relativistic laws and spatiotemporal causality.

In this framework, what in traditional interpretations appears as a problem—instantaneous communication, non-local hidden variables, collapse of the wave function—becomes in this framework a natural effect of the original relational structure. The paradoxes admit an ontological resolution within this framework in the existence of R' . The quantitative treatment of how R' accounts in detail for observed phenomena will be developed in the following sections.

The quantities Ω and Π are introduced here as ontological primitives, not as physical observables or dynamical variables; their translation into measurable physical quantities is deferred to future developments and is not required for the internal coherence of the present framework.

2.3 Proposed framework

Having established in the ontological assumptions the existence of an original reality R' and the central role of entities $\mathbf{e}'$ and their relations, the next step is to construct a theoretical structure that translates these principles into an operational model. This step is not merely descriptive, but a methodological necessity: only by defining a coherent and structured framework is it possible to transform an ontological hypothesis into a theory capable of producing testable predictions.

In this context, the proposed model is articulated on three distinct yet interconnected conceptual levels:

1. Level 1 — Reality R' : the ontologically primary domain, devoid of space and time, populated by entities $\mathbf{e}'$ whose only possible description is given by their mutual degree of coexistence Ω .
2. Level 2 — Function Π : the mapping that enables the emergence of entities and relations from R' to R . Π may operate in discrete mode (quantized events) or continuous mode (progressive transformations).
3. Level 3 — Reality R : the emergent domain in which entities $\mathbf{e}$, in one-to-one correspondence with entities $\mathbf{e}'$ in R' , manifest endowed with physical properties and subject to spatiotemporal laws.

The parameter Ω quantifies relational intensity in R' :

- $\Omega = 1$: total coexistence, indistinguishable entities in R' and perfect correlations in R , independent of distance or experimental conditions.
- $\Omega = 0$: absence of relation in R' , no observable correlation in R .
- $0 < \Omega < 1$: partial correlations.

The function Π governs the transition between the two domains:

- Discrete Π : emergence occurs through quantized jumps, generating abrupt variations in observed physical properties.
- Continuous Π : changes in R' are reflected in R gradually, with transitions observable as progressive variations in correlation.

The proposed framework is not merely an interpretative hypothesis, but a theoretical structure that integrates quantum and macroscopic phenomena into a single scheme, preserving realism while overcoming the conceptual difficulties of traditional interpretations. The following sections will develop the quantitative formalization of Ω and Π and show how these can be employed to derive experimental predictions.

2.4 Comparison with existing paradigms

Compared to the Copenhagen interpretation [23, 24], the present formulation goes beyond the notion of a purely instrumental description of phenomena: here, the correlations observed in R derive from an ontologically primary reality R' , rather than from a mere probabilistic formalism. The “collapse” is not an arbitrary process, but the manifestation in R of a relational change in R' .

When contrasted with hidden-variable interpretations (e.g., de Broglie–Bohm [25, 27]), the model does not postulate a deterministic evolution within spacetime, but a pre-spatiotemporal dynamics in which entities $\mathbf{e}'$ are described solely by their degree of coexistence Ω . Fundamental information is not transported through spacetime, but is intrinsic to the relations themselves.

Unlike many-worlds interpretations (Everett [28, 29]), the proposed framework does not require an ontological proliferation of branching universes. The uniqueness of R is ensured by the mapping Π , which selects and actualizes a coherent set of entities and relations from R' .

In comparison with emergent spacetime models (e.g., holographic approaches [30] or causal set theories [31, 32]), the present approach is distinguished by the primary and non-derivative character of relations in R' . Space and time do not emerge from a network of causal events in R , but are parameters derived from preexisting coexistences in R' .

The holographic principle, as formulated by Bousso [33], also represents a significant precursor to emergent-spacetime approaches, emphasizing the informational and thermodynamic nature of gravitational degrees of freedom.

These proposals are conceptually connected to thermodynamic-gravity frameworks such as those of Jacobson [12] and Padmanabhan [13], and to Verlinde’s entropic-gravity formulation [14, 17]. In contrast, the TCR postulates a deeper ontological layer R' in which relations themselves are primary, preceding both geometry and energy–entropy dualities.

In contrast with quantum gravity models, the proposed framework offers a reinterpretation of gravity as the universe’s natural and constant tendency to increase coexistence among entities [10].

3 Conceptual consequences and results

3.1 Mathematical formulation of the ontological assumptions

In Chapter 2, the ontological assumptions motivating the introduction of the original reality R' , the coexistence parameter Ω , and the emergence function Π were outlined. These elements were presented as the logical and parsimonious consequence of a phenomenological analysis of quantum systems—particularly entanglement—and as a coherent alternative to traditional interpretations based solely on spatiotemporal structure.

In this section, we translate these assumptions into an essential mathematical formulation, with the goal of showing how the properties of R' and the relations among its entities can generate the observable correlations in R . The results presented here thus constitute the first step toward a quantitative modeling of the proposed framework, capable of directly connecting original relational quantities with experimental measurements in spacetime.

Let

$$R' = \{e'_1, e'_2, \dots\} \quad (1)$$

denote the *original reality*, composed of purely relational entities e'_i , lacking spatiotemporal coordinates and intrinsic physical properties, and let

$$R = \{e_1, e_2, \dots\} \quad (2)$$

denote the *emergent reality*, in which the entities e_i possess observable physical properties.

One-to-one correspondence

We postulate the existence of a bijective mapping

$$\Pi : R' \longrightarrow R, \quad e_i = \Pi(e'_i), \quad \Pi^{-1}(e_i) = e'_i \quad (3)$$

where Π is the *emergence function*, responsible for assigning physical properties to the entities of R' .

Coexistence parameter

We define a function

$$\Omega : R' \times R' \longrightarrow [0, 1] \quad (4)$$

that measures the degree of *relational coexistence* between two entities e'_i and e'_j in R' , with the following properties:

$$\Omega(e'_i, e'_j) = \Omega(e'_j, e'_i) \quad (\text{symmetry}), \quad (5)$$

$$\Omega(e'_i, e'_i) = 1 \quad (\text{identity}), \quad (6)$$

$$\lim_{\Omega(e'_i, e'_j) \rightarrow 0} d_R(e_i, e_j) \rightarrow \infty \quad (\text{relational separation in } R). \quad (7)$$

Observable correlations in R

The projection of the correlations Ω of R' into reality R is given by:

$$R_{ij} = \Pi \Omega_{ij} \quad (8)$$

which, in extended form, can be written as:

$$\begin{array}{c|ccccc} & e_1 & e_2 & \cdots & e_{n-1} & e_n \\ \hline e_1 & e_{11} & e_{12} & \cdots & e_{1,n-1} & e_{1n} \\ e_2 & e_{21} & e_{22} & \cdots & e_{2,n-1} & e_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ e_{n-1} & e_{n-1,1} & e_{n-1,2} & \cdots & e_{n-1,n-1} & e_{n-1,n} \\ e_n & e_{n1} & e_{n2} & \cdots & e_{n,n-1} & e_{nn} \end{array} = \Pi \begin{array}{c|ccccc} & e'_1 & e'_2 & \cdots & e'_{n-1} & e'_n \\ \hline e'_1 & 1 & [0,1] & \cdots & [0,1] & [0,1] \\ e'_2 & [0,1] & 1 & \cdots & [0,1] & [0,1] \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ e'_{n-1} & [0,1] & [0,1] & \cdots & 1 & [0,1] \\ e'_n & [0,1] & [0,1] & \cdots & [0,1] & 1 \end{array} \quad (9)$$

Limiting regimes

$\Omega = 1$ $e'_i = e'_j$: entities are indistinguishable and inseparable in R' ; in R they manifest as perfect correlations, independent of distance:

$$R(e_i, e_j) = \Pi \quad \text{independent of } d_R(e_i, e_j). \quad (10)$$

$\Omega = 0$ Absence of relation in R' , no correlation in R :

$$R(e_i, e_j) = 0, \quad d_R(e_i, e_j) \rightarrow \infty. \quad (11)$$

$0 < \Omega < 1$ Partial correlations.

Nature of the function Π

- *Discrete* Π : the projection generates quantized states during the emergence of a relation in R , with jumps in observable properties.
- *Continuous* Π : the projection produces progressive and smooth transitions in R when relations evolve within the temporal domain.

3.1.1 Minimal correlation diagram

Figure 1 presents the empirical form of $\Omega(r)$, which is not fixed *a priori*, but, for illustrative purposes, an exponential decay is adopted in this section. The monotonic decay reflects the basic relational principle: the lower the ontological coexistence, the greater the separation in the spatiotemporal projection R .

This minimal form is of central importance, as it represents the baseline behavior upon which more complex physical contributions are superimposed.

3.1.2 Sensitivity of distance to variations in Ω

Figure 2 shows $\Omega(r)$ highlighting two regimes of physical relevance:

- **High- Ω regime** (filaments, galaxy clusters): in this region Ω is large and stable. Small variations in Ω correspond to negligible variations in the physical distance r . Local expansion of space is therefore strongly suppressed.
- **Low- Ω regime** (cosmic voids): here Ω is already small. Even minimal decreases in Ω correspond to large increases in r . This naturally leads to accelerated expansion in voids, without invoking a uniform “dark energy” field.

This property of the function $\Omega(r)$ is qualitatively consistent with astronomical observations showing differential expansion rates between underdense and overdense regions of the Universe.

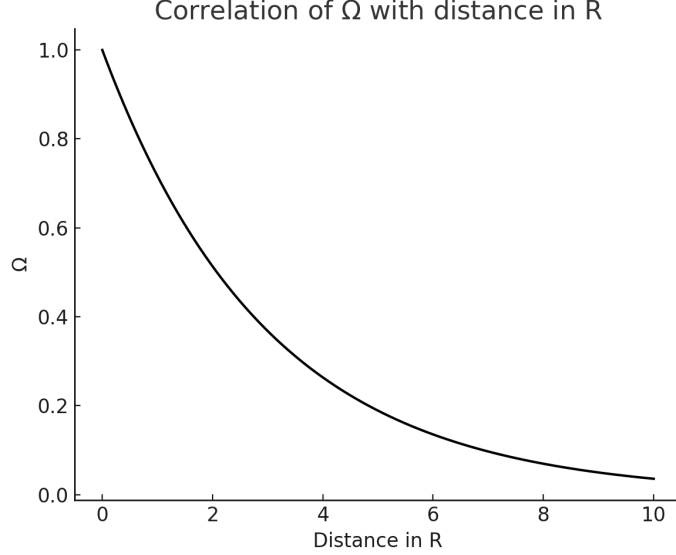


Fig. 1 Minimal correlation between Ω and distance in R . The curve shows the monotonic decay of Ω with distance, without additional contributions.

3.2 Limiting case: the Big Bang

3.2.1 Model in R'

In the standard model, the Big Bang [34, 35] is interpreted as the origin of space and time. In the TCR, however, spacetime does not constitute an ontological foundation, but rather a phenomenon derived from the actualization of relations among original entities in R' .

Before the Big Bang, in the original state R' , all entities were mutually coexistent in potential, that is, each was connected to all the others according to the following scheme:

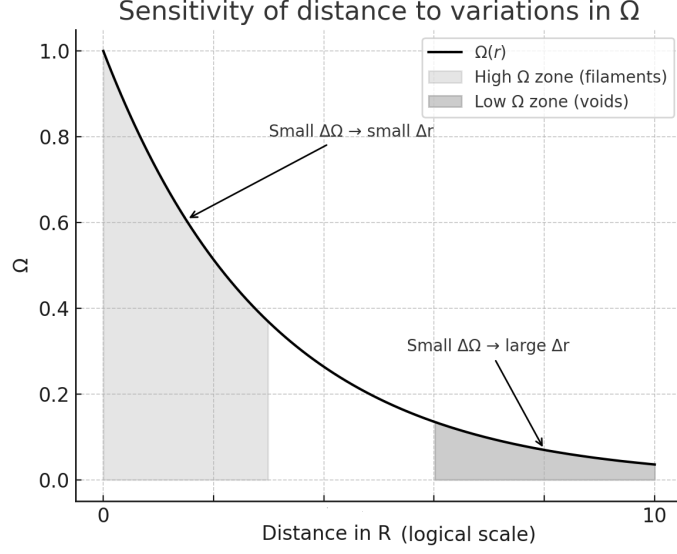


Fig. 2 Sensitivity of the physical distance r to variations in Ω . The plot shows how, in low-coexistence regions, small variations in Ω produce large variations in r .

$$\Omega_{ij} = \begin{array}{c|ccccc} & e'_1 & e'_2 & \cdots & e'_{n-1} & e'_n \\ \hline e'_1 & 1 & 1 & \cdots & 1 & 1 \\ e'_2 & 1 & 1 & \cdots & 1 & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ e'_{n-1} & 1 & 1 & \cdots & 1 & 1 \\ e'_n & 1 & 1 & \cdots & 1 & 1 \end{array} \quad (12)$$

Conditions of maximal coexistence

- Each entity $e'_i \in R'$ is maximally related to every other e'_j , including itself.
- The coexistence function satisfies: $\Omega(e'_i, e'_j) = 1 \quad \forall i, j \in \{1, \dots, n\}$.
- The resulting configuration corresponds to a fully filled, symmetric, and homogeneous matrix (fully connected).

This condition of perfect symmetry can be described as an “external instant,” characterized by the absence of variation. In such a regime, time in R did not exist, as it was unnecessary, and likewise space was undefined: all entities were fused in total coexistence, rendering the actualization of R itself superfluous.

Emergence of R

We may conclude that the actualized reality R in which we live is an emergent phenomenon of the breaking of the initial perfect symmetry in R' . R arises from the variation of perfect coexistence among entities in R' .

Comparative ontology

In other terms:

- The existence of R (the actualized reality) is contingent.
- The existence of R' (the original reality) is necessary, eternal, and self-sufficient.

At this stage it becomes necessary to introduce the parameter τ , conceived as the functional equivalent of time within R' . It does not represent a physical quantity, but rather a logical-mathematical construct that allows one to describe and model the order of variations of the coexistence function Ω in R' . In this sense, τ should be understood solely as a formal representational tool, devoid of its own ontology.

It is important to stress that the relational parameter τ does not play the role of a hidden or auxiliary time variable. Variations of τ do not correspond to the passage of time in the emergent reality R , nor do they define a global temporal ordering. Instead, a given variation of τ may give rise to different amounts of emergent time in R , depending on the initial state of relational entropy and on its local rate of variation. Time in R is therefore not a direct image of τ , but an emergent quantity whose local flow depends on how relational entropy evolves in each region of spacetime. As a consequence, distinct regions of R may experience different effective temporal rates for the same variation of τ , reflecting the fundamentally local and relational nature of time in the TCR framework.

Summary

- Time in R derives from the variation of Ω along τ .
- Space in R derives from the separation of entities not perfectly coexistent in R' .
- Actualization in R is necessary only in the presence of imperfect coexistence.

3.2.2 Relational temperature

We may define relational temperature as the sum of the oscillations (in amplitude and frequency) of the coexistences Ω between an entity e' and all entities connected to it in R' :

$$T_{\text{rel}} \propto \sum_i A_{e'_i} \cdot f_{e'_i} \quad (13)$$

where:

- $A_{e'_i}$ is the amplitude of the oscillation of coexistence $\Omega_{e'_i}$,
- $f_{e'_i}$ is the frequency of the same oscillation,
- the sum extends to all entities e'_i connected to e' in R' .

3.2.3 Initial temperature of the universe

On the basis of the previously introduced definition of relational temperature, and assuming the existence of a correlation between the temperature T_{rel} in R' and the temperature T in R , one may deduce that, at the initial instant and for an extremely brief interval, the temperature of the universe was $T = 0$, subsequently increasing rapidly and massively during the inflationary phase [36, 37].

3.2.4 Cosmic inflation

Cosmic inflation [6–9, 36] can be interpreted as a sudden decrease of coexistence in R' and, simultaneously, as the emergence of R as the actualized domain.

$$\Omega_{ij} = \begin{array}{c|ccccc} & e'_1 & e'_2 & \cdots & e'_{n-1} & e'_n \\ \hline e'_1 & 1 & 0.555 & \cdots & 0.556 & 0.557 \\ e'_2 & 0.555 & 1 & \cdots & 0.556 & 0.556 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ e'_{n-1} & 0.556 & 0.556 & \cdots & 1 & 0.555 \\ e'_n & 0.557 & 0.556 & \cdots & 0.555 & 1 \end{array} \quad (14)$$

This decrease led to the emergence of space and time in R , where entities began to separate, and it dramatically increased both the generated temperature and space. But if the variation of coexistence $\Omega_{e'_i}$ manifested as the emergent effect of the discrete creation of space and time in R , we may deduce that every variation of Ω in R' discretely creates or destroys space and time. As Ω decreases, space and time emerge, whereas as it increases, they are reduce. Through a sequence of logical steps, within the framework both the reasons for the expansion of space and time and the mechanisms by which it occurs. In the next paragraph, the theoretical and practical implications of this phenomenon will be discussed.

3.3 Relational entropy

Starting from an initial state of maximal order in R' , the universe transitioned, through inflation, toward a chaotic configuration. This transition naturally allows the introduction of the notion of relational entropy.

In the TCR, we define *relational entropy* S_{rel} as the global measure of the dispersion of entities due to the cumulative loss of coexistence in R' . Formally, it is expressed as the negative sum of coexistence variations. Relational entropy can be defined in two equivalent forms, depending on whether finite or infinitesimal variations of coexistence are described.

Discrete form.

When coexistence variations are treated as finite quantities:

$$S_{\text{rel}}(\tau) = - \sum_{i < j} \Delta \Omega_{ij}(\tau) \quad (15)$$

Continuous form.

In the differential limit, the definition becomes:

$$\frac{dS_{\text{rel}}}{d\tau} = - \sum_{i < j} \frac{d\Omega_{ij}(\tau)}{d\tau} \quad (16)$$

In this way, S_{rel} globally measures the loss of coexistence, while its derivative with respect to τ represents the growth rate of relational entropy.

This entropy is not merely a measure of relational disorder, but represents the intrinsic tendency of original reality to lose coherence among its configurations.

This progressive loss of relational coexistence is identified as the primary cause of several fundamental phenomena, which will be described in 4.1.

3.4 Fundamental forces as anti-entropic tendencies

Within the TCR framework, the fundamental forces of the universe assume a new and unifying role: they represent modalities through which the cosmos attempts to counteract the natural entropic drift inherent in the relational evolution of entities. In particular, if entropy is defined as the negative sum of coexistence variations in R' , then every force that acts to stabilize, reinforce, or maintain coexistences may be interpreted as an anti-entropic tendency, in continuity with insights already discussed in the literature [38, 39], but developed here within a coherent relational framework.

Gravity, in this context, is a force that, at every point in the cosmos, tends to increase relational coherence among entities, opposing the structural degradation that leads to fragmentation of bonds.

This reinterpretation resonates with prior attempts to link gravity to thermodynamic quantities, notably Jacobson's derivation of Einstein's equations from Clausius relations [12], Padmanabhan's thermodynamic view of horizons [13], and Verlinde's formulation of gravity as an entropic force [14, 17]. Within the TCR, these results acquire a direct ontological grounding: entropy and gravitation emerge from the same relational dynamics in R' .

In this sense, all fundamental interactions act as anti-entropic forces to relational entropy, generating structures, local coherences, persistences, and symmetries—phenomena that would otherwise be incompatible with a universal tendency toward the dissolution of relations. However, these anti-entropic forces do not prevail across most of the universe: the coherence they produce always remains local. The ordered structure of the universe—stars, planets, molecules, life—is therefore not an anomaly to be explained, but the local effect of a dynamic balance between increasing entropy and forces seeking to restore lost coexistence.

3.5 Relational entropy, decoherence time, and the flow of time

In the TCR, quantum decoherence is interpreted as a local consequence of the increase of relational entropy [40]. Consider an actualized entity e in the domain R , associated with its original counterpart e' in R' . The coexistence function $\Omega_{e'_i}(\tau)$ is defined as the degree of coherence between e and each of the entities e'_i connected to it in R' , at relational time τ .

The *relational coherence* of e at a given instant is given by:

$$C_{\text{rel}}^{(e)}(t) = \sum_i \Omega_{e'_i}(\tau) \quad (17)$$

This quantity measures the level of integration of e within its relational environment. If all coexistences are perfect ($\Omega_{e'_i} = 1$), C_{rel} attains its maximum value and the system is fully coherent. Conversely, if the coexistences collapse, C_{rel} tends to zero, indicating system decoherence.

When *relational entropy* (15) assumes positive and significant values, this implies a progressive reduction of coexistences, with a corresponding loss of coherence. There exists a critical threshold, C_{crit} , below which the system can no longer sustain coherent superpositions. In such a case, that is when $C_{\text{rel}}(t) < C_{\text{crit}}$, *effective decoherence* occurs: the wave function can no longer remain extended, and reality actualizes one of the possible outcomes through the function Π .

From this perspective, decoherence is not a sudden event, nor does it depend on an external observer, but rather emerges as a progressive and intrinsically relational process. The so-called “quantum measurement” is merely the manifestation of the crossing of a relational threshold: an ontological collapse due to the local loss of coexistence. The phenomenon of decoherence therefore appears as a particular case of the overall evolution of relational entropy in the cosmos.

Within the TCR framework, the flow of time is directly linked to the growth rate of relational entropy. Environmental noise represents the observable manifestation of this growth: the more noise a system experiences, the faster new relations are actualized in R , and the faster relational entropy increases. Cooling and isolating a quantum system can thus be understood as an attempt to reduce the derivative of relational entropy, thereby slowing the passage of time.

Formally, this relation can be expressed as:

$$t_{\text{int}} \propto \frac{dS_{\text{rel}}}{d\tau} \propto \frac{1}{\tau_{\text{dec}}} \quad (18)$$

where t_{int} denotes the internal time of the system, S_{rel} the relational entropy, and τ_{dec} the characteristic decoherence time.

This formulation implies that shorter decoherence times correspond to a faster flow of time, while longer decoherence times correspond to a slower flow. In the limit $\tau_{\text{dec}} \rightarrow \infty$, time halts, and for $\tau_{\text{dec}} < 0$, the arrow of time reverses.

In conceptual limiting case $\tau_{\text{dec}} < 0$, the system naturally undergoes the opposite transition: from a corpuscular state in R back to a wave-like superposition in R' , in contrast to ordinary decoherence in our everyday experience, where the spontaneous and natural process is the transition from wave to corpuscle.

Within the TCR framework, the notion of inverted arrow of time requires a fundamentally different interpretation from that usually adopted in spacetime-based theories. Time is not conceived as a continuous, globally defined dimension along which histories can be retraced, but as a finite, emergent quantity generated locally through variations of relational entropy. Consequently, the inversion of the temporal arrow does not correspond to a return to a past state or to the re-traversal of an earlier history. Rather, it denotes a process of re-approach toward configurations of higher relational coexistence, which can be realized through infinitely many distinct relational paths. In this sense, moving “backward in time” is analogous to approaching a region of space from different directions: the destination may be similar in relational structure, but

the trajectory is never the inverse of the one previously actualized. Since actualized configurations in R are discrete outcomes of the mapping Π , once realized they are not physically accessible again. As a result, concepts such as closed timelike curves, temporal loops, or causal paradoxes are not merely forbidden but are rendered physically meaningless within the TCR ontology.

3.6 Postulates

Postulate 1 – Existence of a relational domain R'

There exists an original ontological domain R' , composed of original entities e'_i , devoid of spatial localization and temporal dynamics, which exist in relation to one another through a symmetric coexistence function:

$$\Omega : R' \times R' \rightarrow [0, 1] \quad (19)$$

where $\Omega(e'_i, e'_j)$ represents the degree of coexistence between two original entities.

Postulate 2 – Perfect coexistence as an eternal stationary state

If for all entities $e'_i, e'_j \in R'$ one has $\Omega(e'_i, e'_j) = 1$ and Ω is constant along the internal relational parameter τ , then such a configuration is atemporal, aspatial, and non-actualizable. The actual reality R does not exist under these conditions.

Postulate 3 – Perfect coexistence and absolute zero

Perfect coexistence ($\Omega = 1$ for all pairs of entities $e'_i, e'_j \in R'$) is realized exclusively at zero relational temperature ($T_{\text{rel}} = 0$). In this condition:

$$\forall i, j \quad \Omega(e'_i, e'_j) = 1 \iff T_{\text{rel}} = 0 \iff T = 0 \quad (20)$$

Postulate 4 – Temperature as a relational effect

The temperature of an actualized entity $e \in R$ is derived from the relational temperature (13) of its original counterpart $e' \in R'$.

Postulate 5 – Relational entropy and the emergence of time

In R' , relational entropy S_{rel} (15) is defined as the negative sum of coexistence differences among all entities $\mathbf{e}'$. It determines the arrow of time as the privileged direction of decreasing coexistence.

The flow of time is directly linked to the growth rate of S_{rel} : the internal time of a system is proportional to $\frac{dS_{\text{rel}}}{d\tau}$ and inversely proportional to the decoherence time τ_{dec} ,

$$t_{\text{int}} \propto \frac{dS_{\text{rel}}}{d\tau} \propto \frac{1}{\tau_{\text{dec}}}. \quad (21)$$

Shorter decoherence times correspond to a faster flow of time, while longer decoherence times correspond to a slower one. In the limit $\tau_{\text{dec}} \rightarrow \infty$, time halts, whereas

for $\tau_{\text{dec}} < 0$ the arrow of time reverses. In this inverted regime, the natural spontaneous transition is from corpuscular states in R back to wave-like superpositions in R' , in contrast to ordinary decoherence in our everyday experience, where the natural process is the transition from wave to corpuscle.

Postulate 6 – Creation of spacetime

Every modification of relational entropy produces space and time in R . Spacetime is not a pre-existing continuous background, but an emergent effect of changes in coexistence within R' .

$$\frac{dV_R}{d\tau} \propto \frac{dS_{rel}}{d\tau}, \quad \frac{dt}{d\tau} \propto \frac{dS_{rel}}{d\tau}. \quad (22)$$

- If $\frac{dS_{rel}}{d\tau} > 0$: new units of space and time are generated, producing expansion. In this regime the arrow of time is positive, and temporal flow unfolds in the same direction as in common experience, providing the phenomenological basis of ordinary temporality.
- If $\frac{dS_{rel}}{d\tau} = 0$: the creation of new units halts, and the already actualized spacetime remains constant. In this condition the arrow of time is suspended and temporal flow ceases, corresponding to a state of halted temporality.
- If $\frac{dS_{rel}}{d\tau} < 0$: previously actualized units are progressively subtracted, leading to a contraction of space and time that disappears in the limit $\Omega \rightarrow 1$. In this regime the arrow of time reverses, and temporal flow acquires an inverted orientation with respect to ordinary experience.

At the present stage, it is not established whether space and time are discrete or continuous. The formula represents an effective description.

4 Discussion

In this chapter we examine the physical and conceptual implications of the results obtained in the previous sections, with particular attention to the central role of relational entropy in the dynamics of the universe and in the emergent phenomena of R . The aim is to show how the TCR provides a unifying interpretative key for processes that, in standard physics, are treated separately and described by independent laws: the growth of entropy, the arrow of time, quantum decoherence, and cosmological expansion. This perspective is not only of conceptual value, but also paves the way for the construction of coherent and predictive mathematical models.

This approach makes it possible to trace apparently heterogeneous phenomena back to a single principle.

4.1 Relational entropy and physical implications

In the TCR, relational entropy (15) is not defined in terms of spatial disorder or microstatistical multiplicity, as in the classical formulations of Boltzmann [41] or Gibbs [42], but rather as a measure of the relational indifferentiation among the original entities e' in R' .

This concept extends the thermodynamic interpretation of gravity introduced by Bekenstein [43] and Hawking [44], later unified by Jacobson [12] and Padmanabhan [13], where spacetime geometry obeys an equation of state. The TCR generalizes this principle beyond geometric thermodynamics, interpreting entropy growth as a manifestation of the loss of coexistence among entities in R' .

Arrow of time

In the TCR, time emerges from the tendency of coexistences in R' to degrade. The temporal arrow is therefore defined by the direction in which S_{rel} increases.

Quantum decoherence

Within the TCR framework, quantum decoherence is interpreted as a local entropic process: the loss of phase coherence in a quantum system corresponds to a reduction of relational specificity encoded in the coexistence parameters Ω_{ij} . This reduction entails an increase of the relational entropy S_{rel} , which is conceptually analogous to the increase of the von Neumann entropy [45] of the reduced density matrix in the standard formalism. In this sense, decoherence and entropy growth are understood in the TCR as complementary manifestations of the same underlying relational process, rather than as independent phenomena.

Cosmic expansion

The expansion of the universe is viewed as the projection in R of the average relational thinning in R' . Since the loss of constraints is globally the most probable process, cosmological expansion does not cease as long as

$$\frac{dS_{\text{rel}}}{d\tau} > 0. \quad (23)$$

This distinguishes it from the standard interpretation, in which expansion depends on the balance between gravity and dark energy: in the TCR, by contrast, it is a structural phenomenon tied to the arrow of time.

Gravity as an anti-entropic force

In the TCR, gravity is the emergent effect proportional to gradients of Ω in R' . It acts as an anti-entropic force, seeking to increase coexistence and reduce S_{rel} . In extreme conditions, such as in black holes, gravity may prevail locally, driving the system to maximal coexistence. However, on cosmological scales, the anti-entropic contribution of gravity is insufficient to counterbalance the processes of global indifferentiation, and thus cannot halt universal expansion.

4.2 An explicit cosmological illustration of the framework: TCR-Cosmo model

In TCR framework the geometry of spacetime and the evolution of the universe emerge from variations in the network of coexistences. From this perspective, cosmic expansion is not merely a stretching of spatiotemporal metrics, but rather a macroscopic manifestation of the increase of relational entropy, that is, the progressive loss of coherence in the structure of relations.

This relational-cosmological view shares partial conceptual affinities with relational approaches to time and spacetime, such as those developed by Barbour [46] and Rovelli [10, 47]. In these approaches, temporal and spatial notions are not treated as fundamental primitives.

The TCR extends this line of inquiry by introducing explicit ontological mechanisms—encoded in the relational parameter Ω and the emergence function Π —designed to generate a coherent relational foundation for quantitative cosmological modeling.

Within this ontology, local density acts as a fundamental variable to explain observational phenomena such as accelerated expansion. In particular, the TCR predicts that regions of the universe characterized by low density, the so-called cosmic voids, exhibit a higher expansion rate than denser regions. This occurs because, in the absence of strong relations among entities (i.e., high- Ω coexistences), the entropic tendency toward separation acts more efficiently and undisturbed. Conversely, in galaxies and black holes, where gravity and nuclear forces maintain high relational coherence, expansion is more limited or counterbalanced.

This interpretation carries with it a verifiable prediction: for equal material content, larger cosmic voids should expand more rapidly.

In this dynamic, time assumes a derived and relational role: its direction and intensity depend on the entropy gradient among coexistences. However, the presence of gravity locally limits the rate at which entropy grows, thus slowing down the emergence of space and time into R .

The current distribution of cosmic structures thus reflects the thermodynamic history of coexistences. Galaxies, stars, and planets represent islands of coherence, configurations resistant to entropy, emerging within the overall flow of relational disintegration.

The theory suggests an alternative interpretation of dark energy: the observed accelerated expansion of the universe may not require the introduction of a new form of energy, but may instead arise directly from the relational structure of R' . In this view, acceleration emerges in low-density regions, where entropy coexistences tend to zero, leading to a faster emergence of both temporal and spatial degrees of freedom.

From these conceptual foundations, the TCR-Cosmo model was developed [48], providing the demonstration of the internal operability of the TCR in the cosmological domain. This model is grounded in a pre-spatiotemporal physical framework and is capable of achieving an illustrative quantitative realization to observational data from supernovae, baryon acoustic oscillations, and cosmic chronometers.

4.3 Conclusions

4.3.1 A concrete example of applicability: the TCR-Cosmo model

A crucial point concerns the transition from conceptual ontology to quantitative implementation. From the relational framework of the TCR, the cosmological model *TCR-Cosmo* has been developed [48]. Specifically, TCR-Cosmo has been tested against low-redshift observations (SN, BAO, CC), showing a consistent fit to precision data.

Although still limited to high redshift, the TCR-Cosmo framework opens the path toward systematic numerical and observational investigations, establishing a direct bridge between foundational ontology and empirical validation.

4.3.2 Limitations of the TCR

Despite its conceptual coherence and explanatory capacity across diverse phenomena, the TCR currently presents several significant limitations that define its scope and indicate future directions for development.

- **Incomplete mathematical formalism.** The theory has so far been formulated primarily at the ontological and conceptual level. Although the concepts of coexistence Ω , actualization Π , and relational entropy S_{rel} provide a unifying language, a fully developed mathematical formalism is still lacking, allowing for systematic derivations and detailed predictive calculations.
- **Experimental predictions still preliminary.** No laboratory experiments have yet been carried out with the explicit purpose of validating or falsifying the TCR.
- **Epistemological acceptance.** The adoption of a primary ontological domain R' represents a radical conceptual shift. Such an approach might encounter opposition, especially within a community that regards spacetime as the fundamental foundation of physics. The challenge will be to translate the relational ontology into mathematical and predictive tools that are acceptable within contemporary physics practice.

The TCR remains a proposal in its early stages, with strong conceptual and predictive points, but also with evident limitations that require further development. Recognizing such limitations does not weaken the theory; rather, it situates it as an open research program, amenable to theoretical, mathematical, and experimental refinement.

4.4 Statements and Declarations

- **Competing Interests.** The author declares no competing interests.
- **Funding.** No external funding was received.
- **Data Availability.** No datasets were generated or analysed during the current study.
- **Ethics approval / Consent / Animal welfare.** Not applicable.

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