The Speed of Light and Its Limits:

Quantum Entanglement as Empirical Evidence

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Abstract. The speed of light, c, is the best-confirmed constant in physics. Within Special Relativity, it defines the causal structure of spacetime and no experiment has ever recorded an object exceeding it. This paper does not dispute any of that.

What this paper argues is that quantum entanglement constitutes direct experimental evidence that the extrapolation of c to a universal limit across all layers of physical reality is not justified by the data. c is the fundamental limit of relativistic spacetime. Whether it is also the limit of whatever substrate gives rise to that spacetime is a question the experiments force us to take seriously—and that current physics leaves genuinely open.

Bell-test experiments, confirmed from Aspect (1982) to the Large Hadron Collider (2023), show that entangled correlations cannot be explained by any local model. Something produces those correlations without any mechanism that respects c. The no-communication theorem shows that this cannot be exploited for signalling—today, within the current framework. It does not show that c governs the mechanism that produces the correlations. Those are different claims, and conflating them has allowed a mathematical result about signal statistics to carry unwarranted ontological weight.

This is a conceptual and philosophical analysis grounded in experimental results. It does not propose a new theory. It argues that the evidence we already have is sufficient to challenge the extrapolation that treats c as an absolute limit across all layers of physical reality. That extrapolation is not forced by the data. It is a theoretical choice—and a contestable one.

Introduction

Special Relativity is one of the most successful theories in the history of physics. Since Einstein's 1905 formulation, c has functioned not merely as the speed of electromagnetic radiation in vacuum but as a structural constant of spacetime itself—the boundary beyond which no signal, no energy, no causal influence can travel. More than a century of experimental confirmation has made this result unassailable within its domain.

The problem is not with the result. The problem is with the extrapolation.

From "c is the causal limit within the relativistic spacetime we observe" to "c is the absolute limit of every physical process in every layer of reality" is a philosophical step, not a physical derivation. Special Relativity was constructed to describe objects moving through the spacetime that we inhabit. It was not constructed to decide what that spacetime is made of, where it comes from, or whether the substrate from which it emerges obeys the same constraints.

Quantum entanglement forces that distinction into the open. Bell-test experiments have confirmed, with loophole-free precision, that entangled correlations cannot be explained by any local model—any model in which c governs all influences between separated systems. Something connects entangled particles across arbitrary distances in a way that no relativistic mechanism accounts for. The standard response is to invoke the no-communication theorem and declare the matter closed. This paper argues that response answers the wrong question.

The no-communication theorem establishes that the correlations cannot be exploited to send a usable message—within the current framework, as tested to date. What the theorem does not establish is that c governs the mechanism that produces the correlations. Those are different claims. The first is about what Alice and Bob can do with the correlations. The second is about what the universe is doing to produce them. The theorem answers the first. Whether it exhausts the second is a question this paper leaves open, and the companion paper [21] addresses directly.

Several strands of the literature already suggest that limiting velocities may be emergent and that spacetime itself may arise from entanglement. The present paper does not aim to re-derive those programs, but to reinterpret modern experimental entanglement results as evidence that c should not be treated as a universal limit across all layers of physical reality. It is worth noting that the question of whether c is truly fundamental has been taken seriously before: Magueijo and Albrecht proposed formally that c may have taken different values in the early universe [17], a proposal that, whatever its reception, demonstrates that challenging the absolute status of c is not outside the bounds of serious physics.

This paper makes three arguments. First, that the experimental record of entanglement constitutes positive evidence that something in physical reality operates outside the domain where c is defined. Second, that two additional physical regimes—gravitational singularities and cosmological inflation—independently demonstrate that c has a bounded domain of validity. Third, that a converging body of theoretical work in emergent spacetime, holography, and quantum information theory makes it physically plausible that c is a property of emergent relativistic spacetime, not of a deeper quantum substrate.

The conclusion is not that Einstein was wrong. The conclusion is that the universe has layers, and c governs one of them.

What Bell Actually Proved

The Theorem

In 1964, John Bell derived a mathematical inequality that any local hidden variable theory must satisfy [1]. A local hidden variable theory is one in which: (a) measurement outcomes are determined by pre-existing values carried by the particles, and (b) no influence between the two measurement sites travels faster than light. Bell showed that quantum mechanics predicts violations of this inequality. If the violations are observed experimentally, at least one of the two assumptions must be false.

The CHSH form of the inequality states:

$$|E(a,b) - E(a,b') + E(a',b) + E(a',b')| \leq 2 \tag{1}$$

where $E(a,b)$ is the correlation between measurements at settings a and b. Quantum mechanics predicts violations up to $2\sqrt{2} \approx 2.83$. Every Bell test ever performed has found violations consistent with the quantum mechanical prediction, not with the local bound of 2.

Four Decades of Confirmation

The experimental record is not a single result. It is a forty-year programme of increasingly precise and loophole-free confirmation.

Alain Aspect and colleagues in 1982 performed the first strong experimental test using polarisation-entangled photons with time-varying analysers, closing the communication loophole [2]. Anton Zeilinger's group extended entanglement distribution to photons separated by kilometres, demonstrating that distance does not weaken the correlations [3]. Ronald Hanson's group in Delft achieved the first loophole-free Bell test in 2015, closing both the detection and locality loopholes simultaneously using electron spins separated by 1.3 km [4]. In 2017, the Chinese Micius satellite distributed entangled photons between ground stations 1,200 km apart with correlation fidelity sufficient to violate Bell inequalities [5].

In 2023, the ATLAS collaboration at the Large Hadron Collider detected quantum entanglement between top quark-antiquark pairs produced in proton collisions at 13 TeV [6]. This is entanglement confirmed at energy scales and timescales—top quarks decay in approximately 5×10^{-25} seconds—far beyond the domain of the photon experiments that established Bell inequality violations. It demonstrates that entanglement is not a low-energy curiosity but a fundamental feature of quantum field theory at the highest energies currently accessible.

What the Results Establish

These experiments establish three things with certainty.

First, the correlations are real. They are not statistical artefacts, not instrumental errors, not classical correlations dressed up as quantum ones. They have been confirmed in independent laboratories, across multiple physical implementations, with loopholes progressively closed over four decades.

Second, the correlations cannot be explained by any local model. Bell's theorem is a mathematical proof, not a physical hypothesis. If the experimental violations are genuine—and they are—then no theory in which c governs all influences between separated systems can reproduce them. That is not a matter of interpretation. It is a logical consequence of the theorem and the data.

Third, no timing signature consistent with c-limited propagation has been observed. At 1,200 km, the light travel time is approximately four milliseconds; no delay of that order appears in the data. No local mechanism—no carrier particle, no field propagation respecting c—has been identified that accounts for the correlations. This is consistent with the hypothesis that whatever produces them operates outside the domain where c is defined, though Bell alone does not uniquely force that ontological reading.

The most direct reading consistent with all of this is that something in physical reality operates outside the domain where c is defined. The question of what that something is remains open. The question of whether it exists does not.

The No-Communication Theorem Is Not the End of the Argument

The standard response to the argument above is immediate: the no-communication theorem [7] proves that these correlations cannot be used to transmit information faster than light. Bob's measurement outcomes are individually random—uniformly distributed regardless of what Alice does with her particles. The correlations only become visible when Alice and Bob compare their results through a classical channel, which is limited by c. Therefore, the argument goes, no physical influence that matters has exceeded c, and the relativistic causal structure is intact.

This response is mathematically correct within its stated domain—the theorem follows from the linearity of quantum mechanics applied to outcome statistics. It is also insufficient as a complete answer to the ontological question this paper is asking.

The theorem proves the following precise statement: for any bipartite quantum state ρ_{AB} and any local operation Λ_A performed by Alice on subsystem A:

$$\rho_B = \mathrm{Tr}_A\big[(\Lambda_A \otimes \mathbb{I}_B)\,\rho_{AB}\big] = \mathrm{Tr}_A[\rho_{AB}] \tag{2}$$

Bob's reduced density matrix—and therefore his outcome statistics—is independent of what Alice does. This follows from the linearity of quantum mechanics and is not in dispute.

What the theorem does not prove is that c governs the physical mechanism that produces the correlations. The theorem is about what Bob can read from his measurement record. It is not about what the universe is doing between the two measurement events. These are different questions, and the theorem answers only the first.

Consider the situation precisely. Two particles are measured at spacelike separation. Their outcomes are correlated. No local mechanism—no carrier particle, no field propagation, no signal travelling at any speed up to and including c—can account for the correlation. Something produces it. The theorem establishes that whatever that something is, it cannot be harnessed by Alice to send a message to Bob. It does not establish that that something respects c.

The theorem defines "signal" operationally: a signal is something Bob can detect by looking at his outcome statistics alone. By that definition, nothing has exceeded c. But that operational definition was constructed to address a specific question—can entanglement be used to communicate?—not to resolve the ontology of the mechanism that produces the correlations. The theorem answers the first question rigorously. Answering the operational question does not close the ontological one.

The honest statement of the situation is this: something produces entangled correlations across arbitrary distances with no propagation delay. We cannot currently exploit it for communication. We do not know what it is. We do not know what rules govern it. And we have no experimental evidence that it respects c—only that it cannot be weaponised into a message under current quantum mechanics. Wigner understood this tension in 1961 [18]: the universal wavefunction, not any local observer, is the frame in which the global entangled state has a single consistent description. From that frame, the two measurement events are not separated at all.

That is a very different thing from saying c is the universal limit of all physical processes.

Two Additional Regimes Where c Loses Meaning

Entanglement is the central argument. Two additional physical regimes reinforce it independently: gravitational singularities and cosmological inflation. Neither is as direct as entanglement, but both show that c has a bounded domain of validity—that it is not a universal limit but a concept defined within a specific physical framework, one that breaks down in identifiable regimes.

Gravitational Singularities

The Schwarzschild metric describes spacetime geometry around a non-rotating mass:

$$ds^2 = -\Big(1 - \frac{2GM}{rc^2}\Big)c^2\,dt^2 + \cdots \tag{3}$$

At the central singularity ($r = 0$), spacetime curvature diverges and General Relativity ceases to provide a description. This is not a coordinate artefact; it is a genuine failure of the theory. General Relativity, the framework in which c functions as a causal limit, predicts its own breakdown at singularities.

When a physical framework predicts its own failure, the standard scientific inference is that the framework has reached the boundary of its domain of validity. The concepts defined within it—including the speed limit c—cannot be extended beyond that boundary by assumption. Whatever physics governs the interior of singularities operates in a regime where the framework that defines c as meaningful does not apply.

Cosmological Inflation

Cosmological inflation [16], the period of exponential expansion in the first fractions of a second after the Big Bang, produced a universe in which distant regions separated faster than c. During the inflationary epoch, the scale factor $a(t)$ grew exponentially:

$$a(t) \propto e^{Ht} \implies \dot{a}(t) > c \tag{4}$$

Distant regions of spacetime receded from each other faster than c. This does not violate Special Relativity because Special Relativity constrains the motion of objects through spacetime, not the expansion of spacetime itself. General Relativity explicitly permits it.

The point is not that inflation refutes c. The point is that the theory which makes c a limit also describes a process in which two points in the universe separate faster than c—and resolves the apparent contradiction by distinguishing between local motion through spacetime and the global evolution of the metric. That distinction reveals that c is a constraint on motion within a fixed background geometry, not a universal limit independent of the geometry itself. When the geometry changes, the constraint changes with it.

If spacetime is dynamic rather than fixed—and General Relativity requires that it is—then c is conditional on the state of the geometry, not absolute.

What the Theoretical Frontier Is Saying

The experimental arguments above show that c has a bounded domain. They do not, by themselves, explain why. A converging body of theoretical work in the past three decades provides a candidate explanation: spacetime itself is not fundamental, and c is a property of the emergent structure, not of the substrate from which it arises.

The holographic principle, formalised through Maldacena's AdS/CFT correspondence [8], established that the information content of a volume of spacetime can be encoded entirely on its boundary surface. Spacetime volume is not primitive—it is a representation of quantum information. This is a precise mathematical result, not a metaphor.

Verlinde proposed that gravity is not a fundamental force but an entropic phenomenon, an emergent consequence of information distribution [9]. Spacetime geometry, in his framework, arises from thermodynamic principles applied to quantum information at a more primitive level.

David Bohm argued from the 1950s that beneath the spacetime we observe there exists a deeper layer—the Implicate Order—where particles that appear separated are aspects of a single undivided whole [14, 19]. The ER=EPR conjecture of Maldacena and Susskind [10] gives that intuition rigorous mathematical content: quantum entanglement between two particles may be physically equivalent to a wormhole—an Einstein-Rosen bridge—connecting them beneath spacetime. The non-local correlations that Bell tests confirm would, in this picture, be a consequence of geometric connections that do not travel through the spacetime where c is defined.

Swingle's tensor network framework [11] provided concrete mathematical support for this picture, showing how the entanglement structure of a quantum state determines the geometry of the emergent spacetime it corresponds to. The geometry—and with it the meaning of a speed limit—is derived from the entanglement pattern, not the other way around.

None of these frameworks proves that spacetime is emergent in our actual universe. AdS/CFT applies strictly to anti-de Sitter spacetime with a negative cosmological constant, not to the de Sitter universe we inhabit. The extension remains an open problem. But taken together, these frameworks make the following picture physically credible: c is a property of emergent relativistic spacetime, arising from the structure of that spacetime the way the speed of sound arises from the properties of a medium. It governs propagation within the medium. It does not govern the substrate from which the medium emerges.

In this picture, the non-local correlations of entanglement are not a puzzle to be explained away. They are what the substrate looks like from within the emergent layer—a glimpse of geometry that precedes the geometry where c has meaning.

There is also a second reason to question whether c is as primitive as its role in physics suggests. In $E = mc^2$, c functions as the conversion factor between mass and energy. But mass is not a primitive quantity. In the Standard Model, the mass of fundamental particles arises through interaction with the Higgs field [12]. Mass is emergent. If c is the conversion factor between an emergent quantity and energy, then c as a fundamental constant inherits that contingency. It may be not the deepest constant of the universe but the characteristic speed of a particular emergent layer of it—the maximum propagation speed available to entities that acquire inertia through the Higgs mechanism.

What This Does Not Prove and What Remains Open

The argument of this paper has a precise scope and it should be stated clearly.

This paper does not claim that c has been experimentally exceeded. It has not. Every direct measurement confirms that no object or signal travels faster than c within the spacetime we inhabit.

The no-communication theorem holds within its domain: outcome statistics are protected. Whether the temporal structure of correlation records is equally protected is a question that domain was not designed to answer. That question is explored in the companion paper [21].

This paper does not propose a new physical theory. The frameworks cited above—AdS/CFT, ER=EPR, tensor networks—are serious physics, but their applicability to our actual universe remains an open question. They are cited as evidence of a direction, not as a completed programme.

What this paper claims is more specific: the evidence is sufficient to strongly challenge the extrapolation that treats c as a universal limit across all layers of physical reality. It is the fundamental limit of relativistic physics—a framework that describes the emergent layer of reality that we inhabit as classical observers. Whether it is also the limit of whatever substrate gives rise to that layer is a question that the evidence reviewed here leaves genuinely open.

That is not a small claim. Treating c as a universal absolute is a philosophical extrapolation that goes beyond what any experiment has demonstrated. The experiments of Bell, Aspect, Hensen, Micius, and ATLAS do not confirm that extrapolation. They are evidence against it.

The question of what governs the mechanism that produces entangled correlations—what rules apply in the substrate where c has not been shown to hold—is one of the deepest open questions in physics. The companion paper [21] proposes a research programme with three experimental protocols to test whether the temporal structure of entangled detection records carries any operationally accessible information. A Lorentz-structured ansatz for concurrence-dependent correlation timing, developed in detail in [22], is available as an optional quantitative framework for Protocol C of that programme. Both the protocols and the ansatz are presented as proposals for future investigation, not as claims of the present paper.

The speed of light governs what we can do within the spacetime we inhabit. It has not been demonstrated to govern everything the universe can do. That distinction is not semantic. It is the core question this paper puts on the table.

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