The Planck Time as a Minimum Bit-Certification Scale: A Derivation from Bit–Contrast Balance and Ticks-Per-Bit Principles

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Abstract

We derive a fundamental lower bound on the substrate cost of certifying a stabilised, non-redundant bit of information. Within the Bit–Contrast Balance (BCB) and Ticks-Per-Bit (TPB) framework, physical evolution is decomposed into elementary substrate steps called *ticks* — pre-metric dynamical updates that carry no intrinsic informational content. Bits (stabilised, non-redundant distinctions registered at physical interfaces) accumulate through irreversible stabilisation of tick sequences, and emergent time is defined by this accumulation: the temporal metric is the macroscopic structure that becomes well-defined when bit density is sufficient to support smooth parameterisation.

We formulate three conditions — a Certification Locality Principle (an operational consequence of finite propagation of correlations, not an independent postulate), a Quantum Speed Limit (the Mandelstam–Tamm / Margolus–Levitin bound on distinguishable evolution), and a conservative No-Trapping Condition on the compactness of the certification region — and apply them as emergent constraints within any regime admitting a locally valid effective causal metric. The derivation distinguishes between the dynamical energy scale E_{dyn} (driving distinguishability, constrained from below by the QSL) and the total gravitating energy E_{grav} (determining compactness, constrained from above by the NTC), connected by the conservative inequality $E_{dyn} \leq E_{grav}$. A minimax argument over these energy scales yields a minimum certification scale that, expressed in the emergent metric, scales as $\Delta t_{min} \sim \sqrt{\hbar G/c^5}$, recovering the Planck time up to order-one numerical factors.

The argument does not assume saturation of either bound, does not depend on the hoop conjecture, and does not require energy localisation as an independent postulate. We use the emergent duration Δt only as an effective parameter; the bound is derived as a consistency condition on the existence of such a parameter. The Planck scale emerges (in the effective causal description) as a structural fixed point — the minimum spatial support required to stabilise and outwardly certify one non-redundant bit within an effective causal regime, where distinguishability demand (QSL) balances admissibility (NTC). Equivalently, the bound may be read as a minimum certification-region scale $R_{min} \sim \ell_P$, with the temporal form t_P following as the corresponding causal interval in the emergent metric. Below the Planck scale, the bit-certification rate is insufficient to sustain the effective causal metric in which the constraints were stated, yielding a self-consistent boundary rather than a circular dependence. We do not claim the bound is saturated in nature, only that no protocol can certify a non-redundant bit at smaller scale without violating one of two necessary conditions. The result does not imply temporal discreteness, a fundamental clock, or a one-bit-per-Planck-time correspondence.

Abstract for General Readers

Everything that happens in the universe unfolds through tiny steps on a substrate — a deeper level of reality beneath the time and space we experience. Most of these steps leave no lasting trace. Only occasionally does a step contribute to something permanent: a recorded change, a stored distinction, a *bit* of information.

Here is the key idea: *time itself is built from these recorded bits.* Time is not a background stage on which events happen — it is what emerges when enough permanent records accumulate. A clock doesn't measure time flowing past; a clock counts bits being written.

This creates a puzzle. If time is made of bits, we can't ask "how fast can a bit be written?" — because "fast" already assumes time exists. Instead, we ask: *what is the minimum cost, in substrate steps, of writing a single bit?*

Two constraints compete to answer this. Quantum mechanics says that drawing any distinction requires a minimum expenditure of substrate steps — and that reducing this cost demands more energy. Gravity says that if you concentrate too much energy in too small a region, the region seals itself off — entering a black-hole-like censorship regime that destroys the surface where the bit would have been recorded.

When we translate this minimum substrate cost into the language of emergent time, it equals the Planck time: roughly 5.4×10^{-44} seconds. This is not a tiny chunk of time. It is the scale at which there aren't enough bits being written to sustain the notion of time at all. Below it, "time" hasn't been built yet. In the BCB/TPB ontology, the Planck scale is not treated as a primitive unit of space or time. It is the minimum structural support required for certifiable irreversible commitment — and space and time are simply the macroscopic bookkeeping language of such commitments.

Principal Results

Result 1. The joint constraints of quantum distinguishability (QSL) and gravitational admissibility (NTC), applied within a causal certification region, yield a minimum bit-certification scale that reproduces the Planck time:

$$\Delta t_{min} \sim \sqrt{\hbar G/c^5} = t_P$$

up to order-one numerical factors, via a minimax argument that assumes neither bound is saturated.

Result 2. Within the BCB/TPB framework, t_P is interpreted as a *minimum bit-certification scale* — the smallest effective emergent duration within which a non-redundant bit can be certified at a surviving interface — not as a fundamental tick, a discreteness quantum, or a universal clock period. Sub-Planck substrate evolution proceeds freely; it simply cannot contribute to the informational record from which the emergent temporal metric is constructed.

Result 3. The Planck scale is neither fundamentally temporal nor fundamentally spatial as a primitive: it is the fixed point of the certification minimax squeeze. In any regime admitting an effective causal metric, it can be expressed equivalently as a minimum spatial support for certification, $R_{min} \sim \ell_P$, or as the corresponding minimum causal interval, $\Delta t_{min} \sim t_P$, with $t_P = \ell_P/c$ holding within the emergent causal metric.

What This Means (For General Readers)

Result 1 says there is a shortest possible interval over which the universe can commit anything to the permanent record. That interval is the Planck time — about a ten-millionth of a trillionth of a trillionth of a trillionth of a second. We derive this not by assuming it, but by showing that two independently well-established constraints — one from quantum mechanics, one from gravity — squeeze from opposite directions and leave no room below this scale. Quantum mechanics demands more energy to write a record faster; gravity destroys the recording surface if too much energy is concentrated in one place. The Planck time is where those two demands meet exactly: any smaller, and the energy required just to distinguish "something happened" from "nothing happened" would be so concentrated that it would enter a black-hole-like causal censorship regime — swallowing the very surface on which the record was supposed to be written.

Result 2 says what this means for how bits form — and what the Planck time *is not*. Bits do not snap into existence one per Planck tick, like frames in a film. Bit formation is a costly, inefficient process: the substrate churns through vast numbers of reversible steps for every single permanent record that gets written. The Planck time is not a tiny grain of time, like a pixel on a screen, and the universe does not advance in Planck-time steps. Activity below the Planck time happens freely — fields fluctuate, quantum states evolve — but none of it produces a bit. The Planck time is the threshold of recordability: the point below which the universe can do things but cannot remember having done them.

Result 3 says the Planck scale can be read as a minimum amount of room needed to write a permanent record. To commit anything to the permanent record, the universe needs a region large enough to tell two possibilities apart and lock one of them in, but not so energy-dense that gravity seals it off. The Planck length is that minimum region. The Planck time is how long light takes to cross it. Neither is more fundamental than the other — both are ways of expressing the same structural constraint: the smallest possible commitment the universe can make to its own record.

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1. Introduction

The Planck time, $t_P = \sqrt{\hbar G/c^5} \approx 5.39 \times 10^{-44}$ s, appears throughout theoretical physics as a natural timescale at which quantum mechanics and gravity intersect. Various authors have derived Planck-scale bounds from combinations of quantum and gravitational constraints — notably Lloyd (2000) on ultimate computational limits, Ng and van Dam (2003) on quantum foam, and the foundational observations of Mead (1964) on minimum measurable lengths. These treatments work within a framework where time is a background parameter and the Planck time represents either a discreteness scale or a computational speed limit.

The Bit–Contrast Balance (BCB) and Ticks-Per-Bit (TPB) framework, developed within the Void Energy-Regulated Space Framework (VERSF), takes a fundamentally different starting point: time is not background but emergent. Physical evolution occurs through pre-metric substrate steps (ticks), and time is the macroscopic variable that emerges when irreversible bit stabilisation produces a sufficiently dense record. This ontology creates a circularity problem absent from prior treatments: one cannot ask "how fast" a bit is certified without invoking the temporal metric that bit accumulation constructs.

The present work resolves this circularity and derives the Planck-scale bound within a time-emergent ontology. The strategy is threefold:

First, we formulate the problem in tick-space, treating the substrate tick-count as the fundamental resource and emergent duration as a derived effective parameter.

Second, we observe that in any regime where sufficient bit accumulation has established a locally valid effective causal metric, the quantum speed limit and gravitational admissibility apply as emergent constraints on the tick-to-bit conversion process.

Third, we show that these emergent constraints impose a minimum tick-cost for bit certification, and that this minimum cost, expressed in the emergent metric, scales as t_P. Below this scale, the bit-certification rate is too low to sustain the effective causal metric in which the constraints were formulated — the description becomes self-undermining. The Planck time is thus not an externally imposed bound but a self-consistency condition: the smallest scale at which the emergent temporal description can sustain itself through ongoing bit certification.

The derivation employs three conditions: a Certification Locality Principle (an operational consequence of finite propagation, not an additional postulate), the Mandelstam–Tamm / Margolus–Levitin quantum speed limit, and a conservative no-trapping condition on compactness. A minimax argument over the certification energy yields the bound without assuming saturation and without invoking the hoop conjecture.

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2. Definitions

Tick. A tick is an elementary substrate step of physical evolution. Ticks are pre-metric: they are dynamical updates on the substrate that do not individually carry temporal or spatial content. Ticks may be fully reversible, unitary, and leave no lasting record. The ordering of ticks is logical (substrate-sequential), not temporal — temporality is a higher-order structure that emerges from patterns of bit stabilisation.

Bit. A bit is a stabilised, non-redundant distinction that persists at an interface. Bit formation is irreversible: once a bit is written, the process cannot be undone without additional thermodynamic cost. Bit formation typically requires many ticks. The accumulation of bits constitutes the raw material from which the emergent temporal metric is constructed.

Emergent time. Time is the macroscopic parameter that tracks the accumulation of certified bits within a region. It is not a background variable in which ticks occur but a derived effective parameter that becomes well-defined when bit density is sufficient to support a locally smooth effective causal metric. The relationship between tick-count N and emergent duration Δt is mediated by the local bit-certification rate and the energy content of the region.

Interface (Record Surface). An interface is any physical subsystem *I* such that:

(i) *Stability: I* possesses at least two metastable, distinguishable macrostates $\{|0\rangle_I, |1\rangle_I\}$ with persistence far exceeding the tick-cost of their formation.

(ii) *Non-redundancy:* the state of *I* is not gauge-equivalent or relabeling-equivalent to a state of the environment; that is, *I* can serve as a certificate accessible to external degrees of freedom.

(iii) *Causal certification:* the information "which macrostate" is available within a certification region *R* whose extent is bounded by the effective causal structure of the emergent metric (or, at the substrate level, by the finite propagation depth of substrate correlations).

This definition is deliberately operational: it never mentions observers, only the availability of a stable, non-redundant, causally accessible certificate.

Scope note. The bound derived in this paper concerns the certification of bits on pre-existing interfaces that admit metastable macrostates; it does not attempt to derive the formation or longevity of such interfaces from substrate dynamics.

Destruction of an interface consists of any process that eliminates condition (i) or (ii): formation of a causal censorship regime that prevents the certificate from propagating to any external degrees of freedom, or dynamical destruction of metastability such that no two long-lived distinguishable macrostates survive.

Bit-eligible tick. A tick is bit-eligible if it could, in principle, participate in irreversible bit stabilisation at an interface. Not all ticks are bit-eligible; most are fully reversible and never contribute to a recorded distinction.

Degree of freedom (substrate). A degree of freedom is an independent component of substrate structure capable of carrying distinguishability. "Independent" means its state is not determined by the states of other components; "capable of carrying distinguishability" means it can participate in the separation of alternatives required for bit formation. In this paper we do not compute a substrate participation count; we work in the effective description where certification requires a finite region R. A “participation” reading — in which the minimum certification-region scale corresponds to a minimum count of engaged substrate degrees of freedom — is optional and serves only as intuition for what R represents at the substrate level.

These definitions establish a hierarchy:

ticks (pre-metric, mostly reversible) → many ticks → irreversible stabilisation → bit → accumulated bits → emergent temporal metric

General reader note: Think of ticks as the universe's raw substrate activity — the deepest level of "things happening," prior to any notion of duration or distance. A bit is the rare event where something permanent gets recorded. A degree of freedom is one independent moving part at the substrate level — a piece of structure that can change on its own. Writing a bit requires a region of sufficient extent, which can be thought of as engaging a minimum number of these independent parts. Time itself is what you get when you zoom out and count those permanent records. Asking "how fast does a bit form" is like asking "how many bricks does it take to build the floor you're standing on" — the floor doesn't exist before the bricks, so you have to count in bricks, not in floor-lengths.

An intuitive explanation of "certification region" and "compression limit" is given in Appendix A.

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3. The TPB Efficiency Principle

The Ticks-Per-Bit framework asserts that the tick-to-bit conversion is fundamentally inefficient. Defining the informational efficiency as

η_{info} = (bits certified) / (ticks elapsed)

TPB asserts:

$\eta_{info} \leq 1$, with $\eta_{info} \ll 1$ typical.

Most ticks do not produce bits. This inefficiency is not a deficiency but a structural necessity with two faces:

Physical face: Coherent quantum evolution requires reversibility. If every tick produced a bit ($\eta_{info} = 1$), every substrate step would be irreversible, and the superpositions that underlie quantum interference, entanglement, and quantum computation could not exist.

Metric face: The emergent temporal metric is coarse-grained over many ticks. The relationship between tick-count and emergent duration is meaningful precisely because most ticks are non-informational — they provide the substrate depth over which a smooth effective metric is defined. If $\eta_{info} = 1$, there would be no separation between the substrate and the emergent description, and the concept of a smooth temporal metric would not arise.

The central result of this paper — that the QSL and NTC jointly enforce a minimum tick-cost per bit — can be understood as the structural origin of TPB inefficiency. The $\eta_{info} \ll 1$ regime is not merely observed; it is enforced by the mutual constraints of quantum distinguishability and gravitational admissibility.

General reader note: Imagine stirring two drops of different-coloured paint into a pot. Each stir is a tick. Most stirs just swirl the paint around — nothing permanent happens, and in principle you could reverse the motion. But occasionally, at some interface between the two colours, an irreversible mixing event occurs: the colours blend in a way that can never be undone. That's a bit. The TPB principle says this is always the case: the universe stirs far more than it mixes.

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4. The Circularity Problem and Its Resolution

4.1 Statement of the Problem

Prior derivations of Planck-scale bounds (Lloyd 2000; Ng and van Dam 2003) ask: what is the minimum *time* required to perform a computation or certify a bit? This question takes time as given — a background parameter with respect to which processes are measured.

In BCB/TPB, time is emergent. It is constructed from bit accumulation. Asking "what is the minimum time to certify a bit" is therefore circular: the answer depends on the temporal metric, which depends on the bit-certification rate, which is what we are trying to bound.

4.2 Resolution: Two Levels of Description

The circularity is resolved by recognising that the derivation operates at the boundary between two levels of description:

Level 1: Tick-space (substrate). Ticks, interfaces, and bit formation are defined without reference to emergent time. The fundamental resource is tick-count, not duration.

Level 2: Emergent spacetime. In any region where sufficient bit accumulation has occurred, a locally valid effective causal metric exists. The quantum speed limit, causal structure, and gravitational dynamics are emergent constraints that apply at this level.

Throughout this paper, we use Δt only as an effective parameter of the Level 2 description, valid in regimes where a local effective causal metric exists. The bound is derived as a consistency condition on the existence of such a regime — not as a statement about background time.

The derivation proceeds as follows:

(a) Assume we are in a regime where Level 2 is locally valid — that is, enough bits have been accumulated to define an effective causal metric.

(b) Within this regime, apply the emergent constraints (QSL and NTC) to determine the minimum tick-cost of certifying one additional bit.

(c) Express this minimum tick-cost in terms of the effective parameter Δt to obtain the Planck time.

(d) Verify self-consistency: the Planck time is exactly the scale at which the bit-certification rate becomes too low to sustain the Level 2 description. Below it, the effective causal metric is not well-defined, and the question "how fast" loses meaning.

This is not a vicious circle but a self-consistency condition. The emergent constraints are applied in the regime where they are valid, and they identify the boundary of their own validity. The Planck time is the bootstrapping threshold of the emergent temporal description.

General reader note: Imagine a society that defines "one year" as "the time it takes to harvest one crop." You can't ask "how many months does it take to grow a crop?" if months are defined by crops. But you *can* ask: "what is the minimum number of days of sunlight and rain needed before a crop can grow?" — and if the answer turns out to be approximately one year's worth, you've found the self-consistency condition. The Planck time is physics' version of this: the smallest interval that can sustain its own definition.

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5. Condition 1: Certification Locality (Causal Certification Principle)

Certification Locality Principle (CLP). A bit is certified within emergent duration Δt only if there exists a finite region R within which (i) the interface is settled into a definite macrostate and (ii) the certificate is physically available — that is, checkable by degrees of freedom within R. In any regime admitting an effective causal metric, this implies $\mathrm{diam}(R)$ is bounded by the causal domain of the certification event.

This is not an additional physical law; it is the operational meaning of "certified by Δt" in any theory with finite propagation of correlations. Specifically:

(a) R contains the degrees of freedom that settle I into $|0\rangle$ vs $|1\rangle$.

(b) R contains enough of the correlated imprint to make the distinction non-redundant — that is, physically checkable within R.

In any regime admitting an effective causal metric, certification cannot outrun the causal domain associated with the process; hence R is bounded by the causal horizon of the certification event (written as $R \lesssim c\Delta t$ in standard units, where Δt is the effective emergent duration of the process). We require only that R be bounded by a constant multiple of $c\Delta t$ within the effective causal regime; any geometric prefactors are absorbed into η.

The CLP does not assert that energy must be localised. It asserts that the certification event — the moment at which the bit value becomes definite and verifiable — must have a finite spatial footprint determined by the causal structure. Any nonlocal scheme still requires some local region where the record becomes definite and checkable; otherwise the bit has not been certified by Δt.

General reader note: If you want to claim a bit was written, there must be a region of space where the record actually exists and could, in principle, be checked. You can't claim a bit exists everywhere and nowhere. This isn't about observation; it's about the record having a physical address. And since information can't travel faster than light, that address must fit inside a region limited by how far light could have travelled during the process.

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6. Condition 2: Quantum Speed Limit (QSL)

In any regime where the emergent effective causal metric is valid, quantum mechanics imposes a speed limit on how fast a system can evolve between distinguishable states. This is an established result in quantum information theory:

(QSL) $\Delta t \geq \kappa\hbar / E\_dyn$

where Δt is the effective emergent duration of the certification process, E_dyn denotes the dynamical energy scale available to drive distinguishability within the certification region R, $\hbar$ is the reduced Planck constant, and κ is an order-one constant.

More precisely, E_dyn can be taken as the energy uncertainty ΔE for the Mandelstam–Tamm bound (Mandelstam and Tamm, 1945) or as $\langle E\rangle - E_0$ (mean energy above ground state) for the Margolus–Levitin bound (Margolus and Levitin, 1998). Both give the same $\hbar/E$ scaling; the precise value of κ (= $\pi/2$ in both standard formulations) is absorbed into the order-one prefactor of the final bound.

The physical content is: achieving a distinguishable evolution within Δt requires a dynamical energy scale in the certification region satisfying $E\_dyn \gtrsim \kappa\hbar/\Delta t$. Lower available dynamical scale means slower distinguishability, which means the bit takes longer to certify.

Scope of the QSL application. Bit certification in practice involves amplification, decoherence, and stabilisation — typically open-system dynamics, not purely unitary evolution. Our use of the QSL is intentionally minimal: we apply it only to the smallest dynamical step within the certification region that produces a distinguishable branching sufficient to imprint the interface macrostate. Any subsequent amplification, dissipation, or relaxation required for metastability can only increase the total certification duration. The QSL therefore supplies a necessary lower bound on one component of the certification process without assuming that the full process is unitary or that it saturates the bound. This is consistent with the minimax logic of §8: we bound the fastest possible route, and all realistic routes are slower.

Which system the QSL applies to. The QSL is applied to the smallest closed quantum subsystem contained within the certification region R whose unitary dynamics generates the distinguishable branching that imprints the interface (e.g. the measured degrees of freedom together with the local pointer/environment modes they couple to inside R). Concretely, if H_R is the Hamiltonian governing this local subsystem and $\rho_R(t)$ its state, the QSL bounds the minimum Δt required for ρ_R to evolve to a distinguishable state (orthogonality or specified fidelity threshold) in terms of the relevant energy scale of H_R (e.g. ΔE_R or $\langle H_R\rangle - E_{0,R}$). Energy stored in distant, non-interacting degrees of freedom does not accelerate local branching and is therefore not the relevant E_{dyn} for certification within R. With this choice, E_{dyn} is a local dynamical scale in R, and the bridge $E_{dyn} \leq E_{grav}$ remains conservative.

Ontological status within BCB/TPB. The QSL is not a substrate-level postulate. It is an emergent constraint: a property of the effective quantum dynamics that holds in any region where sufficient bit accumulation has established a valid effective causal metric and Hilbert space structure. It is a feature of the effective description supported by the existence of stable records. We apply it at Level 2 to constrain the tick-to-bit conversion process, with the understanding that its applicability is part of what we are checking for self-consistency.

Translation to tick-space. If N ticks of the substrate correspond to effective emergent duration Δt in a given region, and the local dynamical energy scale is E_{dyn}, then the QSL constrains the minimum tick-count: $N \geq \kappa\hbar/(E_{dyn} \cdot \delta t)$, where δt is the effective emergent duration per substrate tick in that region. The product $N \cdot \delta t = \Delta t$ recovers the standard QSL. The content is that distinguishable evolution has a minimum substrate cost that scales inversely with available dynamical energy scale.

General reader note: Quantum mechanics says you cannot tell two states apart instantly. The more energy you have, the fewer substrate steps you need — but there is always a minimum. This isn't about clocks; it's about the physics that emerges from accumulated bits enforcing a cost floor on creating the next bit.

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7. Condition 3: No-Trapping Admissibility (NTC)

For the interface to survive and the bit to be certifiable, the certification region must not enter a causal censorship regime in which the certificate cannot propagate to any external degrees of freedom.

We formulate this as a conservative sufficient condition for outward certification, not as a claim about exact collapse thresholds:

No-Trapping Condition (NTC). Reliable outward certification requires that the compactness of the certification region remain subcritical:

$$2GE_{grav} / (c^4R) \leq \varepsilon$$

where ε is an order-one constant (optionally $\varepsilon \ll 1$ for a conservative safety margin), E_{grav} is the total gravitating energy in the certification region (ADM or Bondi quasi-local energy as appropriate), and R is its characteristic areal radius. We use R as an areal radius for the certification region; geometric dependence (spherical vs. non-spherical configurations) enters only through order-one factors absorbed into ε.

If this condition fails, outward certification is not guaranteed: the region may contain or rapidly evolve toward a trapped surface from which the certificate cannot escape. For our purposes — deriving necessary conditions for bit certification — "not guaranteed" is equivalent to "inadmissible."

The NTC is a conservative sufficient safety condition for avoiding causal censorship of the certificate; it is stronger than necessary, which makes the resulting bound conservative. The NTC does not invoke the hoop conjecture in its full generality. It requires only the widely accepted principle that order-one compactness is incompatible with reliable outward information transfer.

Domain note. The NTC is imposed only within regimes where an effective causal metric and semiclassical gravitational notions (e.g., trapped/censored regions at order-one compactness) are reliable. Since our goal is a necessary-condition bound on certification within such effective regimes, we adopt the NTC as a conservative safety condition and then explicitly check self-consistency of that regime at the Planck threshold (§8.4). If quantum-gravity effects substantially weaken causal censorship/trapping near order-one compactness, the NTC jaw may open and the present bound may become non-binding; we therefore treat NTC as a conservative assumption about the effective regime, not a theorem about the deep substrate.

Applying CLP (in any effective causal metric, $R \lesssim c\Delta t$):

(NTC) $E_{grav} \leq \varepsilon\, c^5 \Delta t / (2G)$

For brevity, we absorb $\varepsilon/2$ into a single order-one constant η, writing:

$E_{grav} \leq \eta (c^5/G) \Delta t$

where η is order-one (and may be taken small for a conservative safety margin).

Ontological status. Like the QSL, the NTC is an emergent constraint. Gravitational dynamics — including the formation of causal censorship regimes — is a feature of the effective description supported by the existence of stable records. The NTC says: within the emergent description, concentrating too much gravitating energy in the certification region prevents outward propagation of the certificate. This is a constraint that the emergent physics imposes on its own source material.

General reader note: If you cram too much energy into too small a region, gravity seals it off — information falls in but can't get out. This isn't about the region "collapsing" in a dramatic sense; it's about the recording surface being cut off from the rest of the universe. We don't need to know the exact threshold; we just need to stay safely below it.

8. Derivation and Proof

8.1 Energy Scales in the Certification Region

Two distinct energy scales enter the derivation:

E_dyn = the dynamical energy scale relevant for the QSL — that is, the energy uncertainty ΔE (Mandelstam–Tamm) or the mean energy above the ground state $\langle E \rangle - E_0$ (Margolus–Levitin). This is the scale that drives distinguishable evolution within the certification region.

E_grav = the total gravitating energy contained in the certification region (ADM or Bondi quasi-local energy as appropriate). This is the scale that determines the compactness of the certification region.

These are related by a conservative inequality:

$E_{dyn} \leq E_{grav}$

On the bridge inequality. The QSL involves an available dynamical energy scale E_dyn: either $E_{dyn} = \Delta E$ (Mandelstam–Tamm) or $E_{dyn} = \langle E \rangle - E_0$ (Margolus–Levitin). The no-trapping constraint involves the total gravitating energy E_grav contained in the certification region (quasi-local ADM/Bondi energy). In both cases $E_{dyn} \leq E_{grav}$ is conservative: (i) for Mandelstam–Tamm, the uncertainty ΔE cannot exceed the total energy budget present in the region; (ii) for Margolus–Levitin, subtracting the ground state makes E_dyn smaller still, so the inequality is generically strict. Vacuum/ground-state renormalisation can only reduce E_dyn relative to any gravitating energy budget relevant for compactness. This makes the bound conservative and avoids dependence on the detailed treatment of E_0 (noting that the cosmological-constant problem precisely concerns the gravitational status of vacuum energy).

The QSL constrains E_dyn from below; the NTC constrains E_grav from above. Since $E_{dyn} \leq E_{grav}$, upper bounds on E_grav are *a fortiori* upper bounds on E_dyn, and the minimax chain connects cleanly.

8.2 Lemma (Bit-Certification Lower Bound; Planck Scaling)

Let a physical process produce a stabilised, non-redundant bit within effective emergent duration Δt, in a regime where the effective causal metric is locally valid. Assume:

(1) *Certification locality (CLP):* There exists a certification region *R* of characteristic areal radius R bounded by the causal domain of the certification event ($R \lesssim c\Delta t$ in the effective metric) within which the bit value is encoded in an interface *I* with metastable distinguishable states.

(2) *Quantum speed limit (QSL):* Achieving a distinguishable evolution within Δt requires a dynamical energy scale E_{dyn} in *R* satisfying $\Delta t \geq \kappa\hbar/E_{dyn}$ (where E_{dyn} denotes ΔE for Mandelstam–Tamm or $\langle E\rangle - E_0$ for Margolus–Levitin; κ is order-one).

(3) *No-trapping admissibility (NTC):* Reliable outward certification requires subcritical compactness of the total gravitating energy E_{grav} in *R*, so $E_{grav} \leq \eta(c^4/G)R$ with η order-one.

(4) *Energy budget:* $E_{dyn} \leq E_{grav}$ (the dynamical scale cannot exceed the total energy budget of the region).

Then any such bit certification must satisfy

$$\boldsymbol{\Delta t \geq \sqrt{(\kappa/\eta)} \cdot \sqrt{(\hbar G/c^5)} \sim t_P}$$

up to order-one factors. Moreover, this bound coincides with the self-consistency threshold below which the effective causal metric invoked in (1)–(3) ceases to be sustained by ongoing bit certification.

8.3 Proof

The logical structure is a minimax squeeze: certification requires (i) a dynamical scale E_{dyn} sufficient for distinguishability within Δt (QSL), pushing required energy up as Δt decreases, and (ii) subcritical compactness of *R* (NTC), pushing allowed gravitating energy down as Δt decreases. Since $E_{dyn} \leq E_{grav}$, these close to a nonzero floor.

Step 1. From (3) and (1): since $R \lesssim c\Delta t$, we have $E_{grav} \leq \eta(c^4/G)(c\Delta t) = \eta(c^5/G)\Delta t$.

Step 2. From (4): $E_{dyn} \leq E_{grav} \leq \eta(c^5/G)\Delta t$.

Step 3. From (2): $\Delta t \geq \kappa\hbar/E_{dyn}$.

Step 4. Substituting the upper bound from Step 2 into Step 3:

$$\Delta t \geq \kappa\hbar / E_{dyn} \geq \kappa\hbar / [\eta(c^5/G)\Delta t]$$

Step 5. Multiplying both sides by Δt (positive):

$$\Delta t^2 \geq (\kappa/\eta)(\hbar G/c^5)$$

Step 6. Taking the positive square root:

$$\Delta t \geq \sqrt{(\kappa/\eta)} \cdot \sqrt{(\hbar G/c^5)} \sim t_P \ \blacksquare$$

No assumption has been made that either bound is saturated. The argument holds for any pair (E_{dyn}, E_{grav}) satisfying $E_{dyn} \leq E_{grav}$: low dynamical scale makes the QSL dominant (longer Δt), high gravitating energy makes the NTC dominant (longer Δt). The floor applies regardless of whether any physical process reaches the crossover. Notably, dimensional analysis permits t_P to appear in many roles; the minimax chain fixes its role here specifically as a no-go for certification within $\Delta t < t_P$ under the stated necessary conditions.

We do not claim the bound is achieved in nature, only that any protocol which certifies a non-redundant bit within effective emergent duration Δt must avoid causal censorship while meeting a quantum distinguishability requirement, yielding an unavoidable Planck-scaling floor.

8.4 Self-Consistency Check

Package consistency. CLP, QSL, and NTC are not asserted as substrate-level axioms. They are joint constraints of the effective causal description that holds only when stable records are sufficiently dense to support a local metric and causal propagation. The self-consistency check below applies to the entire package: below the derived threshold, the very conditions required to state "certified within Δt" cease to be jointly satisfiable within an effective causal regime.

The derivation was conducted within Level 2 — the emergent description where the effective causal metric, quantum mechanics, and gravitational dynamics are valid. The result identifies $\Delta t_{min} \sim t_P$ as the minimum effective emergent duration per bit certification.

We take "locally valid effective causal metric" to mean that for the coarse-graining windows relevant to the effective description, the expected number of certified bits $N_b(\Delta T)$ satisfies $N_b(\Delta T) \gg 1$, so that records admit a smooth parameterisation. The Planck-scale floor marks the regime where N_b cannot be increased by refining ΔT further: at $\Delta t \sim t_P$, the minimum tick-cost of certifying a single bit is reached, and no additional bits can be packed into a smaller interval.

For any putative effective duration $\Delta t < t_P$, no protocol can certify a non-redundant bit within that Δt while preserving outward certification and quantum distinguishability. The bit-certification rate therefore drops below what is needed to define $N_b(\Delta T) \gg 1$ at that scale, so the effective causal metric is not sustained, and the Level 2 description in which the constraints were formulated ceases to apply.

This is self-consistent, not circular. The emergent constraints are applied in the regime where they are valid, and they identify the boundary of their own domain of validity. The Planck time is the bootstrapping threshold: the smallest effective emergent timescale at which the temporal description can sustain itself through ongoing bit certification.

General reader note: The two constraints — quantum mechanics and gravity — are features of the effective description supported by the existence of stable records. These features turn out to limit how efficiently new entries can be added to the record. The Planck time is where this feedback loop bottoms out: go smaller, and there aren't enough new entries to sustain the effective description, so the constraints stop applying, and the question stops making sense. It's like a self-governing society that has a rule requiring a minimum population to hold a valid vote — below that population, the rules themselves are no longer in force.

8.5 Robustness

"Nonlocal energy configurations circumvent the bound." The CLP does not require energy localisation; it requires that certification — the event at which the bit value becomes definite and checkable — occur within the causal domain of the process. This is the operational meaning of "certified by Δt" in any theory with finite propagation of correlations. Any nonlocal scheme still needs a local certification event; otherwise the bit is not certified by Δt.

"The hoop conjecture is not proven in full generality." The NTC does not invoke the hoop conjecture. It requires only that subcritical compactness is a sufficient safety condition for avoiding causal censorship of the certificate. Geometric dependence on the shape of the certification region enters only through order-one factors absorbed into η.

"Slow, low-energy pathways avoid both bounds." Such pathways do not violate the floor; they only increase Δt. The minimax chain holds for all energy values: low dynamical scale makes the QSL constraint dominant, yielding longer Δt.

"The bound assumes saturation of both constraints." It does not. The inequality chain $\kappa\hbar/\Delta t \leq E_{dyn} \leq E_{grav} \leq \eta(c^5/G)\Delta t$ is valid for any (E_{dyn}, E_{grav}) in the admissible range, not only at the crossover point.

"The argument is circular because time is emergent." The result identifies the boundary of the effective description's validity. For any putative $\Delta t < t_P$, no protocol can certify a non-redundant bit within that Δt while preserving outward certification and quantum distinguishability. This is a self-consistency condition, not a circular dependence (see §4.2 and §8.4).

"The QSL bounds energy uncertainty ΔE, not total gravitating energy." Correct, and the derivation respects this distinction. E_{dyn} is bounded from below by the QSL; E_{grav} is bounded from above by the NTC. The bridge inequality $E_{dyn} \leq E_{grav}$ connects the two. The gravity jaw constrains E_{grav}, which is *a fortiori* an upper bound on E_{dyn}.

"The QSL bounds unitary evolution, but certification involves decoherence and amplification." The QSL is applied only to the minimal dynamical distinguishability step — the smallest unitary branching that creates separable states sufficient to imprint the interface. All subsequent open-system processes (amplification, dissipation, relaxation to metastability) can only add to the total certification duration. The bound is on the fastest possible component, not on the whole macroscopic process.

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9. The Planck Scale as a Structural Fixed Point

9.1 What the derivation establishes, and an interpretive reading

The derivation in §8.3 is not fundamentally a derivation of a minimum time, a minimum length, or even a minimum geometry. It identifies a *minimum certification interval and hence a minimum certification-region scale* — the smallest spatial support within which a non-redundant bit can be stabilised and outwardly certified.

A bit is a commitment. To stabilise that commitment, the certification region must:

- separate alternatives (create a distinguishable branching),
- stabilise one branch (imprint the interface),
- maintain it against reversal (certify the record outward).

If the certification region is made smaller, two competing tendencies emerge:

Distinguishability compression. As the certification region shrinks, the gradients of distinguishability must steepen. The QSL quantifies this: reducing the certification-region scale demands increasing the dynamical energy scale E_{dyn}.

Admissibility. As energy concentrates into a smaller certification region, the conditions for causal censorship are approached. The NTC quantifies this: beyond a compactness threshold, the region is sealed off and the record cannot propagate outward.

As the certification region shrinks, the required dynamical scale grows while the admissibility ceiling falls. At a finite scale they meet; in emergent metric units this fixed point scales as $R_{min} \propto \sqrt{\hbar G/c^3} \equiv \ell_P$ (up to order-one factors).

Not because of time. Not because of spatial discreteness. But because there exists a minimum certification-region scale below which the certification process becomes self-defeating — either too weak to distinguish or too intense to certify.

This is a structural fixed point: the compression limit of certifiable irreversible commitment.

The mathematics treats R and Δt symmetrically via CLP; the spatial-first reading is an interpretive choice aligned with the VERSF ontology, not a consequence forced by the algebra.

9.2 What "compression" means

It is important to be precise about what is being compressed. The claim is not that a minimum number of metres is required, or that a minimum number of seconds must elapse. Both metres and seconds are emergent.

Compression means: reducing the spatial extent of the certification region required to host a single bit. Within the emergent effective description, the certification region has a characteristic scale R. The derivation shows that R has a nonzero lower bound.

One may optionally interpret R in terms of substrate degrees of freedom (§2): a smaller certification region engages fewer independent components, and the bound on R corresponds to a minimum count of engaged components. This interpretation is suggestive but not required by the derivation, which operates entirely within the effective causal description.

What the derivation does require is:

- a fixed-magnitude bit (one stabilised commitment),
- a certification region of variable scale R,
- two constraints (distinguishability and admissibility) that set a floor on R.

Below $R_{min} \sim \ell_P$, no certification region can simultaneously support distinguishable branching and maintain outward certification.

9.3 Metric shadows

The derivation yields a minimum causal certification interval Δt_{min}; identifying $\Delta t_{min} \sim \sqrt{\hbar G/c^5} \equiv t_P$, and invoking CLP ($R \lesssim c\Delta t$), this corresponds to a minimum certification-region scale:

$$R_{min} \sim \ell_P = \sqrt{\hbar G/c^3}$$

And once the emergent geometry includes a causal metric with finite propagation speed, the spatial support maps to a temporal bound:

$$\Delta t_{min} \sim t_P = \ell_P/c = \sqrt{\hbar G/c^5}$$

These are not independent results. They are two representations of the same structural fixed point:

minimum certification-region scale (ℓ_P) → causal interval (t_P)

The relation $t_P = \ell_P/c$ holds only within the emergent causal regime; it is not a substrate-level definition but the internal geometry of the effective description.

The primary statement of the bound is spatial: a non-redundant bit cannot be certified within a region smaller than ℓ_P while maintaining outward certification and distinguishability. The temporal statement (Planck time) follows from the spatial statement via the emergent causal metric.

Weakest-case geometry. CLP provides an upper bound on the certification-region size, $R \lesssim c\Delta t$. In deriving a universal floor we intentionally take the least restrictive case, effectively $R \sim c\Delta t$, because smaller R only tightens the NTC and increases the minimum certification interval. Thus t_P is a weakest-case necessary bound; realistic certification processes with $R \ll c\Delta t$ will generally have effective floors $\Delta t \gg t_P$, consistent with TPB inefficiency and the expected non-saturation of Planck-scale bounds.

9.4 Substrate level

At the deepest level of the BCB/TPB ontology, there is no fundamental time, no fundamental space, and no fundamental speed. The substrate consists of ticks (reversible updates) and bits (irreversible commitments) on a pre-metric void. Nothing at this level has units of metres or seconds. There is no Planck time and no Planck length at the substrate level.

What exists at this level is a compression limit: a minimum structural support required to stabilise one bit without violating distinguishability and admissibility. Whether this is best described as a minimum region, a minimum count of engaged degrees of freedom, or some other substrate-native quantity is a question for the full VERSF programme. The present derivation operates within the effective causal description, where the compression limit appears as $R_{min} \sim \ell_P$.

The speed of light c appears only when an effective causal metric has emerged — when sufficient bit accumulation has established light cones and a maximum signal propagation speed. In that effective regime, the spatial bound acquires a temporal companion: $t_P = \ell_P/c$. But the spatial bound is the primary output of the derivation.

9.5 Why this is not circular

The logical structure is:

(a) Assume a regime where an effective causal metric exists.

(b) Within that regime, apply QSL and NTC to identify the minimum certification-region scale where distinguishability compression balances admissibility.

(c) Express that fixed point in the emergent metric as ℓ_P (spatial) or t_P (temporal).

(d) Verify self-consistency: below this scale, the bit-certification rate is insufficient to sustain the effective metric, so the regime assumed in (a) ceases to hold.

This is not using time to derive time, or space to derive space. It is using the effective causal structure to identify the boundary of its own validity — a domain-of-applicability argument, not a circular one. The procedure is analogous to assuming a coordinate system, pushing the equations until they fail, and finding the boundary where that coordinate system stops being valid.

The appearance of circularity arises because t_P is conventionally defined using c, which is a speed, which involves time. But c in this derivation is a throughput bound in the emergent regime — a structural property of the effective causal metric — not an assumption of fundamental time. The derivation does not assume fundamental time at any step; it uses the effective metric only to label the boundary of its applicability.

9.6 What the Planck scale really is

The Planck length is the minimum spatial support for certifiable irreversible commitment. Nothing in the derivation requires space to be discrete; it requires only that irreversible commitment cannot be localised below this support scale. The Planck time is its causal shadow in the emergent metric.

Within the VERSF ontology, the void supports reversible churn and bits are irreversible commitments. To stabilise a commitment, a certification region of sufficient extent must separate alternatives, stabilise a branch, and certify the record outward. That region cannot be compressed below the scale where distinguishability demands exceed admissibility limits.

That compression limit appears in the effective description as ℓ_P (spatial) and $t_P = \ell_P/c$ (temporal). Whether it corresponds, at the substrate level, to a minimum count of engaged degrees of freedom or to some other pre-metric quantity is an open question within the VERSF programme. What the present derivation establishes is the effective-regime bound: $R_{min} \sim \ell_P$, with t_P as its causal image.

General reader note: To write a permanent record, the universe needs a minimum amount of room — enough to tell two possibilities apart and lock one of them in, but not so much energy packed into that room that it enters a causal censorship regime. That minimum room is the Planck length. The Planck time is how long light takes to cross it. Neither is the deeper truth; both are ways of expressing the same constraint: the smallest possible commitment the universe can make to its own record.

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10. Scope and Relation to Prior Work

Shown:

1. There exists a minimum effective emergent timescale for bit certification, arising from the joint constraints of quantum distinguishability and gravitational admissibility within a causal certification region.
2. This scale is the Planck time, up to order-one factors, derived via a minimax argument over distinct energy scales (dynamical E_{dyn} and gravitating E_{grav}) that assumes neither constraint is saturated.
3. The Planck scale is the fixed point of the certification minimax squeeze. It can be expressed as a minimum spatial support for certification ($R_{min} \sim \ell_P$) or as the corresponding minimum causal interval ($t_P = \ell_P/c$). The temporal form follows from the spatial via the emergent causal metric.
4. The gravitational constraint is formulated as a conservative safety condition on compactness, independent of the full hoop conjecture.
5. Within VERSF/BCB/TPB ontology, the Planck time is the self-consistency threshold of the emergent temporal metric: the smallest scale at which the effective causal description sustains itself.
6. The structural inefficiency $\eta_{info} \ll 1$ (many ticks per bit) is not merely observed but enforced by the QSL and NTC jointly.

Not shown or claimed:

1. **Time is not discrete.** The result does not imply that time advances in Planck-time steps. Sub-Planck ticks occur freely on the substrate — they simply cannot contribute to bit certification or to the construction of the emergent temporal metric.
2. **No fundamental clock.** There is no claim that a universal clock ticks at the Planck rate. Ticks are pre-metric and do not define a universal rhythm.
3. **No one-bit-per-Planck-time rule.** Bit formation requires many ticks ($\eta_{info} \ll 1$) and the effective emergent duration per bit is typically far above t_P.
4. **No tightness claim.** We prove a floor, not an achievability result. Whether nature saturates the bound is an open question.
5. **No claim of unique derivation.** The algebraic structure of the two-sided squeeze appears in prior work (Lloyd 2000; Ng and van Dam 2003; cf. Mead 1964). The contributions here are: (a) the interpretive reframing within BCB/TPB as a bit-certification threshold rather than a discreteness or computational bound; (b) the resolution of the circularity inherent in deriving temporal bounds within a time-emergent ontology; (c) the identification of the Planck time as the self-consistency boundary of the emergent metric; (d) the identification of the Planck scale as the fixed point of the certification minimax squeeze (minimum spatial support for certifiable commitment) rather than a primitive temporal unit; (e) the clean separation of dynamical and gravitating energy scales ($E_{dyn} \leq E_{grav}$); and (f) the tighter logical structure (operational interface, CLP as operational consequence, conservative NTC, minimax proof).

Relation to Lloyd-type bounds

The algebraic structure of the derivation is not new. Lloyd (2000) used the same two-sided squeeze — a quantum speed limit from one side, gravitational collapse from the other — to obtain the same Planck scaling. The minimax chain here (QSL floor on energy vs. NTC ceiling on energy within a causal region) is essentially Lloyd's argument with different labels. The present work does not claim a tighter numerical bound or a novel algebraic structure.

What differs is what the derivation is taken to prove, along three axes:

(i) What is being bounded. Lloyd asked: given a physical system with energy E, what is the maximum number of operations per second it can perform? He applied Margolus–Levitin (ops/sec $\leq 2E/\pi\hbar$), noted the system cannot be smaller than its Schwarzschild radius, and obtained a Planck-scale limit on computational speed. His target is generic computational operations. The present paper bounds a different quantity: the certification of a non-redundant bit at a surviving interface — an irreversible, causally certified commitment to a distinguishable macrostate. This is a narrower and operationally sharper target than "operations per second," and it is the quantity that matters for constructing an emergent temporal metric from accumulated records.

(ii) What the energy variables mean. Lloyd treats the system's total energy E as simultaneously driving computation and sourcing gravity. This is natural in his setting but conflates two roles. The present derivation separates the dynamical energy scale E_{dyn} (the energy available to drive distinguishable evolution within the certification region, constrained from below by the QSL) from the total gravitating energy E_{grav} (the energy that determines compactness, constrained from above by the NTC), connected by the conservative bridge inequality $E_{dyn} \le E_{grav}$. In scenarios where $E_{dyn} \ll E_{grav}$ (e.g. large ground-state energy offsets, weakly driven transitions, or systems with significant non-dynamical rest mass), the separation makes the bound strictly more conservative than single-energy treatments. It does not alter the Planck scaling but clarifies what is and is not constrained by the QSL: the dynamical scale, not the total gravitating mass.

(iii) What the result means. Lloyd's framing is: time is a background parameter, the system is a computer, and t_P is the fastest clock tick any physical computer can sustain before it collapses into a black hole. Time exists independently of computation; the bound is a speed limit within that background. The present framing is the reverse: time is not background but emergent, constructed from accumulated certified bits. The Planck time is not a speed limit on a computer running within time; it is the self-consistency threshold of the emergent temporal metric — the smallest scale at which the effective causal description sustains itself. Below it, the bookkeeping variable "time" defined by record accumulation cannot be refined further, not because a clock is forbidden from ticking faster, but because there are not enough certified records to constitute a clock.

These three differences — operational target, energy decomposition, ontological status — are the paper's contributions. But there is a fourth, which constitutes a structural critique rather than a reinterpretation:

(iv) Compatibility with quantum coherence. Lloyd's bound permits and, at saturation, requires a distinguishable state transition at every QSL interval. A system operating at this rate undergoes a decoherence-equivalent event at every step, leaving no room for the coherent superposition that underlies quantum interference and entanglement. Lloyd's framework contains no sub-operational layer and therefore no structural prohibition against $\eta_{info} = 1$. The BCB/TPB framework identifies this as physically inadmissible: the TPB efficiency principle (§3) requires $\eta_{info} \ll 1$, with most substrate steps being reversible and non-informational. This is not an optional feature but a structural necessity — without a reservoir of reversible ticks between bit-certification events, the quantum dynamics from which the QSL itself is derived could not exist. Lloyd's bound is therefore internally tensioned: it invokes the QSL (a consequence of coherent quantum evolution) to bound a computational rate that, if saturated, would destroy coherent quantum evolution. The present framework resolves this tension by making the sub-QSL layer explicit and requiring it to be mostly reversible ($\eta_{info} \ll 1$), thereby preserving the coherent dynamics on which the QSL depends.

The Planck scaling is Lloyd's. The resolution of the coherence tension is not.

Accordingly, the paper stands or falls primarily on its operational reframing and ontology-consistent interpretation, not on a new Planck-scale scaling law.

Dimensional analysis vs. the content of the derivation

It is true that $t_P = \sqrt{\hbar G/c^5}$ is the unique timescale one can form from $\hbar$, G, and c. Dimensional analysis alone, however, does not establish (i) that a nonzero lower bound on certification duration exists, (ii) that the bound is a lower bound rather than an upper bound or a mere crossover scale, (iii) that the bound arises from a two-sided minimax squeeze (a required distinguishability scale opposed by an admissibility/censorship ceiling), or (iv) what the bound means operationally. The contribution here is to identify the bound as a lower limit on non-redundant bit certification, to derive it from a minimax structure without assuming saturation, and to interpret it as a self-consistency threshold for the existence of an effective causal metric within a time-emergent ontology.

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11. Discussion: The Planck Time as a Bootstrapping Threshold

The standard interpretation of Planck-scale bounds takes one of two forms: either the Planck time represents a fundamental discreteness of spacetime, or it represents an ultimate speed limit on physical computation. Both assume time is a background parameter.

The BCB/TPB interpretation is fundamentally different. Time is not background but emergent — constructed from the accumulation of certified bits on a pre-metric substrate. Within this ontology, the Planck time acquires a meaning unavailable to background-time frameworks:

The Planck time is the self-consistency threshold of the emergent temporal metric.

Relation to standard Planck-scale breakdown. The self-consistency argument here does not claim a new ultraviolet completion or a different quantitative breakdown scale than standard Planck-scale reasoning. Rather, it supplies a BCB/TPB diagnostic for why the effective causal metric ceases to be meaningful: below the certification floor, no new non-redundant records can be produced within the region, so the bookkeeping variable ("time") defined by record accumulation cannot be refined further. This reframes the usual statement "quantum-gravitational corrections become order-one" into an operational criterion tied to certifiable distinctions. Determining whether this diagnostic predicts deviations from standard semiclassical breakdown is a programmatic question beyond the present note.

Relation between the informational and geometric validity criteria. The BCB/TPB criterion for a locally meaningful effective causal metric is phrased in informational terms: over coarse-graining windows relevant to the effective description, the expected number of certified bits satisfies $N_b(\Delta T) \gg 1$. Standard semiclassical gravity expresses validity geometrically: quantum fluctuations of the metric are small relative to the background, which operationally corresponds to curvature radii being large compared to ℓ_P (and to stress-energy fluctuations being small on the coarse-graining scale). These criteria may coincide, but the present note does not assume their equivalence.

A conservative reading is that $N_b(\Delta T) \gg 1$ is an information-theoretic translation of the semiclassical condition: if certified bits are the degrees of freedom that support spacetime structure, then having many bits within the coarse-graining window is tantamount to having many effective gravitational degrees of freedom, which typically corresponds to curvature radii $\gg \ell_P$. In this case the BCB/TPB diagnostic does not introduce a new breakdown scale; it provides an operational restatement of the familiar semiclassical regime in terms of certifiable distinctions.

A stronger (and potentially independent) reading is that the informational criterion could diverge from the geometric one in principle: BCB/TPB singles out not only curvature, but the ability to generate and propagate certifiable distinctions. One can therefore ask whether there exist regimes in which curvature remains small (geometrically "benign") while certification becomes sparse or inhibited (informationally "thin"), causing $N_b(\Delta T)$ to fail before geometric fluctuations become large. Conversely, one can imagine regimes of high curvature where certification remains abundant because the relevant degrees of freedom remain rapidly distinguishable and outwardly certifiable on the coarse-graining scale. The geometric criterion is sensitive primarily to curvature and stress-energy fluctuations, whereas the informational criterion is additionally sensitive to the availability of stable interfaces and outwardly propagating records on the coarse-graining scale. Whether such divergent regimes exist in physical models is an open question for the broader programme; the present work identifies the operational diagnostic and shows that, within the effective causal regime, it reproduces the standard Planck-scale floor for certification.

Programmatic distinction. This framing yields a clear empirical/programmatic target: determine whether $N_b(\Delta T) \gg 1$ reduces to the standard semiclassical condition (a translation), or whether it predicts additional constraints on metric validity tied to distinguishability and certification (an independent diagnostic). Either outcome is valuable: the former clarifies the operational content of semiclassical validity; the latter would constitute a genuine extension of standard breakdown criteria.

Above t_P, the bit-certification rate is high enough to sustain a locally smooth effective causal metric. The emergent constraints (QSL, NTC, causal structure) are valid, and processes can be described in temporal language. The vast majority of physics operates in this regime.

At t_P, the minimum tick-cost of bit certification is reached. The emergent constraints are still valid but identify their own floor.

Below t_P, for any putative effective duration $\Delta t < t_P$, no protocol can certify a non-redundant bit within that Δt while preserving outward certification and quantum distinguishability. No new entry is added to the temporal record at this scale, so the effective causal metric is not being constructed here. The emergent description does not fail catastrophically — it simply has nothing to describe at this scale. Sub-Planck substrate evolution continues (ticks still occur), but it is pre-metric: reversible, non-informational, and invisible to the emergent description.

This resolves a long-standing interpretive tension. If the Planck time is a discreteness scale, what sustains quantum coherence below it? Standard answers invoke speculative quantum-gravity structures. In BCB/TPB, the answer is immediate and non-speculative: sub-Planck evolution is substrate activity that doesn't certify bits, so it doesn't face the constraints that apply to bit certification. Quantum coherence is not threatened because coherent (reversible) evolution is precisely the kind that doesn't write to the record.

The TPB efficiency parameter $\eta_{info} \ll 1$ is thus architecturally essential. The universe *must* be tick-inefficient at producing bits, because:

(a) the QSL and NTC enforce a minimum tick expenditure per bit;

(b) coherent quantum evolution requires a reservoir of reversible, non-informational ticks;

(c) the emergent temporal metric requires coarse-graining over many ticks to be smooth.

These three requirements are mutually consistent and jointly satisfied by the $\eta_{info} \ll 1$ regime. The Planck time is where this architecture is most tightly constrained.

11.1 Space as the Equilibrium of Distinguishability and Admissibility

The result derived in this paper has a natural implication that extends beyond the Planck-scale bound itself. We state it here as a conceptual consequence, not as a proven theorem — it identifies the direction in which the BCB/TPB programme leads.

In VERSF, space is not a background. It is emergent from the accumulation of certified bits: each irreversible commitment contributes structure to the spatial fabric. The present result identifies a minimum spatial support for any certified bit within an effective causal regime; if space is built from such certified bits, this minimum support sets a coherence threshold for space-building.

Combining these two claims:

(a) Space is built from certified bits.

(b) Each bit requires a minimum certification-region scale ($R_{min} \sim \ell_P$) to be certified.

It follows that:

The Planck scale is not merely a limit on spatial resolution. It is the minimum coherent patch of space-building itself — the smallest certification-region scale that can host an irreversible commitment and thereby contribute to the construction of spatial structure.

The compression boundary derived in §9 is, from this perspective, the space-formation threshold. Distinguishability says: you need enough participating structure to separate alternatives. Admissibility says: you cannot pack too much dynamical intensity into that structure. Their balance point is the smallest substrate configuration that can host a certified bit — and since certified bits are what space is made of, that balance point sets the coherence scale of spatial emergence.

This is not discreteness. There is no claim of a spatial lattice, a minimum voxel, or a hard pixel. Sub-Planck substrate structure exists and supports reversible churn. What does not exist below this scale is *committed* structure — irreversible records that contribute to the spatial fabric. The Planck scale is a commitment threshold, not a resolution limit.

The analogy is instructive: a crystal has a minimum lattice spacing, but the atoms that form the crystal exist at all scales. The lattice spacing is not a claim about the non-existence of sub-lattice structure; it is the minimum coherent unit of the emergent order. Similarly, the Planck scale is the minimum coherent unit of spatial emergence — the scale at which the balance between distinguishability and admissibility permits the first irreversible commitment that contributes to geometry.

If this interpretation is correct, then the Planck scale is not a parameter of nature discovered by dimensional analysis. It is a structural inevitability: the fixed point at which the two principles governing irreversible commitment — the need for sufficient distinguishability and the constraint of admissibility — produce the minimum viable patch of emergent space. The task of the full VERSF programme is to derive this threshold from substrate dynamics directly, without importing the emergent constraints (QSL, NTC) as the present paper does. The bootstrapping argument presented here identifies the target; the substrate derivation would close the loop.

Space-side analogue of the bootstrapping argument. The claim that space is built from certified bits is an ontological postulate of VERSF, not derived here. Accordingly, the inference that ℓ_P sets a coherence threshold for space-building should be read in the same domain-of-validity spirit as the time argument: we assume an effective spatial metric exists, identify the minimum certification-region scale within that regime, and then interpret that scale as a candidate lower limit on how finely committed spatial structure can be added. A fully closed “space bootstrapping” derivation — showing that committed spatial structure cannot be refined below ℓ_P without undermining the existence of the effective spatial metric — remains an open target for the broader programme.

General reader note: If space is built from permanent records — each certified bit adding a tiny piece of structure to the spatial fabric — then the Planck scale is the smallest piece that can be added. Not because space comes in pre-cut tiles, but because writing a permanent record requires a minimum cooperation among the universe's parts, and that minimum cooperation, when translated into distance, is the Planck length. The Planck scale is not a property of space. It is a property of *space-building*: the smallest act of construction that the universe can perform on its own geometry.

Philosophical note. Within the VERSF ontology, time is accumulated commitment and space is the structured support of commitment. Neither is primitive; both are the macroscopic bookkeeping language of irreversible records. The Planck scale, in this view, is where the bookkeeping system bottoms out — the smallest entry that the ledger can accommodate. The "minimum degrees of freedom" reading (§9.2) offers an intuition for what this means at the substrate level: the universe cannot make a certifiable commitment with zero independent parts; there is a minimum structural involvement. But the present paper does not derive that substrate count. What it derives is the effective-regime bound: the minimum certification-region scale $R_{min} \sim \ell_P$, and its causal companion t_P. Whether the deeper substrate description reveals a discrete participation count, a continuous density threshold, or something else entirely is a question for the full VERSF programme. The insight this paper offers is that the Planck scale is not an externally imposed parameter but an internally generated fixed point — the place where the universe's own commitment machinery encounters its structural floor.

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12. Assumptions and Open Questions

1. **Certification Locality Principle.** The CLP is an operational consequence of finite propagation of correlations plus the interface definition (condition (iii), causal certification). It could be questioned in frameworks where emergent causal structure is violated entirely at the Planck scale. Within any framework that preserves even approximate finite propagation, the CLP follows rather than being assumed.
2. **Applicability of emergent constraints at the boundary.** The derivation applies the QSL and NTC in the regime where they are valid and extrapolates to identify the boundary of that regime. This is standard practice (e.g., identifying the limits of classical mechanics by applying it until it fails), but a fully rigorous treatment would require a substrate-level derivation of the constraints, bypassing the emergent description entirely. This is a direction for future work within VERSF.
3. **No-Trapping Condition.** The NTC is a conservative sufficient safety condition for avoiding causal censorship: subcritical compactness is a sufficient (not necessary) condition for outward certification. This makes the bound conservative — the true floor could be higher if causal censorship occurs below the compactness threshold. The NTC does not require the full hoop conjecture but does assume that classical gravitational trapping at order-one compactness is not circumvented by quantum gravitational effects.
4. **Order-one prefactor.** The coefficient $\sqrt{(\kappa/\eta)}$ depends on which QSL is cited, the safety margin for the NTC, and the geometry of the certification region (entering through the areal radius and the order-one factors absorbed into η). Whether this prefactor carries physical content or is purely conventional is an open question.
5. **Tightness.** The bound is a floor. Whether physical systems exist that certify bits at durations approaching t_P remains open and depends on the existence of systems that simultaneously approach both the QSL and the compactness threshold.
6. **Interface metastability.** The result is conditional on the existence of interfaces whose metastability timescales exceed the certification interval by a large factor, as is true for ordinary macroscopic records. Deriving the conditions under which such interfaces arise from substrate dynamics is a separate question within the VERSF programme.
7. **Extension to curved backgrounds.** The derivation implicitly assumes an approximately flat background within the certification region. On strongly curved backgrounds, both the QSL and the compactness criterion may require modification.
8. **Substrate derivation of the QSL.** The present treatment imports the QSL from emergent quantum mechanics. A deeper programme would derive the QSL (or its substrate

analogue) directly from tick dynamics, establishing the bound without reference to the emergent level. This would close the bootstrapping argument entirely and is a primary target of ongoing VERSF research.

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Appendix A: Intuitive Explanation (Non-Technical) — Certification Region and Compression

When the universe makes a bit, it is not a floating idea — it is a committed record: something that says "this happened, not that," and is stable enough that the rest of the world could, in principle, find out. For that to be true, the bit has to live somewhere. There has to be a patch — a region — where the outcome gets settled, the record becomes stable, and the information could spread outward. That patch is the **certification region**: the smallest place where the universe can honestly say "this bit is real and can be checked."

Compression means trying to make that patch smaller and smaller while still expecting it to reliably produce and hold a bit — shrinking the workspace where a decision becomes permanently recorded. A **compression limit** means there is a smallest possible workspace in which a real, checkable record can be created. Below that size, one of two problems happens: either (a) the workspace is too small to clearly separate the alternatives — the difference between "this" and "that" becomes too weak to count as a stable commitment; or (b) the workspace becomes so intense that it seals itself off from the rest of reality, meaning the record cannot spread outward and does not count as a certifiable bit.

An analogy: imagine stamping a wax seal on a letter. If the seal is big enough, it leaves a clear mark that stays. If you try to stamp it using an area that is too tiny, either the mark is too faint and smudges (no stable record), or you press so hard to make it visible that you tear the paper (the record zone fails). The universe has an equivalent constraint: there is a minimum stamp-size for making a true irreversible mark. In this paper, the Planck length is that minimum stamp-size, and the Planck time is the minimum spread-time associated with that patch in an emergent causal world.