

Quantum gravity cannot be both consistent and complete

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Abstract

General relativity, despite its profound successes, fails as a complete theory due to presence of singularities. While it is widely believed that quantum gravity has the potential to be a complete theory, in which spacetime consistently emerges from quantum degrees of freedom through computational algorithms, we demonstrate that this goal is fundamentally unattainable. Gödel's theorems establish that no theory based on computational algorithms can be both complete and consistent, while Tarski's undefinability theorem demonstrates that even within quantum gravity, or any computational framework, a fully consistent internal determination of true propositions is impossible. Chaitin's incompleteness theorem further reinforces this conclusion, revealing intrinsic limits to any computational theory. We discuss some possible consequences for descriptions of physical systems, and note that a non-algorithmic approach is essential for any theory of everything.

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INTRODUCTION

Physics was developed to describe and predict phenomena occurring in spacetime. However, the theory of general relativity—linking gravity to the curvature of spacetime—is a theory of spacetime itself. It has had overwhelming success in explaining gravitational phenomena, from the perihelion precession of Mercury to the recent detection of gravitational waves [1, 2]. Despite its success, general relativity predicts its own breakdown at singularities, which occur at the center of black holes, and at the initial instant of the big bang [3, 4]. At these points the very structure of spacetime breaks down and becomes ill-defined. Thus, this theory is not complete as it cannot describe physics at such points.

Singularities are not exclusive to general relativity; they emerge across various fields of physics [5, 6], at scales where a given model no longer adequately describes the system. They are expected to disappear when the full theoretical framework is applied. A prominent example is flow discontinuities in classical fluid mechanics, which are associated to curvature singularities of an effective (acoustic) metric and are resolved through a full quantum hydrodynamic framework [7, 8]. Similarly, in different approaches to quantum gravity, such as loop quantum gravity (LQG) and string theory, curvature singularities are replaced with finite, well-defined structures. In loop quantum cosmology (LQC), a symmetry-reduced model of LQG, the big bang singularity is resolved through a "quantum bounce," where the universe transitions from contraction to expansion [9, 10]. In string theory, the fuzzball paradigm replaces black hole singularities with extended structures [11, 12].

The disappearance of singularities suggests something deeper: spacetime as represented by the smooth manifold of classical relativity is an emergent structure that breaks down in certain situations. This is similar to the emergence of effective manifolds in condensed matter physics from a mean-field representation of underlying quantum dynamics [8]. In the context of string theory, using double field theory (DFT), T-duality can be incorporated as a fundamental symmetry [13]. T-folds, a concept based on it, extend spacetime geometry by allowing transition functions involving T-duality transformations. This further reinforces the idea that spacetime is an emergent structure within quantum gravity, as spacetime is not always well-defined in this case [14]. Likewise, spin foam models in loop quantum gravity (LQG) indicates the emergent nature of spacetime. These models describe spacetime as arising from a discrete network of quantum structures [15]. Thus, both string theory and LQG exemplify the emergent nature of spacetime, wherein the smooth manifold of classical relativity arises from a deeper quantum gravitational degrees of freedom.

These developments strongly align with Wheeler's "it from bit" hypothesis, along with its

contemporary formulations within string theory [16, 17] and loop quantum LQG [18], which assert that information fundamentally underpins physical reality [19]. The inability of classical theories to describe singularities further supports this perspective: spacetime, as an emergent phenomenon, cannot account for regions where its underlying quantum information structure cannot be described in terms of spacetime geometry. While ‘it’—representing spacetime and matter fields in it—is not complete, it is expected that ‘bit’—representing quantum gravity—could be complete and consistent computational ‘theory of everything’. We will argue here, however, that it is not possible to construct such a theory based on algorithmic computations.

QUANTUM GRAVITY

Quantum gravity aims to unify the principles of quantum mechanics and general relativity within a single consistent framework. Despite significant advancements in approaches such as string theory [20, 21] and loop quantum gravity (LQG) [22, 23], a complete and definitive theory remains elusive. So, we have different approaches to quantum gravity, and based on those different approaches multiple axiomatic constructions of quantum gravity have been proposed [24–30]. In general, we first note that any viable candidate for quantum gravity must adhere to fundamental axioms that ensure both physical and mathematical coherence. Furthermore, such a formal mathematical axiomatic system, \mathcal{F}_{QG} , generates spacetime rather than existing within it [31]. The essential axioms required for quantum gravity to qualify as a theory of everything, can be summarized as follows:

1. Effectively Axiomatizable: The axioms $\{A_1, A_2, \dots\}$ of \mathcal{F}_{QG} are finite. This is important for the theory to be computationally well-defined. Spacetime should emerge as a consequence of these axioms [8, 31]. For example, in string theory, spacetime emerges from the dynamics of extended objects [21, 32], or as a result of quantum information using holography [16, 17], and in LQG, spacetime is an emergent feature of spin networks and spin foams [15, 22], and can be again derived from quantum information [18].

2. Sufficient Expressiveness: The system \mathcal{F}_{QG} is capable of encoding basic arithmetic operations over natural numbers, including addition and multiplication. Quantum gravity must describe physical phenomena, which reduce to both classical spacetime and standard quantum mechanics in certain limits, and so it must be capable of allowing numerical calculations (e.g., scattering amplitudes, curvature, entropy etc), which inherently require arithmetic. It maybe noted that both string theory and LQG reproduce results from general relativity and quantum mechanics/quantum

field theory in appropriate limits [20–23].

3. Consistency: A theory of quantum gravity must be internally consistent, and so \mathcal{F}_{QG} does not derive any contradictions. Apart from mathematical consistency, it should be physical consistent, avoiding unphysical results like negative probabilities. String theory achieves consistency through anomaly cancellation [21, 33], while LQG ensures it through the rigorous quantization of geometric degrees of freedom [22, 34].

4. Completeness: The theory must describe phenomena across all scales, from the Planck scale to cosmological scales. This includes the resolution of singularities, such as those found in black holes and the big bang [9, 11]. A complete theory should also encompass the origin of universe, which is attempted via quantum cosmology in LQG [10, 22] or colliding branes in string theory [35]. It should be consistent with all observational data.

These axioms should produce a formal structure that satisfies some important properties. A viable theory of quantum gravity must reduce to standard theories, in the limit those theories have been tested and verified. For example, both string theory and LQG fulfill this requirement by recovering quantum field theories and general relativity in appropriate limits [20, 22, 23].

It must also properly address the measurement problem by providing a mechanism for the apparent collapse of the wavefunction. Furthermore, this has to be intrinsic to explain the quantum-to-classical transition in cosmology [36]. Models based on gravitationally induced objective collapse [37, 38], suggest that quantum gravity may naturally resolve this issue by linking wavefunction collapse to spacetime structure. This is neither random nor algorithmic nor computational, but is fundamentally related to non-algorithmic understanding.

The theory must also explain the emergence of spacetime as a macroscopic phenomenon arising from more fundamental quantum structures. It is important that the emergent spacetime does not lead to contradictions, such as closed timelike curves, which would require principles like the Novikov self-consistency principle [39], again based on non-algorithmic understanding.

Furthermore, spacetime singularities should be naturally resolved in quantum gravity. Such resolution of singularities occurs in principle in string theory due to extended objects [11, 32], and in LQG due to discrete quantum geometries [9, 10]. However, it is important to note that these involve Planck scale physics, and it has been demonstrated that quantum gravity prevent its own measurement at such scales [40, 41]. So, dealing with this require non-algorithmic understanding as that described by the Lucas-Penrose argument [42–46]. As this non-algorithmic understanding operates at a fundamental level in nature, it is not possible to explain all natural phenomenon using computational algorithms alone. As such there is a more fundamental reason why quantum

gravity, when based solely on computation, cannot be both consistent and complete.

GÖDEL'S AND TARSKI'S THEOREMS IN QUANTUM GRAVITY

In this section, we demonstrate how Gödel's incompleteness theorems [47, 48] and Tarski's undefinability theorem [49, 50] apply to quantum gravity if it is formulated as a formal axiomatic system [26, 51]. This formal system \mathcal{F}_{QG} , apart from consistency (\mathcal{F}_{QG} does not derive any contradictions, i.e., $\mathcal{F}_{QG} \not\vdash \perp$.) will only be required to be sufficiently expressive and effectively axiomatizable for these theorems to hold.

As \mathcal{F}_{QG} is consistent and sufficiently expressive, then there exists a scientific fact/statement G in the language of \mathcal{F}_{QG} such that: $\mathcal{F}_{QG} \not\vdash G$ and $\mathcal{F}_{QG} \not\vdash \neg G$ [47, 48]. Assign a unique Gödel number $\text{GN}(\phi) \in \mathbb{N}$ to every scientific fact/statement ϕ in \mathcal{F}_{QG} . This Gödelization process ensures that such scientific statements in the formal system can be encoded as integers. Now we can define the provability predicate $\text{Prov}_{\mathcal{F}_{QG}}(x)$, which asserts that x is the Gödel number of a provable statement in \mathcal{F}_{QG} . We can also construct a self-referential statement G such that: $G \equiv \neg \text{Prov}_{\mathcal{F}_{QG}}(\text{GN}(G))$. This statement asserts, “ G is not provable in \mathcal{F}_{QG} .” Here, we analyze the two cases: If $\mathcal{F}_{QG} \vdash G$, then $\text{Prov}_{\mathcal{F}_{QG}}(\text{GN}(G))$ holds, contradicting the definition of G . However, if $\mathcal{F}_{QG} \vdash \neg G$, then \mathcal{F}_{QG} proves G is not provable. However, this implies G is true, leading to a contradiction. Thus, G is undecidable within \mathcal{F}_{QG} .

The undecidability of G implies that there are scientific facts/statements in a purely algorithmic axiomatic system such as any purported theory of quantum gravity that are true by the very construction of the system, but inherently not provable within \mathcal{F}_{QG} . In fact, it has already been proposed that the measurement problem in quantum mechanics is related to Gödel theorem in objective collapse models [37, 38].

Furthermore, while \mathcal{F}_{QG} is consistent, \mathcal{F}_{QG} cannot prove its own consistency: $\mathcal{F}_{QG} \not\vdash \text{Con}(\mathcal{F}_{QG})$, where $\text{Con}(\mathcal{F}_{QG})$ is the statement: $\text{Con}(\mathcal{F}_{QG}) \equiv \neg \text{Prov}_{\mathcal{F}_{QG}}(\text{GN}(\perp))$ [47, 48]. Here, we assume $\mathcal{F}_{QG} \vdash \text{Con}(\mathcal{F}_{QG})$. By Gödel's first theorem, there exists a statement G undecidable in \mathcal{F}_{QG} . If $\mathcal{F}_{QG} \vdash \text{Con}(\mathcal{F}_{QG})$, then \mathcal{F}_{QG} can prove G , contradicting the undecidability of G . Thus, $\mathcal{F}_{QG} \not\vdash \text{Con}(\mathcal{F}_{QG})$. The consistency of \mathcal{F}_{QG} must be established externally, through a meta-theoretical framework, which is not algorithmic.

Now we will analyze the implication of Tarski's undefinability theorem for \mathcal{F}_{QG} [52]. The truth predicate $\text{True}_{\mathcal{F}_{QG}}(x)$ for statements in \mathcal{F}_{QG} cannot be defined within \mathcal{F}_{QG} [49, 50]. To demonstrate this, assume $\text{True}_{\mathcal{F}_{QG}}(x)$ is definable within \mathcal{F}_{QG} . Then construct a statement ψ such

that: $\psi \equiv \neg \text{True}_{\mathcal{F}_{QG}}(\text{GN}(\psi))$. By the definition of $\text{True}_{\mathcal{F}_{QG}}(x)$, ψ is true if and only if ψ is not true, which is a contradiction. The undefinability of the truth predicate suggests that the “truth” of certain scientific statements in any algorithmic proposed theory such as quantum gravity, again requires external meta-theoretical frameworks for full comprehension. It is not possible to fully internally define scientific truth computationally. It had been argued by Weinberg that if we had a final computational theory of everything, a full theory of quantum gravity, then all scientific truths would be computationally derived from the axioms of that theory [53]. Tarski’s undefinability theorem shows that this is impossible.

CHAITIN’S INCOMPLETENESS THEOREM

Even though formal mathematical systems are based on logic, and Gödel’s and Tarski’s theorems demonstrate implicitly the limitations of quantum gravity, real calculations in quantum gravity are done using computational algorithms. If we want to explicitly analyze such limitations, we need to analyze similar limitations in algorithmic information theory. Chaitin’s incompleteness theorem [54, 55] is a profound result in algorithmic information theory, which results in similar fundamental limitations as Gödel’s theorems (and is directly related to them [56]). In essence, it states that in any consistent and sufficiently expressive formal system, there exists a bound on the provability of statements based on their algorithmic complexity. This theorem complements Gödel’s incompleteness theorems by demonstrating that the inability to prove certain truths arises from their informational complexity.

We now explore how Chaitin’s theorem applies to quantum gravity, formulated as a formal system. As \mathcal{F}_{QG} denotes the formal system describing quantum gravity, with axioms $\{A_1, A_2, \dots\}$. Chaitin’s theorem states that there exists a constant $K_{\mathcal{F}_{QG}}$, determined by the axioms of \mathcal{F}_{QG} , such that no statement S with Kolmogorov complexity $K(S) > K_{\mathcal{F}_{QG}}$ can be proven within \mathcal{F}_{QG} . The Kolmogorov complexity $K(S)$ of a statement S is defined as: $K(S) = \min\{|P| : U(P) = S\}$, where P is a program for a universal Turing machine U , and $|P|$ denotes the length of P in bits. Now each statement S in \mathcal{F}_{QG} can be encoded as a finite binary string. Let $\text{GN}(S)$ denote the Gödel number of S , which allows us to measure the Kolmogorov complexity $K(S)$.

Since \mathcal{F}_{QG} is effectively axiomatizable, all proofs in \mathcal{F}_{QG} can be enumerated as P_1, P_2, \dots . Let P_i be a proof of length $|P_i|$, which corresponds to a provable statement S_i . There are at most 2^n proofs of length $\leq n$, and thus only finitely many statements S_i with $K(S_i) \leq n$. By the Kraft inequality [57], the total number of binary strings with Kolmogorov complexity $K(S) \leq n$ is

bounded by $2^{n+1} - 1$. However, the number of binary strings of length n is 2^n , meaning that there exist strings S with $K(S) > n$. These strings cannot be generated by programs of length $\leq n$, and hence cannot correspond to provable statements in \mathcal{F}_{QG} . Suppose, for example, that \mathcal{F}_{QG} proves a statement S with $K(S) > K_{\mathcal{F}_{QG}}$. Then there exists a proof P such that $|P| = K(S) > K_{\mathcal{F}_{QG}}$, contradicting the definition of $K_{\mathcal{F}_{QG}}$. Thus, no such statement S can be proven within \mathcal{F}_{QG} .

Chaitin's theorem has profound implications for quantum gravity. Many scientific facts/statements in quantum gravity, such as those describing the microstates of black holes, involve high complexity. The Bekenstein-Hawking entropy, for instance, scales as $S_{BH} \sim A/(4\ell_p^2)$, where A is the horizon area. If information about individual microstates require Kolmogorov complexity exceeding $K_{\mathcal{F}_{QG}}$, they will be unprovable within the formal system of quantum gravity. It has already been argued that quantum gravity prevents its own measurement near the Planck scale [40, 41]. Similarly, detailed descriptions of spacetime topology at the Planck scale might involve complexities beyond the provability threshold of \mathcal{F}_{QG} , suggesting that some truths in quantum gravity, though valid, would lie outside the reach of computational derivation.

APPLICATION TO PHYSICAL PROBLEMS

We now discuss some applications of these results, starting from the black hole information paradox [58]. It could be that the information stored a black hole associated with Planck scale physics, where quantum fluctuations and traditional notions of geometry appear to break down, cannot be microscopically algorithmically computed due Chaitin's incompleteness theorem, as alluded to above. In this case, the emergence of smooth spacetime from Planck-scale physics would occur through thermalization, where microscopic quantum gravitational degrees of freedom collectively evolve into a macroscopic geometric state. This could be beyond algorithmic computation, as in general it has been explicitly proven that determining whether a given system thermalizes is computationally undecidable [59].

Thermalization appears to be very important in existing quantum gravity models for understanding the emerges of classical spacetime from Planck scale physics. In string theory, via AdS/CFT, perturbations drive a rapid gravitational collapse that thermalizes the bulk into a smooth black hole horizon with well-defined thermodynamic properties [60]. Furthermore, in fuzzball theory, thermalization emerges as the collective behavior of numerous microstate geometries that statistically reproduce the black hole's thermal radiation spectrum [61]. Similarly, in loop quantum gravity, coarse graining thermalizes discrete quantum geometries into a continuum

phase that recovers classical spacetime [62]. As it appears to be impossible to computationally determine if a given system thermalizes [59], such emergence of spacetime could be uncomputable. This might be deeply related to not only the black hole information paradox, but the emergence of spacetime itself. So, it is possible that a full resolution of information paradox and explanation of the emergence of spacetime can only come from a meta-theoretical framework whose principles transcend conventional computation.

It has also been demonstrated that no computational algorithm can decide whether a quantum many-body Hamiltonian is gapped or gapless [63]. This is done by constructing a family of Hamiltonians, whose spectral gap encodes the halting problem, so that determining the presence of a spectral gap is fundamentally undecidable. This result holds because the halting problem [64], which is directly related to the Chaitin's incompleteness theorem [65], proves that no algorithm can universally decide whether an arbitrary program will halt, thus establishing a fundamental limit on computation.

This result has motivated the study of such behavior in the full renormalization group (RG) flows, which have been shown, in quantum many-body systems, to not be computable [66]. RG flows in both string theory [67], and LQG [68], play an important role in the emergence of spacetime [69, 70]. If RG flows in quantum gravity are algorithmically uncomputable, the emergence of spacetime from quantum gravity could be beyond algorithmic computations. It is also worth noting that certain properties of tensor networks are not computable [71]. Tensor networks have been used both in string theory [72] and LQG [73] to explain the emergence of spacetime from quantum gravity.

Similar problems also occur in other aspects of quantum gravity. For example, it has been explicitly demonstrated that as a consequence of Gödel's incompleteness theorems, it is not computationally possible to determine if a given two dimensional supersymmetric theory breaks supersymmetry [74]. As supersymmetry is an important ingredient in superstring theories [33], these results could again have important consequences in quantum gravity.

Also, using an explicit construction of quantum spin models whose phase diagrams encode uncomputable problems, it has been demonstrated that no general algorithm can fully determine these diagrams [75], implying intrinsic computational limits to predicting phase transitions and understanding complex quantum matter. Now as the quantum spin model and LQG are closely related mathematically [76], this may have important implications for LQG. So, it is possible that the full phase diagram of LQG, like quantum many-body systems, is fundamentally not computable.

These results suggest that certain truths lie beyond the computational domain of any consistent and sufficiently expressive theory of quantum gravity. Note that the principle of sufficient reason states that every fact has a reason, which forms the basis of science itself [77, 78]. The absence of an algorithmic explanation does not contradict this principle; rather, it suggests that while some explanations may be expressed in algorithmic terms, others reside in a non-algorithmic understanding, which still provides a sufficient explanation for the phenomena in question.

In fact, several undecidable problems occur due the link between certain properties of physical systems and the Turing’s halting problem [79]. It has been argued using a Stewart approach that non-algorithmic understanding can overcome such intrinsic computational limitations [80]. This is closely related to the Lucas-Penrose argument [42–46]), indicating that there is something intrinsically non-computational in nature, and its description in terms of computational algorithms is rather limited.

The Novikov self-consistency principle [81] provides another compelling example of non-algorithmic understanding. Originally formulated in the context of time travel and closed timelike curves in general relativity, it posits that events within regions of spacetime containing causal loops must be self-consistent. So, any action taken by a time traveler must have already been part of history, ensuring that the timeline remains consistent and free from contradictions [39]. This principle cannot be computationally derived from general relativity axioms but is an intuitive addition that resolves paradoxes due to self-referentiality. Similarly, in quantum gravity, principles inspired by the Novikov self-consistency framework may enable the resolution of truths that exceed the provability limits of formal systems due to self-referentiality, offering a broader understanding of phenomena that cannot be computational derived.

Gravitationally induced objective collapse, which addresses the measurement problem in quantum mechanics using an objective physical process tied to gravitational effects, also exemplifies the application of non-algorithmic understanding [37, 38]. In this framework, measurement occurs independently of an observer, and is neither random nor computational. In this regard, it has been explicitly demonstrated that quantum logic is inherently undecidable due to incompleteness theorems [82, 83]. So, an approach based on non-algorithmic understanding [37, 38] produces a better physical explanation of the measurement problem. It is well established that there are limitations to computations in various problems of physics [84]. Here we have argued that these similarly imply it impossible for quantum gravity based on computations to be both consistent and complete.

To address the inherent limitations of formal systems in quantum gravity, a meta-theory of

everything \mathcal{M}_{ToE} is needed, which contains non-algorithmic understanding. This meta-theory of everything would extend the computational-based formal system \mathcal{F}_{QG} by introducing a truth predicate $T(x)$, enabling the recognition of truths beyond formal provability. Specifically, \mathcal{M}_{ToE} would allow for the acceptance of Gödel statements G as true, the resolution of undefinable truths, and the acknowledgment of high-complexity statements S with $K(S) > K_{\mathcal{F}_{QG}}$. This meta-theory would satisfy: $T(G) = 1$ for G true but unprovable in \mathcal{F}_{QG} . By transcending the algorithmic limits of \mathcal{F}_{QG} , \mathcal{M}_{ToE} would provide a framework to explore truths that lie beyond computation. Inspired by principles such as Novikov self-consistency, and similar principles based on non-algorithmic understanding, this approach could integrate rigorous computations with non-algorithmic insights. It could potentially resolve challenges like the black hole information paradox and the complexities of Planck-scale physics.

Considerations of quantum gravity have suggested that physics should evolve from a focus on ‘it’ (i.e. matter fields moving in spacetime) to a focus on ‘bit’, i.e., information being more fundamental. The considerations we present here show that neither ‘it’, nor ‘bit’ is fundamental. Namely, a non-algorithmic understanding must operate at a fundamental level in any theory of everything.

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