Superluminal Transformations and Indeterminism

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The status of indeterminism in fundamental physics remains one of the most persistent and conceptually challenging questions at the intersection of quantum theory, relativity, and the philosophy of physics. Quantum mechanics is widely regarded as introducing objective indeterminism into physical law: even with maximal specification of a system's state, measurement outcomes are, on standard interpretations, only probabilistically constrained. This is supported by the Heisenberg uncertainty principle, which limits the simultaneous determination of conjugate quantities, and by violations of Bell inequalities, which, under natural assumptions, imply that the outcomes of Bell experiments cannot be predetermined [1]. In contrast, classical physics is traditionally viewed as deterministic, with probabilities reflecting only incomplete knowledge. Yet this neat contrast has been increasingly scrutinized [2–21]. The standard narrative presents classical theory as deterministic. However, this conclusion can only be drawn from two joint assumptions: (i) at the dynamical level, the solutions to the equations of motion in classical physics—as represented by ordinary partial differential equations—admit a unique continuation both into the past and into the future; provided that (ii) at the kinematical level, the initial conditions are infinitely precise—as represented by real numbers in the theory. One line of argument, initiated by N. Gisin and one of us (FDS) [9], has investigated the consequences of relaxing assumption (ii) by adopting a principle of finite information density. Rejecting the assumption of infinite information amounts to discarding real-number representations, most of which are uncomputable (infinite Kolmogorov complexity) and encode infinite informational content [10, 14]. By relaxing the requirement of infinite precision, indeterminacy is no longer uniquely quantum but can also be intrinsic to classical physics. When combined with chaotic dynamics, this opens the possibility that classical systems inherently display indeterministic behaviour [9, 16, 21].

At the same time, Dragan and Ekert [22] recently employed superluminal transformations (SpTs)—first introduced in [23], extending the Lorentz group to include superluminal velocities—to argue that such transformations may give rise to indeterminism in quantum physics. They derive linear superluminal Lorentz boost (SpLT) in (1+1) dimensions in accordance with special theory of relativity as:

$$\begin{bmatrix} x' \\ t' \end{bmatrix} = \pm\frac{V}{|V|}\begin{bmatrix} \frac{1}{\sqrt{\frac{V^2}{c^2}-1}} & \frac{-V}{\sqrt{\frac{V^2}{c^2}-1}} \\ \frac{-V/c^2}{\sqrt{\frac{V^2}{c^2}-1}} & \frac{1}{\sqrt{\frac{V^2}{c^2}-1}} \end{bmatrix}\begin{bmatrix} x \\ t \end{bmatrix} \tag{1}$$

where c is the constant speed of light. In this new perspective on tachyons, they argue that the causality issues of superluminal observers are only an apparent paradox, which vanishes if one drops the assumption of local determinism. The idea is that with large enough uncertainties, observers cannot say whether they actually observed superluminal signaling. Thus, they argue, the inherent randomness that we are familiar with from quantum theory could be not just reconciled with the theory of relativity but the former can be understood as a consequence of the latter. This observation motivates a foundational question: if one takes such transformations seriously as part of an extended relativity principle, what are their conceptual and physical consequences? In a

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previous work, one of us (AS) analyzed superluminal quantum reference frames for thermodynamic and operational probabilistic consistency [24].

In this work, we bring together these two approaches to indeterminism—i.e., based, respectively, on finite information and superluminal transformations, to formulate a no-go result that would hold for any theoretical framework above and beyond quantum theory. We analyze the structure of superluminal transformations, with particular attention to the subclass of superluminal Lorentz transformations (SpLTs) [23], and their implications for the distribution of finite information in spacetime. Our argument does not rely on the specific linear form of SpLTs introduced in [23] and studied in [22, 24] but applies more generally to transformations, including non-linear ones, that fail to preserve the temporal order of timelike-separated events (SpTs). SpTs reverse the temporal order of at least one set of spacetime points or events with respect to the initial reference frame (e.g., SpLTs).

To begin, if we accept that finite information imposes fundamental limits on how precisely physical properties are determined, the classical deterministic narrative yields to a more flexible picture—causality without determinism. This is where the notion of propensities enters: in Ballentine's words, propensities are "a form of causality that is weaker than determinism" [25]. The evolution of a system can be described using a directed acyclic multigraph and the state of a system can be defined as an ordered collection

$$G(t) : [E(t), \Omega(t), P(t)]$$

, where $E(t)$ is the set of all events (nodes), $\Omega(t)$ is the set of all (potential and actual) causal connections (edges) which cover all possible alternative histories and futures, $P(t)$ is the set of individual propensities (weights), all at the considered time t. The information content of the whole graph is $I(G(t)) = I(E(t), P(t))$ described by Kolmogorov complexity and $\Omega(t) = \{(i, j)|p_{ij} > 0,\ p_{ij} \in P(t),\ i, j \in E(t)\}$ represents the potential causal connections. To better understand the foundations and implications of SpTs on this causal structure in the form of a no-go theorem, we consider the following assumptions:

A0. **Existence of non-order-preserving SpTs**
A transformation with $|v| > c$ that maps timelike-separated events to spacelike-separated events, and vice versa. For example, the anti-symmetric Lorentz extension in Eq (1) with $v > c$ where $x \to t'$ and $t \to x'$ at $v \to \infty$ in $1 + 1$ dimensions.

A1. **Principle of finite information**
A finite spacetime region contains at most $N < \infty$ bits of information such that:

$$I(G(t)) = I(E(t)) + I(P(t)|E(t)) + C_0 \leq N. \tag{2}$$

where C_0 is constant. Here, the bound N should be understood as a structural constraint on physically realisable information, rather than a statement about mathematical representations.

A2. **Time symmetry of total information**
We assume that total available information is not overwhelmingly biased toward either temporal direction. If there are in total N bits of storable information in the universe, about N/2 bits are used to record information about the past, that is, $I(G(t))_{\text{past}}$, and the other N/2 are recording $I(G(t))_{\text{future}}$, making $I(G(t))_{\text{past}} \approx I(G(t))_{\text{future}}$.

A3. **The past holds memory**
In any inertial reference frame, the past stores determinate events (records of outcomes that have already actualised), while the future contains only potential events represented by nonextremal propensities. The past records actualised events, such that $P(t)_{\text{past}} \in \{0, 1\}$, while future propensities can take any rational value in $[0, 1]$, encoding potentialities: $P(t)_{\text{future}} \in \mathbb{Q} \cap [0, 1]$. Thus, the amount of bits needed to encode rational propensities relative to the future is, in general, greater than the past propensities that each contain only one bit of information since they

are already actualised, making, $I(P(t)|E(t))_{\text{past}} < I(P(t)|E(t))_{\text{future}}$. This assumption reflects an operational notion of memory rather than a commitment to a specific metaphysics of time.

A4. **Time has a specific role in every reference frame**

We assume that time plays a specific role: it is the parameter along which the causal structure is aligned, and the envelope of the light cone within which actualisation (the act of fundamentally indeterminate events becoming determinate [9, 13, 17, 18, 21]) can occur is defined. Under any physical reference frame transformation, it should remain the parameter along which deterministic equations evolve, and, more importantly, the parameter relative to which causal relations are defined. We then derive a no-go theorem.

Theorem: The conjunction of all assumptions A0.- A4. cannot hold simultaneously.

A detailed proof can be found in our paper on Arxiv here. Intuitively, if past events are determinate while future events remain potential, a non-order-preserving SpT may map events that are indeterminate in one frame into the past of another frame, where they would need to be determinate. Under the finite-information constraint (A1), such reclassification would generally require an increase in encoded information beyond the allowed bound. Thus, in this scenario, it is impossible to maintain both a determinate past in superluminal frames and a finite-information framework with a meaningful direction of time. To our knowledge, this is the first result that connects superluminal extensions of relativity with structural constraints on information content.

One of our interpretations of this violation is therefore that superluminal transformations and finite information cannot coexist within a consistent physical framework, given the other natural assumptions. Any theory that truly incorporates SpTs in this strong structural sense must abandon finite information and accept unbounded informational content. This requirement mirrors known structural tensions in tachyonic extensions of relativity. In particular, one recalls the negative-energy problem of tachyons, whose resolution requires a careful mapping across continuous velocity ranges (over the real numbers with infinite information) to ensure energies remain non-negative [24, 26]. This suggests that the price of superluminal transformations with non-negative energy is a radical commitment to infinite informational structure. This result applies not only to classical reference-frame transformations, but can also be extended to superluminal quantum reference frames [24]. The generalisation follows by applying our proof linearly to each branch in the relevant superposition of reference frames: subluminal and superluminal or superluminal and superluminal.

In principle, the presence of indeterminism and the lack of superluminal signaling, even if the space of SpTs is ontologically deterministic, can be accounted for by the fundamental inaccessibility of the underlying infinite information. In this view, infinite information could in principle determine all events with perfect precision, but physical constraints prevent observers from accessing it. The resulting indeterminacy is therefore epistemic, reflecting subjective limitations on knowledge, in contrast with quantum theory, where probabilities are generally taken to be ontologically fundamental.[1]

Our result represents a deliberate theoretical claim, akin to many foundational proposals, as scenarios involving superluminally boosted transformations or objects remaining beyond the reach of experimental feasibility. Although the result is formulated only for 1+1 dimensions, its implications are broader: the failure of superluminal extensions to account for quantum probabilities in this simplified setting suggests that similar explanations are unlikely to succeed in 3+1 dimensions. Yet the study of superluminal transformations can provide a lens through which foundational tensions regarding (in)determinism, information, and the arrow of time can be reexamined. In this way, they confront us with a choice between formal symmetry and mathematical completeness on the one hand, and physical plausibility grounded in finite information and a determinate past on the other.

[1] We may express this distinction using the *Manifest* domain (like outcomes of measurements, settings, physical data, and records in the environment), and the *non-Manifest* domain (where observables, such as position, are defined) to extract specific data [27]. In the same philosophy, a *Theory* then serves as the bridge between these two domains. In this paper, we argue that this bridging *theory* is *not* Quantum theory.

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