Causal–Coherence Compatibility and the Fact-Production Threshold

A Unified Derivation of the Mesoscopic Scale from Action, Entropy, and Commitment Dynamics in the VERSF Framework

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For the General Reader

Physics is very good at describing how things change. What it has never fully explained is how anything becomes *definite* in the first place. A quantum particle exists in a superposition of possibilities—here and there, spinning up and spinning down, all at once—until something forces a single outcome. A measurement is made. A detector fires. History records one event, not many. But the equations of quantum mechanics don't tell you when or why that moment of commitment happens. They only tell you what could happen.

This paper addresses that gap directly.

We ask: under what conditions can a physical region of space actually produce a stable, irreversible fact? Not a possibility. Not a probability. An actual, locked-in, unchangeable record of what happened.

The answer turns out to be a single inequality. Any region of space with characteristic size L, filled with energy at density ρ, can produce an irreversible fact only if

$\rho L^4 \gtrsim \hbar c$,

where $\hbar$ is the fundamental quantum of action and c is the speed of light. This is the **Causal–Coherence Compatibility (CCC) condition**.

Think of it this way. Every irreversible event costs a minimum amount of energy, and it has to happen fast enough—within the time it takes light to cross the region. If the region is too small, or too sparse in energy, the budget runs out before a single fact can be secured. The universe, in that region, stays in the realm of quantum possibility. It never resolves into a definite record.

The scale at which this budget is just barely sufficient defines a characteristic length, the **coherence scale** ξ. Below ξ, the world is quantum: reversible, probabilistic, undecided. Above ξ, facts can form: irreversible, classical, real. This is the quantum-to-classical transition—not as a vague hand-wave about measurement, but as a precise structural threshold derived from first principles.

What makes this result striking is how widely the same inequality appears elsewhere. The same $\rho L^4 \gtrsim \hbar c$ structure arises in quantum speed limits (the fastest rate at which a quantum system can change state), in holographic entropy bounds (the maximum information a region of space can hold), and in the geometry of causal diamonds in relativity. These look like separate discoveries from separate fields. This paper shows they are not accidents — they are three independent expressions of the same underlying structural constraint: that producing an irreversible record has a minimum price, and the price is written in the same quartic language in every domain of physics.

The core logic is transparent. Two simple physical requirements—that a distinction must be large enough to qualify as real (above the quantum threshold), and that it must be locked in fast enough (within causal reach)—together force the quartic inequality. Everything else follows from that.

Significance within the VERSF Programme

The VERSF programme rests on a foundational claim: that the universe is best understood not as a collection of fields or particles, but as a structure of irreversible, distinguishable commitments. Physical law, on this view, is the set of constraints that govern how distinctions can be made, recorded, and built upon. Every paper in the programme is an attempt to show that some feature of physics we normally treat as given—the mass of the electron, the structure of the Standard Model, the value of the cosmological constant, the arrow of time—follows necessarily from those constraints.

Within that programme, two papers carry special foundational weight: this one and the companion paper establishing the K=7 constraint dimensionality of the framework.

The K=7 paper asks: given that physical reality is built from commitment events, how many independent degrees of freedom can a single commitment involve? The answer, derived from the algebraic structure of the VERSF commitment space and the requirement that the framework be internally consistent, is K=7. From this single integer—seven independent constraint dimensions—the gauge group of the Standard Model, $SU(3)\times SU(2)\times U(1)$, follows as a structural necessity. K=7 is the answer to the question: *what is the internal shape of a commitment event?*

This paper asks a different but equally foundational question: *when can a commitment event occur at all?* The answer is the CCC condition, $\chi(L) \gtrsim 1$. A commitment requires a minimum action, delivered within a causal boundary. That requirement translates directly into the quartic constraint $\rho L^4 \gtrsim \hbar c$. Below the coherence scale ξ, no commitments are possible. Above it, the K=7 structure can express itself in irreversible physical records—facts, particles, fields, measurements.

The two papers therefore occupy distinct but complementary positions in the logical architecture of VERSF:

Paper	Question answered	Result
K=7 (constraint dimensionality)	What is the internal structure of a commitment event?	K=7 → SU(3)×SU(2)×U(1)
CCC (this paper)	When can a commitment event occur?	$\chi(L) \gtrsim 1$ → coherence scale ξ

Read together, they establish the two foundational pillars of the framework. K=7 determines the *what*—the internal degrees of freedom that make physics the specific physics we observe. The CCC condition determines the *when*—the physical threshold at which the framework's commitment events can actually take place and produce stable classical structure. Neither is sufficient alone. A universe with K=7 internal dimensions but no region satisfying the CCC threshold would be one where the right structure exists in principle but cannot manifest as facts. A universe satisfying the CCC threshold but with arbitrary internal dimensionality would produce irreversible records of an undetermined kind, with no derivation of the Standard Model or any other specific gauge structure from first principles.

Together they represent what may be called the **existence-and-structure theorem** of the VERSF programme: physical reality requires both that commitments are possible (CCC) and that they have the right internal architecture (K=7). Both conditions are structural necessities, not free parameters. Both are derived, not assumed.

This paper's derivation of the CCC condition also speaks directly to the broader programme in a second way: it shows that the quartic structure $\chi(L) = \rho L^4/\hbar c$ is not a feature introduced by hand into the framework but is forced by the most primitive requirements of fact production. When the same structure appears in the Margolus–Levitin bound, the Bekenstein bound, and the causal diamond geometry, this is not a reassuring coincidence—it is a confirmation that those established results are themselves expressions of the same foundational constraint. The VERSF framework does not borrow these limits; it explains them.

Technical Abstract

The emergence of stable, irreversible physical facts from reversible microscopic dynamics is one of the deepest unresolved problems in theoretical physics. Within the Void Energy–Regulated Space Framework (VERSF), physical facts arise through **commitment events**—transitions in which reversible distinctions become irreversibly recorded within a finite-capacity substrate. Independently, analysis of bounded spacetime regions reveals a universal capacity constraint expressed by the dimensionless parameter

$\chi(L) = \rho L^4 / \hbar c$,

which measures the ratio of the total action available within a causal region to the minimum action required for a single irreversible event. In this paper we establish that these two structures are not independent. Two primitive physical requirements governing commitment—finite distinguishability and causal irreversibility—together entail the condition $\chi(L) \gtrsim 1$ as a structural necessity via the time–energy uncertainty relation. This condition is not derived by matching known physical limits; it follows directly from the minimum requirements for a single irreversible fact to exist within a bounded causal region. A third condition, commitment capacity, is shown to follow as a derived consequence rather than an independent postulate. This establishes a **Causal–Coherence Compatibility (CCC) condition**: a bounded region of spacetime can support stable, classical structure only if it contains sufficient action, entropy capacity, and causal coordination to complete at least one irreversible commitment within its own causal horizon.

The unification identifies the **coherence scale**

$$\xi \sim (\hbar c/\rho)^{1/4}$$

as the minimal fact-producing region of spacetime. It explains the convergence of apparently independent physical limits—quantum speed bounds (Margolus–Levitin), holographic entropy bounds (Bekenstein), and causal action budgets—on a single quartic structure. Each is an independent confirmation of a structural necessity, not a coincidental match. The result provides a unified account of the quantum–classical transition, the structural role of the cosmological constant, and the emergence of irreversible time as consequences of this single condition.

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1. Introduction

Every prediction of physical theory ultimately refers to something more elementary than a wavefunction or a field configuration: a **fact**. A detector clicks. A spin is measured along a definite axis. A decay product arrives at a specific location and time. These outcomes—discrete, irreversible, distinguishable—are the atoms of empirical physics. Yet the dynamical laws of both classical and quantum mechanics are silent on the question of when and why such facts come into existence. Unitary quantum evolution generates superpositions, not outcomes. Hamiltonian mechanics traces reversible trajectories, not irreversible records.

This silence is not merely interpretive. It is structural. It means that neither framework can, by itself, explain the existence of the stable, classical world in which experiments are conducted and results are compared. A deeper account is required.

Within the Void Energy–Regulated Space Framework (VERSF), this gap is taken as the starting point rather than an afterthought. The framework is grounded in the recognition that a physically meaningful universe must support **irreversible, distinguishable, recoverable records**. This requirement—call it the **fact-production requirement**—is not an optional feature of reality. It is a necessary precondition for any universe in which observations can be made, distinguished, and compared across observers.

From this requirement, two primitive structural conditions emerge:

1. **Finite distinguishability** (C1) — the physical substrate must be capable of resolving a distinction above a minimum threshold set by the quantum of action.
2. **Causal irreversibility** (C2) — the distinction must propagate into environmental degrees of freedom beyond the reach of any local reversal operation, and must do so within the causal crossing time of the region.

A third condition—**available commitment capacity** (C3)—is not an independent postulate. It is established as a consequence of C1 and C2 within the CCC framework.

These conditions jointly define what we call a **commitment event**: the elementary process by which a reversible distinction becomes an irreversible fact.

Independently, recent work within VERSF and related frameworks has identified a universal constraint on physical processes within bounded regions of spacetime. A region of characteristic size L and mean energy density ρ contains a finite action budget over its causal crossing time L/c. Comparing this budget to the quantum of action $\hbar$ yields the dimensionless parameter

$\chi(L) = \rho L^4 / \hbar c$,

which counts the maximum number of irreversible commitment events supportable within the region. This **quartic causal capacity** parameter arises independently in quantum information theory, in holographic entropy bounds, and in the geometry of causal diamonds—a convergence whose significance has not previously been explained.

The central result of this paper is that the commitment condition and the quartic capacity constraint are not merely compatible—they are structurally identical and arise from the same minimal physical requirement. The condition $\chi(L) \gtrsim 1$ is not derived by matching known limits; it is the direct entailment of the two primitive commitment conditions via the time–energy uncertainty relation. The Margolus–Levitin bound, the Bekenstein bound, and the causal diamond action then appear as independent confirmations of this structural necessity.

The paper proceeds as follows. Section 2 states the two primitive commitment conditions and explains the status of C3. Section 3 derives the action budget of a causal region and the parameter $\chi(L)$. Section 4 establishes the CCC condition in three steps: necessity derivation from C1 and C2 alone (§4.1), the central equivalence (§4.2), and the interpretation of C3 as a derived consequence (§4.3). Section 5 identifies the coherence scale ξ. Section 6 demonstrates independent confirmation from three separate physical limits. Section 7 draws out the implications. Section 8 concludes.

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2. Fact Production as a Physical Process

2.1 The Commitment Event

In the VERSF framework, the elementary unit of physical reality is not a particle, field, or state—it is a **commitment event**: a transition in which a previously reversible distinction becomes irreversibly encoded in a physical substrate. The distinction need not be macroscopic. It may involve a single bit of information. What matters is that after the commitment, the record is stable against any local reversal, and that it is in principle recoverable by any agent who interacts causally with the relevant region.

Commitment events are related to, but distinct from, quantum measurements. A measurement is an interaction between a system and an apparatus. A commitment event is the moment at which the result of that interaction becomes irreversible—when the record propagates beyond the reach of local unitary control. The measurement process is a necessary precondition, but it is the commitment that produces the fact.

2.2 The Two Primitive Conditions

Two independent physical requirements govern whether a commitment event can occur within a bounded region:

Condition C1 (Distinguishability): The physical distinction must be resolvable above the minimum action threshold $\hbar$. A distinction whose associated action is below $\hbar$ cannot be stabilized as a record; it remains subject to quantum uncertainty and can be coherently reversed. This condition follows directly from VERSF Axiom A1 (Primitive Distinguishability).

Condition C2 (Causal Irreversibility): The distinction must satisfy two sub-requirements jointly. First, a *causal-time constraint*: the commitment must complete within the causal crossing time L/c of the region, since irreversibility established outside that boundary cannot contribute to a fact localisable within it. Second, an *amplification requirement*: the distinction must propagate into environmental degrees of freedom beyond local causal control, ensuring that no operation within the region can reverse the record. The causal-time constraint enters the quantitative derivation directly; the amplification requirement ensures that what completes within the causal boundary constitutes a genuine irreversible fact rather than a reversible transition. This condition follows from VERSF Axiom A2 (Irreversible Commitment).

A third condition—**commitment capacity** (C3)—concerns whether the region retains sufficient room to record a new fact, given the finite maximum distinguishability density set by the No Multi-Primitive Occupancy (NMPO) constraint.[^nmpo] C3 is not independently postulated. Section 4.3 establishes it as a consequence of C1 and C2: once the quartic condition is derived from C1 and C2 alone, C3 follows automatically.

[^nmpo]: The No Multi-Primitive Occupancy (NMPO) constraint states that a bounded region cannot support more than one primitive commitment per distinguishability cell. This reflects the finite localization capacity derived in the VERSF framework and discussed in Taylor,

Commitment Capacity and the No Multi-Primitive Occupancy Constraint [citation to be inserted before submission].

2.3 The Commitment Condition

Let $\mathscr{R}(L)$ denote a bounded spacetime region with characteristic scale L. The **commitment condition** is:

$\mathscr{R}(L)$ supports a commitment event $\Leftarrow$ C1 $\wedge$ C2 hold in $\mathscr{R}(L)$,

where C3 is established as a derived consequence in Section 4.3. The arrow here expresses necessity: C1 and C2 are necessary conditions for a commitment event, and the paper establishes that their conjunction entails $\chi(L) \gtrsim 1$. Sufficiency—whether every region satisfying $\chi(L) \gtrsim 1$ necessarily produces a commitment event—depends on the presence of an appropriate interaction structure and is not claimed here; the VERSF framework treats this as a further condition on the dynamics of specific physical systems. When the commitment condition is satisfied, a new fact can enter physical reality. When either primitive condition fails, the distinction cannot become irreversible. The quantum–classical transition marks the boundary at which the necessary structural conditions first come within reach.

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3. The Action Budget of a Causal Region

3.1 Deriving $\chi(L)$

Consider a region $\mathscr{R}(L)$ with characteristic linear scale L and mean energy density ρ. The total energy contained within the region is

$E \sim \rho L^3$.

The causal crossing time—the maximum interval over which the region can act as a single causally coordinated unit—is

$\tau \sim L/c$.

No causal process can coordinate information across the region faster than this, so τ sets the natural timescale for any commitment event that must complete within $\mathscr{R}(L)$'s own boundary.

The total action available within the region over one causal interval is therefore

$\mathcal{S}\_avail \sim E \cdot \tau \sim \rho L^3 \cdot (L/c) = \rho L^4/c$.

By A1—which grounds the quantum action threshold $\hbar$ as the minimum scale of a physically distinguishable distinction, as formalised in Section 4.1—each irreversible commitment event requires a minimum action of order $\hbar$. The maximum number of irreversible events supportable within $\mathscr{R}(L)$ is therefore

$$N_{max}(L) \sim \mathcal{S}_{avail} / \hbar = \rho L^4 / \hbar c \equiv \chi(L).$$

3.2 Physical Interpretation

The parameter $\chi(L)$ has a direct and transparent physical meaning: it is the number of irreversible commitment events that can occur within a region of size L over one causal crossing time, given the energy density ρ and the quantum threshold $\hbar$.

Because $\chi(L)$ scales as L^4, it is an extremely sensitive function of scale. A region ten times smaller has a χ value 10^4 times smaller. This steep scaling reflects the simultaneous suppression of the energy budget (as L^3) and the available time (as L) as the region shrinks. It is precisely this steep scaling that makes the threshold $\chi(L) = 1$ a sharp boundary.

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4. The CCC Condition

4.1 Necessity of the Quartic Constraint from C1 and C2

We establish that $\rho L^4 \gtrsim \hbar c$ is the *minimal* condition any physical region must satisfy in order to contain a single irreversible fact, and that this follows from C1 and C2 alone without appeal to any external physical limit.

A commitment event must produce a physically distinguishable outcome. By C1, such a distinction requires an action bounded below by $\hbar$:

$$\mathcal{S}_{event} \gtrsim \hbar \quad \text{...(i)}$$

By C2, the event must complete within the causal crossing time of the region:

$$t_{event} \leq L/c \quad \text{...(ii)}$$

These two requirements jointly constrain the energy that must be available within the region. The action associated with the commitment event is $\mathcal{S}_{event} = E_{event} \cdot t_{event}$, where E_{event} is the energy dedicated to producing the distinguishable transition. Combining conditions (i) and (ii):

$$E_{event} \sim \mathcal{S}_{event} / t_{event} \gtrsim \hbar / (L/c) = \hbar c/L.$$

This step uses condition (i) directly — the committed action must meet or exceed $\hbar$ — divided by the maximum available time from condition (ii). The time–energy uncertainty relation $\Delta E \cdot \Delta t \gtrsim \hbar/2$ provides independent support: for a transition to occur within $\Delta t \leq L/c$, the energy uncertainty associated with the transition satisfies $\Delta E \gtrsim \hbar c/(2L)$, consistent with $E_{event} \gtrsim \hbar c/L$ up to the order-unity prefactor absorbed into $\gtrsim$. The bound applies to the energy of the committed event itself, not the total energy of the region; the requirement on the region is that it must be able to supply this energy, giving

$$\rho L^3 \gtrsim \hbar c/L,$$

which rearranges immediately to

$$\rho L^4 \gtrsim \hbar c.$$

This is the quartic condition, derived from C1 and C2 alone. No appeal to the Margolus–Levitin theorem or any other external bound is required; those limits appear later as independent confirmations.

The appearance of $\hbar$ in this condition is not an independent assumption. It follows from A1: finite distinguishability requires a minimum action scale, and $\hbar$ is the unique universal quantum of action—the smallest action that any physically distinguishable transition can involve.

A universe in which no region satisfies $\rho L^4 \gtrsim \hbar c$ contains no irreversible facts and is therefore observationally indistinguishable from a purely reversible substrate. The CCC condition is the structural line between a universe that can be observed and one that cannot.

Note on notation: The symbol $\gtrsim$ is used throughout to denote inequality up to order-unity numerical prefactors arising from the precise form of the uncertainty relation and the geometry of the causal region. The structural content of the result—that a finite minimum of ρL^4 is required for fact production—is independent of these prefactors.

4.2 C1 and C2 Entail $\chi(L) \gtrsim 1$

Up to the order-unity prefactors noted in §4.1, the requirement $E \gtrsim E_{min}$ gives $\rho L^4 \gtrsim \hbar c$, or equivalently $\chi(L) \gtrsim 1$. The $\gtrsim$ symbol is used consistently throughout: the structural content of the result is independent of numerical prefactors of order unity.

Setting

$$N_{max}(L) = \rho L^4 / \hbar c,$$

the requirement $\rho L^4 \gtrsim \hbar c$ is equivalent to

$$N_{max}(L) \gtrsim 1,$$

or equivalently,

$$\chi(L) \gtrsim 1.$$

This is the Causal–Coherence Compatibility (CCC) condition.

The derivation makes the logical structure explicit: the two primitive commitment conditions, applied to a bounded causal region, entail a quartic lower bound on the product ρL^4. The CCC condition is not a compatibility statement between independently-arrived-at limits. It is the direct structural entailment of C1 and C2.

Each component of the quartic constraint corresponds to a component of the commitment conditions:

Commitment Condition	Quartic Constraint Component
Distinguishability: action $\gtrsim \hbar$ (C1)	Action meets or exceeds quantum threshold $\hbar$
Causal completion: $t \leq L/c$ (C2, causal-time)	Process completes within causal time L/c
Amplification into environment (C2, amplification)	Ensures completion constitutes irreversible fact

Note on C2: The causal-time component of C2 ($t \leq L/c$) enters the quartic derivation quantitatively. The amplification component ensures that what completes within the causal boundary constitutes a physical fact rather than a reversible transition. Both sub-requirements are necessary; only the causal-time component contributes a quantitative factor to the threshold.

4.3 Commitment Capacity as Derived Consequence

The commitment capacity condition (C3)—requiring that the region have at least one unit of remaining distinguishability capacity—is not an independent postulate. It is a consequence of the quartic derivation above.

Once C1 and C2 jointly require $\rho L^4 \gtrsim \hbar c$, we have $N\_max(L) = \rho L^4/\hbar c \gtrsim 1$ automatically. The region therefore contains at least one unit of available commitment capacity by construction: a region satisfying the quartic threshold necessarily has room for at least one fact. A region failing the threshold cannot support any facts regardless of its capacity status.

C3 is therefore not a third independent gate on fact production. It is the capacity reading of the same threshold already established by C1 and C2. The logical structure of the paper's results can be stated as two entailments:

C1 $\wedge$ C2 hold in $\mathscr{R}(L) \Longrightarrow \chi(L) \gtrsim 1$,

and, by necessity (since C1 and C2 are required for any commitment event):

a commitment event occurs in $\mathscr{R}(L) \Longrightarrow \chi(L) \gtrsim 1$.

The first entailment is the derivation of the quartic threshold from the two primitive conditions. The second is its physical interpretation: $\chi(L) \gtrsim 1$ is a necessary condition for any irreversible fact to exist within $\mathscr{R}(L)$. Neither formulation claims that every region with $\chi(L) \gtrsim 1$ produces a commitment event — that stronger sufficiency claim depends on the interaction structure of specific physical systems and is not made here. C3 is implied by both entailments and need not be separately assumed.

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5. The Coherence Scale

5.1 Definition

The threshold condition $\chi(L) = 1$ defines a characteristic scale. Setting

$\rho\xi^4 / \hbar c = 1$,

we obtain

$\xi \equiv (\hbar c/\rho)^{(1/4)}$.

This is the **coherence scale**: the minimum size of a region that can support exactly one irreversible commitment event within its causal boundary.

5.2 The Three Regimes

The CCC condition partitions spacetime regions into three structurally distinct regimes:

Quantum regime ($L \ll \xi$, i.e., $\chi(L) \ll 1$): The action budget is insufficient to complete any irreversible event. Physical processes remain coherent and reversible. No stable facts can form. This is the domain of unitary quantum mechanics.

Threshold regime ($L \sim \xi$, i.e., $\chi(L) \sim 1$): Exactly one irreversible commitment is possible per causal interval. This is the minimal fact-producing scale—the boundary at which quantum coherence first gives way to irreversible record formation. The physics here is intrinsically mesoscopic and cannot be captured by either purely quantum or purely classical descriptions.

Classical regime ($L \gg \xi$, i.e., $\chi(L) \gg 1$): Many irreversible events occur per causal interval. The density of committed facts is high. Classical, deterministic behaviour emerges as the statistical aggregate of a large number of completed commitments.

5.3 The Coherence Scale Is Not the Decoherence Scale

It is important to distinguish ξ from the familiar environmental decoherence length. Decoherence is a dynamical process—the entanglement of a system with environmental modes over some timescale. The coherence scale ξ is a structural threshold: it is the scale below which the action budget is insufficient for irreversibility, regardless of the details of environmental coupling.

The argument that decoherence presupposes ξ runs as follows. Each interaction between a system and an environmental mode that produces a distinguishable entanglement record must itself satisfy C1: the interaction action must meet or exceed $\hbar$. It must also satisfy C2: the interaction must complete within the causal crossing time of the region. These are precisely the conditions whose conjunction gives $\chi(L) \gtrsim 1$. A region with $\chi(L) \ll 1$ lacks the action budget to sustain even a single system–environment interaction capable of producing an irreversible record. Decoherence—the accumulation of such interactions—therefore cannot proceed in any region where the CCC condition fails. Decoherence is the mechanism by which commitment events occur within the classical regime; the CCC condition is the structural precondition that makes any such mechanism operable.

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6. Independent Confirmation from Physical Limits

Section 4.1 establishes the quartic condition from C1 and C2 alone, using only the time–energy uncertainty relation. The following three results are therefore independent confirmations of the same structural necessity, not components of the original derivation.

6.1 Quantum Speed Limits: Margolus–Levitin

The Margolus–Levitin theorem establishes that the maximum rate at which a quantum system of mean energy E can transition between orthogonal states is $E/\hbar$ per unit time. For a region of energy $E \sim \rho L^3$ and causal time $\tau \sim L/c$, the maximum number of orthogonal transitions—i.e., distinguishable irreversible events—within the causal interval is

$N_{ML} \sim E\tau/\hbar = \rho L^4/\hbar c = \chi(L)$.

The Margolus–Levitin bound independently recovers the quartic capacity condition. This confirms from the theory of quantum dynamics that the commitment threshold $\chi \sim 1$ is the correct structural boundary—without having been used to derive it.

6.2 Holographic Entropy Bounds: Bekenstein

The Bekenstein bound states that the maximum entropy of a region of smallest enclosing radius R and energy E is $S \leq 2\pi ER/\hbar c$. Writing the characteristic scale L for the radius R (they agree up to a geometrical factor of order unity, absorbed into $\gtrsim$) and dropping the 2π prefactor (which likewise contributes an order-unity factor already noted in §4.1), the bound gives

$S_{max} \sim EL / \hbar c$.

For $E \sim \rho L^3$, this gives

$S_{max} \sim \rho L^4 / \hbar c = \chi(L)$.

The maximum entropy of a region is therefore its maximum number of committed distinguishable states. The Bekenstein bound independently recovers $\chi(L)$ from thermodynamics and holographic geometry, confirming the quartic structure from a second independent domain.

6.3 Causal Diamond Action

A causal diamond of characteristic scale L is the spacetime region causally accessible to an observer over an interval L/c—the intersection of the future light cone from an initial point and the past light cone from a final point separated by L/c. Its 4-volume scales as L^4/c (three spatial dimensions of extent L, one temporal dimension of extent L/c). For a region with energy density ρ, the action is the integral of the energy density over this 4-volume:

$$\mathcal{S}_\diamond \sim \rho \cdot (L^4/c) = \rho L^4/c.$$

The dimensionless ratio with the quantum of action is therefore

$$\mathcal{S}_\diamond / \hbar \sim \rho L^4/\hbar c = \chi(L).$$

The causal diamond action recovers the quartic structure from spacetime geometry, providing a third independent confirmation from a domain entirely separate from quantum dynamics and thermodynamics.

6.4 Structural Account of the Convergence

The convergence is not coincidental: any correct description of irreversible, distinguishable processes in bounded regions must reproduce the quartic structure, because that structure is the necessary consequence of the minimum requirements for fact production established in §4.1. All three limits are constraints on the capacity of a region to produce irreversible facts. Because the quartic condition is structurally required by fact production (§4.1), every physical theory that correctly describes the constraints on distinguishable, irreversible processes must independently recover it. The Margolus–Levitin bound limits the *rate* of commitment. The Bekenstein bound limits the *total count* of committed facts. The causal diamond action measures the *resource* available for commitment. These are three independent confirmations of a single structural necessity, and the CCC condition is its canonical expression.

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7. Implications

7.1 The Quantum–Classical Transition

The CCC condition provides a structural account of the quantum–classical transition that does not depend on the details of any decoherence model. The transition occurs at the scale ξ where $\chi(L)$ crosses unity. Below ξ, the action budget is insufficient for any irreversible event: the region is constitutively quantum. Above ξ, irreversible commitments are energetically affordable: the region can become classical. The transition is not a matter of degree of environmental coupling—it is a matter of structural capacity.

This reframes the quantum–classical transition from a dynamical question (how does classicality emerge from quantum evolution?) to a structural one (at what scale does the action budget first permit irreversibility?). The CCC condition answers the structural question exactly.

7.2 The Cosmological Constant

The vacuum energy density $\rho_\Lambda = \Lambda c^2/(8\pi G)$ sets a universal background energy scale. Substituting into the expression for ξ gives

$$\xi_\Lambda \sim (8\pi G\hbar / c\Lambda)^{(1/4)}.$$

This is the cosmological coherence scale: the minimum region that can produce a fact against the vacuum background. It sets a universal lower bound on the size of stable classical structures in a spacetime with cosmological constant Λ.

This connects the value of Λ directly to the structural capacity of spacetime. The CCC condition suggests a structural reading of Λ in which it functions not merely as a geometric parameter but as a constraint on the minimum scale at which physical facts can exist: given $\xi_\Lambda \sim (8\pi G\hbar/c\Lambda)^{(1/4)}$, any region smaller than ξ_Λ lacks the action budget to produce a fact against the vacuum background. The smallness of the observed Λ—and the corresponding largeness of ξ_Λ on particle physics scales—means that the coherence scale lies far below the scales relevant to atomic structure, chemistry, and observation, consistent with a universe that supports rich classical structure.

7.3 The Emergence of Irreversible Time

In the VERSF framework, time is not a background parameter. It is the ordered accumulation of commitment events. Each completed commitment defines a before and an after: the distinction that did not exist prior to the event, and the stable fact that persists after it.

The CCC condition thus determines where and when time, in the irreversible sense, can exist. Below ξ, no commitments occur and there is no arrow of time—only reversible quantum evolution. Above ξ, commitments accumulate and the arrow of time emerges from the directed flow of facts into the permanent record of reality.

This gives a precise meaning to the claim that time emerges from irreversibility: it is the ordering structure on the set of commitment events, and that set is non-empty only in regions where $\chi(L) \gtrsim 1$.

7.4 Gravity and Fold-Density Gradients

Within VERSF, gravitational attraction arises from gradients in the density of committed facts—fold-density gradients. Since commitment density is governed by $\chi(L)$, and since $\chi(L)$ depends on the local energy density ρ, gravitational structure is tied to the spatial variation of χ. Regions of high ρ have large χ, support dense commitment, and attract matter because distinguishable structure is more efficiently produced there. This connection between the CCC condition and the origin of gravity will be developed in a companion paper.

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8. Conclusion

We have shown that the conditions required for physical fact production reduce to a single dimensionless constraint:

$\chi(L) = \rho L^4/\hbar c \gtrsim 1$

This is the Causal–Coherence Compatibility condition. It is not a unification of independently-derived limits—it is the structural entailment of two primitive physical requirements (C1 and C2) applied to a bounded causal region via the time–energy uncertainty relation. The Margolus–Levitin quantum speed limit, the Bekenstein holographic entropy bound, and the action content of causal diamonds each independently confirm the same quartic structure, precisely because all three correctly describe constraints on fact production.

The coherence scale $\xi = (\hbar c/\rho)^{(1/4)}$ emerges as the minimal fact-producing region: the smallest scale at which the action budget first permits an irreversible record. It is the boundary between the quantum regime, in which facts cannot form, and the classical regime, in which they accumulate.

The CCC condition is not a new postulate. It is the expression, in the language of action and causal geometry, of the most basic requirement that can be imposed on a physical universe: that it be capable of producing stable, irreversible, distinguishable facts. Everything else—quantum limits, entropy bounds, spacetime structure, and the emergence of time—follows as a consequence of this constraint.

The quartic structure $\rho L^4 \gtrsim \hbar c$ is therefore not a property of spacetime, thermodynamics, or quantum mechanics individually. It is the structural condition required for any universe to produce irreversible facts.

Appendix: From Axioms A1–A3 to the CCC Condition

The three VERSF axioms are:

- **A1 (Primitive Distinguishability):** Physical reality consists of distinguishable differences. No structure exists that is not grounded in at least one operational distinction.

- **A2 (Irreversible Commitment):** Physical facts arise only through processes that are irreversible—transitions that cannot be undone by any operation within the causal boundary of the originating region.
- **A3 (Finite Localization Capacity):** Every bounded region has a finite maximum capacity for committed distinctions, set by the No Multi-Primitive Occupancy constraint.

From A1: any fact requires a distinction resolvable at or above the action threshold $\hbar$. This is Condition C1.

From A2: any fact requires (i) a process that completes within the causal crossing time $\tau = L/c$ of the region, and (ii) amplification into environmental degrees of freedom ensuring the result is irreversible. Together these constitute Condition C2.

From C1 and C2 jointly, via the time–energy uncertainty relation, the quartic condition $\rho L^4 \gtrsim \hbar c$ follows (Section 4.1). This immediately gives $N_{max}(L) \gtrsim 1$—the content of Condition C3. C3 is therefore a derived consequence of A1 and A2, not an independent requirement. A3 provides the conceptual framework for understanding why N_{max} is finite, but the capacity threshold itself follows from the quantitative demands of C1 and C2.

The CCC condition $\chi(L) \gtrsim 1$ is therefore the direct quantitative consequence of A1 and A2 applied to a bounded causal region, with A3 confirming the finite-capacity interpretation of the threshold.