The Theory of Fact Production

Commitment Dynamics and the Emergence of Physical Reality in the VERSF Framework

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For the General Reader

Physics usually describes how states evolve. Equations tell us how particles move, how fields change, and how probabilities shift over time. Yet there is a deeper question that these equations rarely address directly:

How do physical facts come into existence?

Every observation we make corresponds to a definite outcome. A detector clicks. A particle appears in one location rather than another. A measurement result becomes part of the irreversible history of the universe. These events are not merely possibilities — they are facts. Stable records that something happened.

This raises a fundamental puzzle. The microscopic laws of physics are largely reversible. If we reverse the equations, the system can in principle evolve backward. Yet the facts that make up the history of the universe are not reversible. Once a measurement outcome is recorded, the universe is no longer the same as it was before.

The question is therefore not only how states evolve, but how possibilities become facts.

This paper proposes a structural answer within the Void Energy–Regulated Space Framework (VERSF). In this framework, facts are produced when reversible distinctions cross a commitment boundary and become irreversibly recorded within a finite-capacity physical substrate. Fact production is governed by three dynamical conditions that must be satisfied simultaneously: the distinction must become operationally resolvable above a minimum threshold, it must propagate into environmental degrees of freedom beyond local causal control through a process of amplification, and the physical substrate must possess available capacity to store the resulting record.

When all three conditions are satisfied, a commitment event occurs and a new fact enters the irreversible history of the universe. When any one fails, the potential distinction retreats into the reversible substrate — a near-commitment that leaves no permanent record.

In this picture, reality is not simply a system evolving through states. It is a continuously expanding ledger of irreversible commitments.

Abstract

The origin of irreversible physical facts within a universe governed by reversible dynamical laws remains an unresolved conceptual problem in theoretical physics. While quantum measurement theory, decoherence, and thermodynamics each address aspects of this issue, none provides a unified structural mechanism explaining how definite outcomes arise as stable records.

This paper develops a theory of fact production within the Void Energy–Regulated Space Framework (VERSF). Physical facts correspond to commitment events: transitions in which reversible distinguishability relations become irreversibly recorded within a finite-capacity substrate. Fact production is governed by three dynamical conditions — distinguishability threshold, environmental amplification, and capacity allocation — which together constitute the commitment condition. These conditions are not independent postulates but consequences of the structural necessities established in companion work: finite distinguishability (A1), irreversible commitment (A2), and finite localization capacity (A3).

The paper develops the commitment dynamics in detail, including a formal definition of the amplification measure, the relationship between the three conditions, the dynamical structure of the commitment boundary, and the behavior of near-commitment events that fail to cross the threshold. The three conditions are unified into a single core rate law — the Fact Production Rate Equation — whose structure is exactly parallel to nucleation theory in statistical physics: fact production is the nucleation of irreversible records within the reversible informational substrate of the universe, with the commitment barrier playing the role of the nucleation free-energy barrier and the TPB throughput playing the role of the attempt rate. The commitment barrier Φ_c appears as a structural parameter whose derivation from the BCB/TPB substrate is identified as the primary outstanding work; in the only worked example, Φ_c is set by convention rather than derived, so the rate law is a coherent phenomenological proposal rather than a tested prediction. The primary form of the equation uses an exponential barrier factor $\exp(-\Phi_c/\Phi)$, with the standard Heaviside threshold form recovered as the sharp-barrier limit. A spacetime-local generalization is also developed. A stylized model of a two-state system undergoing environmental coupling is worked through explicitly to anchor the abstract framework in calculable structure. Within this architecture, time emerges as the ordered accumulation of commitment events — equivalently, as the rate of fact nucleation — entropy measures the thermodynamic cost of maintaining distinguishable records, and the Entanglement Ledger provides the monotone bookkeeping device that tracks cumulative correlation export across the history of the universe.

The theory reframes quantum measurement, decoherence, entropy production, and the arrow of time as consequences of a single underlying dynamical process: the physical generation of facts through commitment. A dedicated section develops the connection to quantum probability: the Born rule $P(A) = |\psi_A|^2$ is argued, via the companion Double Square framework, to emerge as

the statistical law governing outcome selection at commitment events rather than entering as an independent postulate.

Relationship to Companion Papers

This paper is the third in a sequence within the VERSF Theoretical Physics Programme. Each paper addresses a distinct question, and the three are designed to be read as a unified argument.

The Architecture Paper defines the structural primitives of the framework: the Void substrate, Bit Conservation and Balance (BCB), the Ticks Per Bit (TPB) commitment rate, and the admissibility conditions on physical transitions. It answers the question: *given that physical facts exist, how does the VERSF framework organise the conditions governing them?*

The Necessity Paper establishes that the three core structural conditions — finite distinguishability (A1), irreversible commitment (A2), and finite localization capacity (A3) — are not assumptions but unavoidable prerequisites for any universe capable of supporting physical laws accessible to finite observers. It answers the question: *why must the architecture take this form rather than some other?*

This paper — The Theory of Fact Production takes the structural necessities as its starting point and develops their dynamical consequences: the mechanism by which reversible distinctions become irreversible facts, the conditions governing each commitment event, and the unified interpretation of measurement, entropy, and time that follows. It answers the question: *given that the structural conditions hold, how does physical reality actually come into existence moment by moment?*

The logical dependency is simple: the architecture paper defines the primitives; the necessity paper argues those primitives are unavoidable; this paper develops the dynamics they imply.

The relationship can be summarized as:

Paper	Central question	Role
Architecture paper	How does the framework organise those foundations?	Defines the structural primitives
Necessity paper	Why must the framework have these foundations?	Establishes necessity of A1, A2, A3
This paper	How do physical facts actually come into existence?	Develops the commitment dynamics

A reader encountering VERSF for the first time may find it natural to read the architecture paper first for the formal vocabulary, then the necessity paper for why that vocabulary is unavoidable, then this paper for the dynamics they imply. Alternatively, this paper can serve as a conceptual entry point, with the companion papers providing the foundations underlying it.

Contents

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1. Introduction

The laws of physics describe how physical systems evolve. They do not, by themselves, explain how definite outcomes arise.

In quantum mechanics, a system may exist in a superposition of states, yet every measurement yields a definite result. In thermodynamics, entropy increases irreversibly despite the reversibility of microscopic dynamics. In classical mechanics, physical histories appear fixed and determinate even though the underlying equations permit time-reversal. Each of these observations points to the same conceptual gap: there is no unified account, within standard frameworks, of the physical process by which reversible possibilities become irreversible facts.

This gap has been addressed in fragments. Decoherence theory demonstrates how environmental interactions suppress quantum superpositions and drive apparent classicality, but it does not explain why a specific outcome becomes a stable record — the preferred-basis problem and the problem of definite outcomes remain. Thermodynamics describes the statistical tendency toward entropy growth, but the microscopic formation of individual facts lies outside its scope. Standard quantum measurement theory introduces wavefunction collapse as a postulate, locating the problem rather than solving it.

The Void Energy–Regulated Space Framework approaches the problem from a different direction. Rather than beginning with state evolution and asking where facts come from, it begins with the conditions required for physical facts to exist at all and asks what dynamical process their production requires.

Previous work in this programme has established that any universe supporting physical laws accessible to finite observers must satisfy three structural constraints:

- **A1 — Finite distinguishability**: physical distinctions possess a minimum resolvable granularity $\delta_{min} > 0$.

- **A2 — Irreversible commitment**: forming a physical fact exports correlation irreversibly beyond local causal control.
- **A3 — Finite localization capacity**: there exists an upper bound on the density of stabilizable facts per unit region.

These are not assumptions of the VERSF framework. They are structural prerequisites for any universe in which reproducible observation is possible — not logical necessities for all conceivable universes, but necessary conditions for any universe accessible to finite observers following physical laws. A universe violating A1, A2, or A3 could in principle exist; it would simply be one in which no accessible facts, stable records, or reproducible observations are possible. The arguments that follow are therefore conditional on observability rather than unconditional: A1–A3 are what any universe must satisfy to be the kind of universe we can study. The present paper takes these observability constraints as its starting point and develops their dynamical consequences.

Status of claims. This paper draws on several levels of prior and current work, and it is important to be clear about what is established, what is newly proposed, and what remains conjectural. The structural necessities A1–A3 are established in the necessity companion paper. The Void substrate, BCB capacity, TPB rate structure, and admissibility conditions are organised in the architecture companion paper. The pairwise path-correlation structure and quadratic probability law are developed in the companion paper on pairwise probability. The main new dynamical contributions of the present paper are: (i) the three-condition commitment condition (Section 5), (ii) the fact production rate law — Equation (1) — proposed as a phenomenologically motivated rate law whose nucleation-theoretic form captures the qualitative structure of barrier-crossing commitment but is not yet derived from first principles in the VERSF substrate, and whose commitment barrier Φ_c is a structural parameter set by convention in the only worked example rather than independently computed, (iii) the measurement master equation — Equation (2) — proposed as an effective stochastic equation consistent with the fact-production picture and the pairwise probability rule, rather than a full first-principles derivation, and (iv) the argument that pairwise correlation selection is the minimal admissible mechanism for outcome selection (Section 12.2). The decoherence scaling conjecture and the commitment barrier characterisation are framework-motivated but explicitly conjectural pending full master-equation and microscopic derivations.

Terminology. Four terms are used with distinct technical meanings throughout: a *distinction* is a reversible difference between physical states that has not yet been recorded; a *commitment event* is the irreversible transition by which a distinction crosses the commitment boundary; a *record* is the stabilised physical encoding produced by a commitment event; a *fact* is a stable, recoverable, distinguishable committed record; and an *outcome* is the branch selected at a commitment event when multiple possibilities existed. These terms are not interchangeable and are used consistently below.

Section 2 defines physical facts precisely. Section 3 characterises reversible distinctions and their substrate. Section 4 defines commitment events. Section 5 develops the commitment condition in full, including the nucleation analogy and the core fact production equation. Section 5.6 presents three forms of this equation: a general form in terms of the driving force Φ; an information-theoretic form expressed directly in terms of mutual information, valid in the regime of uncorrelated initial states with unitary evolution; and a candidate covariant form (Equation 1b) in which the frame-dependent attempt rate R_{TPB} is replaced by $T_{\mu\nu} u^\mu u^\nu/\hbar$, the local rest-frame energy density, with commitment events described as a density per unit spacetime four-volume rather than a rate per unit time. Section 6 works through a concrete model of a two-state system to anchor the formalism. Section 7 addresses near-commitment dynamics. Section 8 develops the capacity constraints governing fact production. Section 9 describes the rate structure and admissibility conditions. Section 10 derives time as fact accumulation. Section 11 treats measurement as a special case of commitment dynamics. Section 12 develops the connection to quantum probability and the Born rule, including the structural argument for why selection must operate on pairwise correlations. Section 13 combines the rate law and Born rule into a master equation for measurement as fact production, and contrasts it with standard quantum trajectory theory. Section 14 draws out the implications for decoherence, entropy, and the arrow of time. Section 15 states limitations and outstanding work explicitly. Section 16 concludes.

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2. Physical Facts

A physical fact is defined as a stable, distinguishable record of a physical distinction.

This definition is deliberately operational. It does not presuppose a metaphysical account of what facts are made of, or where they are stored, or how they relate to an underlying ontology. It specifies only what a fact must do: it must record a distinction, it must be stable under perturbation, and it must be distinguishable from alternatives.

More precisely, for an outcome to function as a fact within physical law, three conditions must be satisfied:

2.1 Distinguishability

The outcome must be operationally separable from alternatives. There must exist a physically realizable procedure that reliably discriminates the fact-bearing state from any state in which the fact has not occurred.

2.2 Stability

The record must persist under the perturbations naturally present in the physical environment. A distinction that can be erased by an arbitrarily small perturbation is not a fact but a transient configuration.

2.3 Recoverability

Independent observers, at different times and locations, must be able to access the same record and reach the same conclusion about which distinction has been committed.

2.4 The Fact Definition

Without these properties, reproducible observation is impossible and physical laws lack a stable domain of application. These three requirements are therefore not additional desiderata but consequences of the structural necessity established by Theorem 1 of the companion paper: physical laws require fact-stable state classes.

Facts represent the fundamental units of physical history. Every entry in the causal record of the universe is a fact in this sense — a stable, distinguishable, recoverable commitment.

2.5 Why A1–A3 Are Unavoidable: A Compressed Argument

The three structural constraints A1, A2, A3 are established at length in the companion necessity paper. For the present paper to stand independently, a compressed argument is given here. Each constraint is shown to follow from what any universe capable of supporting physical laws must possess.

A1 — Finite distinguishability ($\delta_{min} > 0$). Suppose distinguishability were infinite — i.e., that arbitrarily fine distinctions could be stabilized as facts. Committing a fact requires state discrimination: reliably determining which of two physical states has occurred. The relevant quantum bound on state discrimination is the Helstrom bound, which gives the minimum error probability for distinguishing two states ρ and σ as $P_{err} = \frac{1}{2}(1 - \frac{1}{2}\|\rho - \sigma\|_1)$. For states separated by fineness ε in some parameter, $\|\rho - \sigma\|_1 \sim \varepsilon$, so $P_{err} \to \frac{1}{2}$ as $\varepsilon \to 0$: states become indistinguishable. Achieving error probability below ½ requires a minimum interaction energy scaling as $\hbar/\varepsilon$ per discrimination attempt (from the time-energy uncertainty relation and the Margolus-Levitin bound on gate speed). As $\varepsilon \to 0$, this energy cost diverges. No finite physical record could discriminate infinitely fine states; no finite observer could confirm that a fact of infinite precision had been committed. A universe with infinite distinguishability would therefore contain no accessible facts. Since the existence of physical laws requires accessible facts (Section 2), distinguishability must be finite: $\delta_{min} > 0$.

A2 — Irreversible commitment. Any finite physical observer P occupies a bounded region of spacetime and has causal access only to their causal past $J^-(P)$. A potential objection should be addressed at the outset: this argument might appear circular — if commitment is *defined* as requiring correlation export outside $J^-(P)$, then irreversibility follows trivially. The substantive claim is not circular but requires justification: *why must forming a stable, recoverable fact require exporting correlation outside the local region at all, rather than forming a purely local record?* The answer lies in the recoverability requirement of Section 2, but the argument requires more than assertion. A purely local record in a fully isolated system would in principle be stable — but full isolation is not achievable for any finite physical system: every finite system couples to environmental degrees of freedom (gravitational, electromagnetic, or thermal), and under this coupling the quantum Zeno effect at best delays decoherence rather than preventing it, since continuous monitoring of a finite system by its environment is itself a coupling that drives entanglement growth. More precisely, the decoherence timescale for a purely local record scales as $\tau\_dec \sim \hbar/\gamma$ where γ is the environmental coupling; achieving stability requires either $\gamma \to 0$ (infinite isolation, physically impossible for any system embedded in a physical environment) or $\tau\_dec \to \infty$ (infinite coherence time, again impossible for any system with non-zero mass or charge). Therefore truly local records are transient, not stable: they decohere on timescales set by environmental coupling. Only when the correlating information has propagated into environmental degrees of freedom outside $J^-(P)$ — where it is inaccessible to any local reversal operation — does the record become genuinely stable and recoverable by independent observers. A potential objection from quantum entanglement — that non-local correlations might allow reversal via entanglement — is handled by noting that exploiting entanglement to reverse a committed distinction requires classical communication, which is itself bounded by $J^-(P)$. The causal irreversibility argument therefore holds: commitment events are generically irreversible. A universe in which commitments were reversible would have no stable history — every record could be undone by sufficiently local operations, violating recoverability.

A3 — Finite localization capacity. Suppose the density of stable facts per unit region were unbounded. Then either (a) distinctions of arbitrarily fine scale are committed — violating A1 — or (b) arbitrarily many coarse distinctions are simultaneously committed in a single region, requiring the environment to absorb unbounded correlation simultaneously. Case (b) requires environmental absorption capacity to be unbounded. But A2 establishes that forming each committed record requires exporting correlation into environmental degrees of freedom outside $J^-(P)$ — a causally bounded region with finite volume and finitely resolvable environmental degrees of freedom within any causal region accessible to a finite observer. A finite causal region contains finitely many independent environmental degrees of freedom, each capable of absorbing at most a finite amount of correlation. Therefore unbounded simultaneous absorption is impossible, and environmental absorption capacity is finite. It follows that the number of simultaneously stable facts per unit region is bounded: a finite localization scale ℓ^* exists.

These three arguments are independent and each follows from the requirements that facts be accessible, stable, and recoverable. They are the minimal structural constraints any universe supporting the definition of Section 2 must satisfy.

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3. Reversible Distinctions and the Void Substrate

Physical systems routinely contain differences that have not yet become facts.

A quantum system in a superposition of position eigenstates contains a difference — a potential distinction — between the two location possibilities. But until a commitment event occurs, this difference has not been recorded. No stable record indicates which possibility has occurred. The distinction is real in the sense that it influences subsequent dynamics; it is not yet real in the sense of constituting a fact.

More generally, the universe contains a vast pre-commitment substrate populated by reversible distinctions: quantum superpositions, microscopic fluctuations, reversible dynamical configurations, entangled but uncommitted correlations. These differences exist and evolve. They interact, interfere, and propagate. But they do not yet constitute physical history.

Within the VERSF framework, this pre-commitment domain is called the **Void**: the reversible substrate in which physical processes remain dynamically active but no stable records have yet formed. For the purposes of the present framework, the Void is modeled as a measure space ($\mathcal{V}$, $\mathscr{F}$, μ) with three properties:

1. **Zero committed entropy**: $S\_comm(\mathcal{V}) = 0$ — no stable records have been formed.
2. **Full reversibility**: For every process P within $\mathcal{V}$, there exists a reverse process P^{-1} such that $P^{-1} \circ P = id\_\mathcal{V}$. This implies that dynamics within the Void are reversible and information-preserving — no dissipative processes occur in the Void itself, since dissipation is an asymmetric, record-forming operation. Any apparent dissipation involves correlation export, which constitutes a commitment event and therefore a transition *out* of $\mathcal{V}$.
3. **Finite capacity**: $\mu(\mathcal{V}) < \infty$ — the reversible configuration measure is finite.

The measure μ represents the statistical weight of reversible configurations in the Void and determines the distribution of attempted distinctions prior to commitment: a distinction drawn from a high-μ region is more likely to be attempted than one drawn from a low-μ region, giving the Void a non-uniform statistical structure that feeds into the attempt rate R_TPB. In this interpretation, μ defines the statistical distribution over reversible configurations prior to commitment and therefore determines the distribution of attempted distinctions entering the commitment condition.

Reversible distinctions exist within this substrate. Commitment events are transitions *out* of it.

The Void should not be confused with empty space or the quantum vacuum. The vacuum in quantum field theory contains fluctuating fields and nonzero energy density, with observable physical consequences. The Void is a characterization of the pre-commitment *status* of physical processes — the domain in which distinctions have not yet been irreversibly recorded — not a statement about the absence of physical activity.

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4. Commitment Events

A commitment event occurs when a reversible distinction undergoes an irreversible transition from the Void substrate into the committed record layer.

Formally, a commitment event is a measurable map

$$\mathcal{T}: (\mathcal{V}, \mathscr{F}, \mu) \to (\Sigma, \mathcal{G}, \nu)$$

from the Void measure space ($\mathcal{V}$, $\mathscr{F}$, μ) to the committed record space (Σ, $\mathcal{G}$, ν), satisfying the admissibility conditions developed in Section 9. Here $\mathscr{F}$ is the σ-algebra of measurable subsets of the Void — the collection of sets of reversible configurations that can be distinguished and measured — and $\mathcal{G}$ is the corresponding σ-algebra on the committed record space. The measurability requirement on $\mathcal{T}$ has a direct physical interpretation: a commitment event must map a measurable (i.e., physically resolvable, distinguishable) subset of Void configurations to a measurable subset of committed records. Commitments that would map unmeasurable Void subsets to records are not admissible, since the resulting records would not correspond to any operationally resolvable distinction.

The map $\mathcal{T}$ is irreversible: there is no inverse map $\mathcal{T}^{-1}$ that recovers the original reversible configuration from the committed record without thermodynamic cost. The commitment event is accompanied by irreversible entropy production $\Delta S_{irr} \geq k_B \ln 2$ per committed bit, as established by the amplification condition in Section 5.2.

The transition can be represented schematically as:

```
reversible distinction (Void)
          ↓
  commitment boundary
          ↓
committed record (physical fact)
```

Commitment events are the elementary particles of physical history. Every fact in the universe corresponds to at least one commitment event. The accumulation of commitment events constitutes the temporal record of the universe.

Two points require emphasis.

First, a commitment event is not the same as a physical interaction. Many physical interactions occur within the Void and leave no committed record. A commitment event is specifically the subset of physical transitions that produce stable, distinguishable, recoverable records. The relationship between physical interaction rate and commitment rate is governed by the TPB structure of Section 9.

Second, commitment is not instantaneous in general. The dynamical process by which a reversible distinction crosses the commitment boundary has structure — it involves amplification, correlation export (tracked globally by the Entanglement Ledger, defined in Section 5.2), and capacity allocation. Section 5 develops this structure in detail. The commitment boundary itself, and the geometry of the transition, is addressed in Section 7.

The four-stage process hierarchy. To prevent ambiguity, the complete path from reversible distinction to committed outcome involves four distinct stages that should not be conflated:

```
reversible distinction
        ↓  (1) decoherence — environmental coupling begins suppressing
superposition
amplification in progress
        ↓  (2) amplification — correlation exports into environmental modes
beyond J⁻(P)
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                                  [Entanglement Ledger, §5.2, begins
incrementing]
threshold reached
        ↓  (3) commitment — all three conditions satisfied; distinction
nucleates as committed record
        ↓  (4) outcome selection — pairwise correlation structure selects
which branch is realised
committed fact (Born-rule outcome)
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Decoherence (1) drives amplification (2); amplification reaching A ≥ A_min, together with D ≥ δ_min and C > 0, constitutes the commitment condition (3); and outcome selection (4) is governed by the Double Square rule operating on the pairwise path correlations at the moment of commitment. These are logically and temporally ordered stages. A distinction can decohere without committing (if capacity is saturated or amplification is insufficient); it can amplify without selecting an outcome (if the commitment threshold is not yet crossed); and it commits before outcome selection (not simultaneously). What commits first is the irreversible availability of a record-bearing event — the fact that *some* outcome will be registered; the branch identity of that record is then resolved by the pairwise correlation structure governing outcome selection.

Figure 1. The four-layer architecture of fact production and outcome selection.

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┌─────────────────────────────────────────────────────────────────┐
│ VOID SUBSTRATE                                                  │
│ Reversible distinctions; zero committed entropy                 │
│ Governed by: BCB/TPB architecture (architecture companion)      │
└─────────────────────────────────────────────────────────────────┘
                          │
                 [reversible unitary
                  dynamics; decoherence
                  raises amplification A]
                          │
                          ▼
┌─────────────────────────────────────────────────────────────────┐
│ COMMITMENT THRESHOLD                                            │
│ Conditions: D ≥ δ_min,  A ≥ A_min,  C > 0                       │
│ Rate: Γ_fact = R_TPB · exp(−Φ_c/Φ) · (1 − N/N_BCB)  [Eq. 1]     │
└─────────────────────────────────────────────────────────────────┘
                          │
                [commitment event:
                 distinction nucleates
                 into irreversible record]
                          │
                          ▼
┌─────────────────────────────────────────────────────────────────┐
│ COMMITTED RECORD                                                │
│ Stable, distinguishable, recoverable fact                       │
│ Branch identity not yet resolved                                │
└─────────────────────────────────────────────────────────────────┘
                          │
                [outcome selection via
                 pairwise correlations;
                 quadratic probability rule]
                          │
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┌──────────────────────────────▼──────────────────────────────┐
│  BORN-RULE OUTCOME                                          │
│  P(A) = |ψ_A|²   (companion paper on pairwise probability)  │
└─────────────────────────────────────────────────────────────┘
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Figure 1: The four layers from reversible Void to Born-rule outcome. Layers 1→2 are governed by fact-production dynamics (this paper, Section 5). The transition 2→3 is the commitment event. Layer 3→4 is governed by pairwise correlation selection (companion paper on pairwise probability). The four processes — decoherence, amplification, commitment, and outcome selection — are sequential and should not be conflated.

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5. The Commitment Condition

A reversible distinction undergoes a commitment event if and only if three dynamical conditions are satisfied simultaneously. These conditions are not independent postulates; each is a dynamical consequence of one of the structural necessities A1, A2, A3 established in previous work.

5.1 Condition 1: Distinguishability Threshold (from A1)

The distinction must exceed the minimum resolvable granularity required for operational separation:

$$\mathbf{D(\rho, \sigma) \geq \delta_{min}}$$

where $D(\rho, \sigma)$ is a distinguishability measure on the state space — for example, trace distance or quantum relative entropy — and $\delta_{min} > 0$ is the finite distinguishability floor established by A1.

A distinction below δ_{min} cannot be stabilized as a recoverable record. No physically realizable procedure can reliably separate states differing by less than δ_{min}; the encoding burden required diverges beyond the capacity of any finite physical process. Such distinctions remain in the Void — they may influence reversible dynamics but cannot constitute facts.

This condition establishes a threshold below which commitment is impossible regardless of the state of the other two conditions.

5.2 Condition 2: Environmental Amplification (from A2)

The distinction must propagate into environmental degrees of freedom beyond local causal control. Define the **amplification measure**:

$$\mathbf{A(\rho_{SE}) = S(\rho_E) - S(\rho_E^{(0)})}$$

where $S(\rho\_E)$ is the von Neumann entropy of the environment after interaction and $S(\rho\_E^{(0)})$ is its entropy before interaction. $A(\rho\_SE)$ measures the increment in environmental entropy produced by the system-environment coupling.

A clarification on the relationship between amplification and mutual information is needed here. Environmental entropy increase ΔS_E and mutual information $I(S{:}E)$ are not generally equal. They satisfy:

$$\Delta S\_E \geq I(S{:}E)$$

with equality holding when the initial state is a product state $\rho\_SE = \rho\_S \otimes \rho\_E$ and evolution is unitary. In the simplified models used in this paper — where the system and environment are initially uncorrelated and interact via a unitary coupling — the equality holds and $A(\rho\_SE) = I(S{:}E)$. In more general settings (initially correlated states, non-unitary evolution), $A(\rho\_SE) = \Delta S\_E$ is an upper bound on $I(S{:}E)$, and the amplification condition should be understood as a lower bound on the correlation exported during commitment. This distinction does not affect the framework's conclusions for the regime treated here, but should be borne in mind when extending to more general open system dynamics.

The amplification threshold condition is:

$$A(\rho\_SE) \geq A\_min$$

where $A\_min = k\_B \ln 2$ per committed bit. This threshold connects to Landauer's principle, but the connection requires care: Landauer's erasure bound applies to the cost of *erasing* a bit, not to writing one. The thermodynamic minimum here arises from the irreversibility of the exported correlations — the fact that the commitment cannot be undone without paying at least $k\_B T \ln 2$ per bit to recover the exported correlation from the environment. The minimum amplification required for irreversible commitment is therefore set by the cost of the correlations that cannot be retrieved, not by the cost of storing the record itself.

Note on A_min as threshold: In the abstract three-condition formulation, $A\_min = k\_B \ln 2$ is presented as a universal threshold. In concrete physical systems, the precise threshold depends on the environmental coupling geometry and the number of environmental modes involved. The two-state worked example of Section 6 treats A_min illustratively as the minimum amplification for a one-bit commitment, noting that a precise treatment specifies A_min as a function of the coupling structure. This caveat applies equally to the abstract A_min appearing here.

This condition is the dynamical realization of structural necessity A2. By the causal boundedness established in the companion paper, no locally bounded agent can access degrees of freedom outside their causal past $J^-(P)$. When a distinction propagates into environmental degrees of freedom beyond $J^-(P)$, the resulting correlation export is causally irreversible: no locally admissible operation can retrieve and reverse it. The Entanglement Ledger $\mathscr{L}(S,E)$ is defined as the system–environment mutual information $I(S{:}E) = S(\rho\_S) + S(\rho\_E) - S(\rho\_SE)$ — a standard quantum information quantity — named here for its role as a monotone bookkeeping device for the cumulative history of correlation exports. The equivalence $\mathscr{L}(S,E) = I(S{:}E)$ is exact and immediate; the VERSF contribution is not the definition but the role: the Ledger enters Equation (1a) as the control parameter in the barrier factor $\exp(-A_{min}/I(S:E))$, making the commitment rate directly computable from the accumulated correlation history. This is what the reframing buys: a connection between the standard mutual information and the dynamical commitment rate that neither standard decoherence theory nor quantum trajectory theory provides. The Ledger increments monotonically with each correlation export beyond $J^-(P)$.

The amplification condition therefore has a precise physical meaning: a commitment event requires that environmental entanglement increase by at least A_{min}, ensuring that the correlation structure of the committed distinction lies outside local causal control. **Amplification is the local dynamical condition** — the requirement that the distinction has propagated sufficiently into environmental degrees of freedom in the immediate coupling region. **The Entanglement Ledger is the global bookkeeping device** — the monotonically non-decreasing cumulative record of all correlation exports across the history of the universe. Amplification satisfying $A \geq A_{min}$ is what causes the Ledger to increment; the Ledger records that it did.

The relationship between amplification and decoherence. Standard decoherence theory describes the suppression of off-diagonal terms in the system's density matrix due to environmental coupling. Within the present framework, decoherence is the mechanism that drives amplification: as environmental degrees of freedom become correlated with the system, $A(\rho_{SE})$ increases. Decoherence is therefore the physical process that enables the amplification condition to be satisfied — it is a necessary but not sufficient condition for commitment. A system may decohere extensively without committing if, for example, capacity is saturated (Condition 3 fails).

5.3 Condition 3: Capacity Allocation (from A3)

The physical substrate must possess available distinguishability capacity to store the resulting record:

$$C = N_{BCB} - N(\tau) > 0$$

where N_{BCB} is the BCB capacity of the relevant region and $N(\tau)$ is the current number of committed records. Equivalently, the system must not be at BCB saturation.

This condition is the dynamical realization of structural necessity A3. Since the maximum stabilizable distinction density is finite (Theorem 4 of the companion paper), a region that has reached capacity cannot accept new committed records. Distinctions that satisfy Conditions 1 and 2 but find no available capacity do not commit — they are absorbed into the environment as dispersed correlations that raise entropy but produce no new stable records.

5.4 The Joint Commitment Condition

A commitment event occurs if and only if all three conditions are satisfied simultaneously:

$$\mathcal{C}_{commit} = 1 \text{ [if } D \geq \delta_{min} \text{ and } A \geq A_{min} \text{ and } C > 0\text{]}; 0 \text{ [otherwise]}$$

The three conditions are logically independent: each can fail while the others are satisfied.

- **$D < \delta_{min}$ with $A \geq A_{min}$ and $C > 0$**: the distinction is too fine to be stabilized. It propagates into the environment but produces no recoverable record — environmental entropy increases but no committed record forms. Net effect: entropy production without fact production.
- **$D \geq \delta_{min}$ with $A < A_{min}$ and $C > 0$**: the distinction is resolvable but has not propagated sufficiently into the environment. It remains potentially reversible. Net effect: a near-commitment that may either amplify further and commit, or dephase and return to undifferentiated Void dynamics.
- **$D \geq \delta_{min}$ with $A \geq A_{min}$ and $C = 0$**: the distinction is resolvable and has amplified irreversibly, but no capacity is available to store the record. The correlation is deposited into the environment without stable localization. Net effect: irreversible correlation export without a new committed record. This regime is associated with high-entropy environments where decoherence occurs continuously but produces diffuse thermalization rather than sharp fact-formation. *Note: the claim that high entropy implies $C = 0$ rests on the conjecture that $N_{BCB,env} \sim S_{local}/k_B$, which is the decoherence scaling conjecture developed in Section 14.1 and flagged there as underived. The two sections are therefore in a logical dependency: §5.4 provides the conceptual motivation and §14.1 provides the (conjectural) quantitative form.*

The three-way independence has physical consequences. It implies that a universe can support extensive environmental decoherence without generating correspondingly extensive fact production, if capacity is saturated. Conversely, in low-entropy, high-capacity regimes — such as the early universe — fact production can be efficient even for fine distinctions, because capacity is far from saturation.

5.5 Fact Production as Nucleation: The Physical Analogy

Before writing the core rate equation, it is worth observing that the commitment condition has a strong structural parallel in the mathematics of barrier-crossing processes in statistical physics: nucleation theory.

In many physical systems, a new phase does not appear smoothly or continuously. Instead, it appears through discrete nucleation events — moments at which a fluctuation crosses a critical threshold and a stable structure abruptly forms.

Physical system	Fluctuation	Threshold	Stable structure
Freezing water	thermal fluctuation	critical ice nucleus	ice crystal
Boiling water	thermal fluctuation	critical bubble radius	vapor bubble
Crystal growth	lattice distortion	activation energy	crystalline domain
Magnetization	spin fluctuation	exchange energy barrier	magnetic domain

In every case the same pattern holds: the system fluctuates continuously, but nothing becomes permanent until a critical barrier is overcome. Below the barrier, fluctuations are reversible and leave no lasting trace. Above it, a stable structure nucleates and the system is irreversibly changed.

The standard nucleation rate law is:

$$\Gamma = \Gamma_0 \exp\left(-\frac{\Delta F^*}{k_B T}\right)$$

where Γ_0 is the attempt rate, ΔF^* is the free-energy barrier to nucleation, and k_BT is the thermal energy available to drive fluctuations over it.

The parallel to VERSF commitment dynamics provides a physically motivated phenomenological model:

Nucleation physics	VERSF commitment
Thermal fluctuation	Reversible distinction in the Void
Attempt rate Γ_0	TPB throughput R_TPB
Free-energy barrier ΔF^*	Commitment barrier Φ_c
Thermal driving force k_BT	Distinguishability driving force Φ
Nucleation event	Commitment event
Stable crystal / bubble	Physical fact (committed record)

Within the present framework, fact production is interpreted as the **nucleation of irreversible records within the reversible informational substrate of the universe**. Reversible distinctions fluctuate continuously within the Void. Most fall back without committing. The framework proposes that a distinction commits — a fact nucleates — when its informational driving force Φ sufficiently exceeds the commitment barrier Φ_c that the environmental amplification and capacity conditions are simultaneously satisfied.

The nucleation formalism therefore provides a natural phenomenological model for commitment dynamics, with a structural correspondence to standard barrier-crossing processes. The analogy is not merely decorative: the same mathematical form — attempt rate × barrier suppression × capacity factor — arises in any threshold-crossing process in which fluctuations stochastically overcome a barrier to produce stable structures. Whether this structural correspondence reflects a deeper substrate-level equivalence is a question for future work; at present the nucleation form is adopted because it correctly captures the qualitative features of commitment and connects the framework to well-understood physics.

One important asymmetry between the analogy and its source should be noted here to prevent surprise later. In classical nucleation theory, the barrier height ΔF^* is independently computable from the thermodynamic properties of the phases — surface tension, latent heat, and supersaturation — without reference to the rate law itself. In the present framework, the commitment barrier Φ_c plays the corresponding role, but its derivation from the BCB/TPB substrate parameters has not yet been achieved. Section 6.5 makes this explicit: in the two-state model, $\Phi_c = 1$ is a normalisation convention rather than a computed quantity. This means that Section 6 does not test the rate law — it normalizes it. A rate law with a free parameter set by convention in the only worked example has not been constrained: the nucleation form is consistent with the worked example by construction. The framework becomes genuinely predictive only when Φ_c can be computed independently for two or more systems with different coupling structures, allowing the rate law to be tested against the variation. Deriving Φ_c from substrate physics is therefore not merely the next step but the step required for the theory to make contact with experiment, and is listed in Section 15 as the primary outstanding item.

5.6 The Core Fact Production Equation

The nucleation analogy motivates the primary form of the fact production rate law.

Defining Φ and Φ_c. The **local distinguishability driving force** Φ should be interpreted as an effective dimensionless control parameter summarizing the local ability of the system–environment interaction to drive amplification beyond the commitment threshold. Its sources include: interaction energy between the system and its environment (which drives amplification), the strength of the system-apparatus coupling, and the energy density available to sustain the commitment process. Formally, Φ scales with the available free energy per distinguishability degree of freedom relative to the commitment cost: $\Phi \sim E_{avail} / (N_{BCB} \cdot k_B T_{eff})$, where T_{eff} is an effective temperature of the environment.

A natural and information-theoretically grounded choice for Φ is to identify it with the mutual information exported to the environment during amplification, normalised by the commitment threshold:

$$\Phi = \frac{I(S:E)}{A_{min}}$$

where $I(S:E) = S(\rho_S) + S(\rho_E) - S(\rho_{SE})$ is the system–environment mutual information and $A_{min} = k_B \ln 2$ is the minimum irreversible information required for commitment (from A2). This identification connects Φ to a quantity already present in the amplification condition (Section 5.2) and the Entanglement Ledger: the barrier ratio Φ_c/Φ becomes $A_{min}/I(S:E)$, expressing the ratio between the irreversibility cost required for commitment and the actual correlation exported.

Regime restriction. A tension with Section 5.2 must be flagged explicitly. The amplification condition is stated as $A(\rho_{SE}) = \Delta S_E \geq A_{min}$, using ΔS_E as the amplification measure. The identification $\Phi = I(S:E)/A_{min}$ uses mutual information instead. Section 5.2 establishes that $\Delta S_E \geq I(S:E)$ in general, with equality when the initial state is uncorrelated and evolution is unitary. In the general case (initially correlated states, non-unitary evolution), $\Delta S_E > I(S:E)$, which means the commitment condition $A \geq A_{min}$ and the barrier factor $\exp(-A_{min}/I(S:E))$ use different quantities and are not equivalent. The consistent general choice for Φ is therefore:

$$\Phi = \frac{\Delta S_E}{A_{min}}$$

which uses the same quantity as the amplification condition throughout. Φ is not merely a reparameterization of entropy transfer: it measures the ratio between the actual environmental entropy export and the minimum entropy required to stabilize a committed record, and therefore represents the normalized irreversibility drive — how strongly the system is pushing toward irreversible commitment relative to the threshold that commitment requires. The $I(S:E)/A_{min}$ identification is a refinement available — and exact — in the regime where $\Delta S_E = I(S:E)$, which is the regime of all models treated in this paper. Equation (1a) below should be understood as applying in this regime; in more general settings, the operative form is Equation (1) with $\Phi = \Delta S_E/A_{min}$.

The **commitment barrier** Φ_c is the minimum value of Φ required for the commitment condition to be jointly satisfied — it is set by the structural necessities A1 and A2: specifically, by the minimum information cost ($\sim k_B \ln 2$ per bit from Landauer, via A2) and the minimum distinguishability granularity (δ_{min} from A1). Φ_c is context-dependent: it depends on the environmental coupling geometry and the local BCB capacity structure. Its derivation from first principles within the VERSF substrate is identified as priority work; what is established here is its role as the threshold below which commitment is suppressed. With the general identification $\Phi = \Delta S_E/A_{min}$, the condition $\Phi \geq \Phi_c = 1$ is equivalent to $A(\rho_{SE}) \geq A_{min}$ exactly; with the regime-restricted identification $\Phi = I(S:E)/A_{min}$, this equivalence holds in the uncorrelated-unitary regime only.

The ratio Φ_c/Φ is therefore a dimensionless control parameter: when $\Phi_c/\Phi \gg 1$, the system is far below threshold and commitment is strongly suppressed; when $\Phi_c/\Phi \to 0$, the system is well above threshold and commitment proceeds at the full TPB rate.

The **fact production rate** is then proposed as:

$$\Gamma_{fact} = R_{TPB} \exp(-\Phi_c/\Phi) \left(1 - \frac{N(\tau)}{N_{BCB}}\right)$$

Equation (1) — The Fact Production Rate Law (proposed)

Equation (1) is written in terms of the dimensionless control ratio Φ_c/Φ; any dimensional realisation of Φ must reduce to this ratio after normalisation by the relevant local commitment scale. Barrier-crossing processes in statistical physics generically exhibit Arrhenius-type suppression: the probability that a fluctuation crosses a barrier of height ΔF scales as $\exp(-\Delta F/k_BT)$. The present framework treats commitment as a threshold-crossing event in informational configuration space, where Φ_c/Φ plays the role of the dimensionless barrier height. The specific exponential form $\exp(-\Phi_c/\Phi)$ is chosen over alternatives — Gaussian activation $\exp(-(\Phi_c - \Phi)^2/\sigma^2)$ or power-law suppression $(\Phi/\Phi_c)^n$ — for three reasons: (i) it recovers the Heaviside threshold in the sharp-barrier limit $\Phi_c/\Phi \to \infty$, which no finite-order polynomial or Gaussian does cleanly; (ii) it is the universal form for thermally activated rate processes under Kramers theory and therefore connects the framework to the widest class of existing physical models; and (iii) it makes the specific prediction that at threshold ($\Phi = \Phi_c$), the rate is suppressed by exactly $e^{-1} \approx 0.37$ relative to the attempt rate R_{TPB} — a specific quantitative prediction about the crossover shape that distinguishes this form from alternatives and is, in principle, testable once Φ_c can be computed independently. This last point is not a mere convenience: it is a physical commitment about the crossover profile that a derived Φ_c could confirm or rule out. The exponential form is therefore adopted as the most physically motivated choice, with the acknowledgment that a derivation from the BCB/TPB substrate could in principle select a different functional form. The sharp Heaviside thresholds of Section 5.4 are recovered as the infinite-barrier limit.

The information-theoretic form. Substituting the identification $\Phi = I(S:E)/A_{min}$ into Equation (1) yields an equivalent form expressed entirely in information-theoretic quantities already defined in this framework:

$$\Gamma_{fact} = R_{TPB} \exp\left(-\frac{A_{min}}{I(S:E)}\right)\left(1 - \frac{N(\tau)}{N_{BCB}}\right)$$

Equation (1a) — Information-Theoretic Form (valid in the regime $\Delta S_E = I(S:E)$, i.e. uncorrelated initial states with unitary evolution; general form uses $\Phi = \Delta S_E/A_{min}$)

In this form the barrier factor $\exp(-A_{min}/I(S:E))$ has a transparent interpretation: it is suppressed when the mutual information exported to the environment is small relative to the minimum irreversible information required for commitment, and approaches 1 when the exported correlation greatly exceeds the threshold. The equation then states that the rate of fact production is determined by three quantities — the maximum throughput R_{TPB}, the ratio between the commitment cost and the actual correlation exported, and the remaining BCB capacity — all of which are definable within the VERSF information-theoretic architecture. The tighter nucleation correspondence also becomes clear:

Nucleation theory	VERSF
Free-energy barrier ΔF^*	Minimum irreversible information A_{min}
Supersaturation (driving force)	Mutual information $I(S:E)$
Thermal fluctuation energy k_BT	Commitment threshold A_{min}
Attempt rate	R_{TPB} (TPB tick rate)

For contexts outside the uncorrelated-unitary regime, Equation (1) with $\Phi = \Delta S_E/A_{min}$ is the operative form, maintaining consistency with the amplification condition $A(\rho_{SE}) = \Delta S_E \geq A_{min}$ throughout. Equation (1a) is the preferred form in the regime where the two coincide, and applies to all worked examples in this paper.

Table 1 — Anatomy of the Fact Production Rate Law

Factor	Meaning	Physical connection
$R_{TPB} \leq 2E/\pi\hbar$	Attempt rate: maximum commitment throughput	Quantum speed limits (Margolus–Levitin)
$\exp(-\Phi_c/\Phi) = \exp(-A_{min}/I(S:E))$	Barrier factor: suppression below commitment threshold	Mutual information exported; Entanglement Ledger; Arrhenius barrier-crossing

Factor	Meaning	Physical connection
$1 - N(\tau)/N_{BCB}$	Capacity factor: production suppressed as substrate approaches saturation	Entropy, holographic bounds, BCB

This table is the single most compact summary of the dynamics of Equation (1). Each factor has an independent physical origin — quantum speed limits, causal amplification, and substrate capacity — and each corresponds to a distinct failure mode for commitment: too little distinguishability, too little amplification, or too little capacity remaining.

Reading the equation. When $\Phi \ll \Phi_c$, the exponential suppresses fact production strongly — distinctions fluctuate in the Void without committing. As $\Phi \to \Phi_c$, the exponential approaches $e^{-1} \approx 0.37$ and significant fact production begins. When $\Phi \gg \Phi_c$ (strong coupling, high energy, well-designed measurement apparatus), the exponential approaches 1 and fact production is limited only by the capacity factor.

The capacity factor $(1 - N(\tau)/N_{BCB})$ follows logistic growth dynamics. As BCB saturation is approached, production slows to zero regardless of the driving force.

The energy landscape picture. The commitment process can be visualized as a distinction moving through a potential landscape:

```
Distinguishability driving force Φ
        |
        |             *
        |           *   *
        |         *       *  ← commitment barrier Φ_c
        |_______*___________*___________
                                     → committed
          below barrier:          above barrier:
          reversible fluctuation   nucleation → physical fact
```

Below the barrier: the distinction fluctuates within the Void and remains reversible. Above the barrier: the distinction amplifies into environmental degrees of freedom, the Entanglement Ledger increments, capacity is allocated, and a committed fact nucleates.

Connection to VERSF time. Since τ counts committed records, the rate of temporal progression is:

$$\frac{d\tau}{dt} = \Gamma_{fact} = R_{TPB} \exp\left(-\Phi_c/\Phi\right) \left(1 - \frac{N(\tau)}{N_{BCB}}\right)$$

The flow of time equals the rate of fact nucleation. Time advances rapidly when distinctions are strongly driven and capacity is available; it slows when driving forces are weak or when the committed record structure approaches saturation.

The spacetime-local form. Since driving force, capacity, and commitment rate all vary across spacetime, Equation (1) generalizes to a local rate density:

$$\Gamma\_fact(x,t) = R\_TPB \exp(-(\Phi\_c)/(\Phi(x,t)))\ (1 - (\rho\_fact(x,t))/(\rho\_max))$$

where $\Phi(x,t)$ is the local distinguishability driving force, $\rho\_fact(x,t)$ is the local committed record density, and $\rho\_max = \delta\_min^{-d}$ is the maximum stabilizable distinction density, with d the effective spatial dimensionality of the emergent geometry. The local form makes explicit that fact production — and therefore the local flow of time — is spatially and temporally variable, governed by the physical conditions at each point in the universe.

Covariant formulation (candidate). The local rate form above retains a frame-dependent element: $R\_TPB = 2E\_avail/\pi\hbar$ involves E_avail, the zeroth component of a 4-vector, which transforms as energy under boosts rather than as a scalar. A more relativistically natural formulation is achieved by recasting the entire equation as a density of commitment events per unit spacetime four-volume. The expected number of commitment events in a spacetime volume element is:

$$dN\_fact = \Gamma\_fact(x) \sqrt{(-g)}\ d^4x$$

where $\sqrt{-g}\, d^4x$ is the covariant volume element. This is the same structure as vacuum decay / bubble nucleation in relativistic cosmology, where bubble formation is described by a nucleation density per four-volume rather than a preferred-time rate. The fundamental object is not events per second but events per spacetime volume — a scalar density that different observers integrate differently along their worldlines. A candidate covariant generalization is:

$$\Gamma\_fact(x) = \alpha\ (T\_\mu\nu\ u\mu\ u\nu)/(\hbar) \exp(-\Phi\_c(x)/\Phi(x))\ (1 - (\rho\_fact(x))/(\rho\_max(x)))$$

Equation (1b) — Candidate Covariant Commitment Density (proposed)

where $T\_\mu\nu$ is the local stress-energy tensor, $u\char`^\mu$ is the effective 4-velocity field of the commitment-supporting substrate — the physical medium whose energy density drives commitment attempts — and α is a dimension-fixing coefficient that absorbs the BCB energy-density scale ρ_* (made explicit in the Step 3 derivation of Section 10 as α_dimless / ρ_*). The quantity T_μν u^μ u^ν is the local rest-frame energy density of this substrate — a Lorentz scalar that replaces the frame-dependent R_TPB. An ambiguity should be named explicitly: T_μν u^μ u^ν requires specifying *whose* u^μ appears — that of the quantum system undergoing commitment, the measurement apparatus, or some effective coarse-grained field representing the BCB substrate. In a full substrate derivation, u^μ is expected to correspond to the coarse-grained four-velocity of the BCB commitment-supporting medium rather than that of individual particles or detectors — analogous to how the fluid four-velocity in relativistic hydrodynamics is a coarse-grained field, not the velocity of any single constituent. In vacuum decay, the analogue quantity is the false-vacuum energy density, which has a clear identification; the VERSF analogue requires an equivalent specification of the commitment-supporting medium, which is part of the derivation left outstanding. Equation (1b) is a candidate rather than a derivation: whether T_μν u^μ u^ν correctly captures the BCB/TPB attempt-rate structure at the covariant level requires that derivation from the underlying architecture. What Equation (1b) establishes is that a covariant form of the right mathematical type exists and is expressible in standard geometric language.

This formulation makes the analogy with relativistic nucleation theory exact in structure rather than merely metaphorical:

Relativistic vacuum decay	VERSF fact production
Bubble nucleation in metastable vacuum	Fact nucleation in reversible substrate
$dP = \Gamma_{vac} \sqrt{-g}\, d^4x$	$dN_{fact} = \Gamma_{fact} \sqrt{-g}\, d^4x$
Bounce action barrier	Commitment barrier Φ_c
Local vacuum energy conditions	Local $T_{\mu\nu} u^\mu u^\nu / \hbar$ attempt density
Bubble count defines phase transition history	Commitment count defines fact history

The shared mathematical form is not a coincidence of notation: both describe the nucleation of irreversible structures from a reversible substrate, governed by a local energy condition and a barrier suppression factor. The VERSF framework is the quantum informational analogue of vacuum decay, with commitment events playing the role of bubble nucleation and the reversible Void substrate playing the role of the metastable false vacuum.

Unification. In a single framework, Equations (1) and (1b) link six phenomena that are standardly treated separately. Note that Equation (1b) is a candidate template rather than a completed equation — the u^μ ambiguity means it is not yet fully specified — and its entries in the table should be read accordingly:

Phenomenon	Role in the framework
Quantum measurement	Barrier factor: outcome requires Φ to exceed Φ_c
Decoherence	Amplification drives Φ upward toward Φ_c
Entropy and holographic bounds	Capacity factor: BCB saturation suppresses production
Quantum speed limits	R_{TPB} ceiling from Margolus–Levitin (Eq. 1); $T_{\mu\nu} u^\mu u^\nu/\hbar$ in covariant template (Eq. 1b, pending u^μ specification)
Flow of time	$d\tau/dt = \Gamma_{fact}$ (coordinate form); $\tau = \int \Gamma_{fact} \sqrt{-g}\, d^4x$ along worldline (covariant form, pending derivation)
Relativistic nucleation	$dN_{fact} = \Gamma_{fact} \sqrt{-g}\, d^4x$ shares mathematical structure with vacuum decay (structural parallel; not yet a derivation)

5.7 Scaling of the Commitment Barrier with Environmental Redundancy

Although Φ_c has not been derived from first principles, the structure of Equation (1) is not unconstrained. The commitment barrier must vary between physical systems in a predictable way, and this variation is the source of the theory's structural predictive content — independently of the normalisation issue in §6.5.

The two-state model of Section 6 implements a single-mode coupling for clarity. The scaling argument developed here considers the extension of that model to N independent environmental modes each acquiring entropy from the interaction. The additivity $A = N S(\rho_E)$ holds exactly only in the regime where the environmental modes are independently and identically coupled to the system. In realistic environments the modes may share correlations through their common interaction with the system, so the scaling derived here should be understood as the independent-mode limit of the framework rather than a universal result.

In this limit, when the system state propagates into N independent environmental degrees of freedom, the total amplification measure becomes the sum of contributions from each mode. For N uncorrelated modes each acquiring entropy $S(\rho_E)$ from the coupling:

$$\mathbf{\Phi = (N S(\rho_E))/(A_{min})}$$

The commitment condition $\Phi \geq \Phi_c$ then requires:

$$\mathbf{\Phi_c \leq (N S(\rho_E))/(A_{min})}$$

In the limit where the per-mode coupling strength is held fixed and the modes couple independently, consistency of Equation (1) requires the effective barrier to scale as $\Phi_c(N) \sim 1/N$. This scaling holds specifically in the regime where environmental modes couple independently with comparable strength; more general coupling geometries — correlated modes, hierarchical coupling, or non-uniform coupling strengths — may produce different N-dependence. The 1/N scaling is therefore a regime-specific consistency requirement rather than a universal result:

$$\mathbf{\Phi_c(N) \sim 1/N}$$

This scaling is consistent with the characterisation of Φ_c in Section 5.6: the minimum irreversible information required for commitment is fixed by A1 and A2, but the effective driving force available to overcome this cost grows with the number of independently amplifying environmental modes. As N increases, the commitment barrier decreases and fact production is easier. The physical content is concrete: a microscopic system coupling to a single environmental mode faces a high barrier $\Phi_c \sim 1$; a macroscopic measurement apparatus coupling to $N \sim 10^{23}$ environmental modes faces a barrier $\Phi_c \sim 10^{-23}$, effectively zero. The rate law therefore predicts, without a full derivation of Φ_c from BCB/TPB parameters, that macroscopic measurement apparatuses commit facts at rates close to R_{TPB} while microscopic systems commit facts only when coupling is strong enough to drive Φ above the single-mode threshold.

This is what we observe. The scaling $\Phi_c(N) \sim 1/N$ is a structural consistency requirement of the rate law — not a derivation of Φ_c from first principles, but a constraint that Equation (1) must satisfy to remain consistent with the amplification condition as N varies. Its significance is that the rate law has non-trivial variation with physical parameters in a direction consistent with observation; the mechanism — environmental redundancy lowering the commitment barrier — is physically transparent. A second worked model varying N would confirm this consistency; its absence is noted as a limitation.

6. A Worked Model: Two-State System with Environmental Coupling

To anchor the commitment condition in calculable structure, we work through a stylized model of a two-state quantum system S undergoing environmental coupling.

6.1 Setup

Let the system S have Hilbert space $\mathscr{H}\_S = \mathbb{C}^2$, with orthonormal basis $\{|0\rangle, |1\rangle\}$ representing two distinguishable states. Let the environment E have Hilbert space $\mathscr{H}\_E$ with N modes, initially in state $|e\_0\rangle$; in this model only one environmental mode participates actively in the coupling, implementing the single-mode case N = 1 (the N-mode extension, in which all modes couple independently, is the subject of §5.7). In the N-mode extension, the coupling replaces the single environmental pointer state with N independently imprinted modes: each mode independently records which branch the system is in, so that environmental amplification grows with N; the single-mode model here implements this structure with N = 1. The initial state of the combined system is:

$$|\Psi_0\rangle = (\alpha|0\rangle + \beta|1\rangle) \otimes |e_0\rangle$$

with $|\alpha|^2 + |\beta|^2 = 1$.

The system-environment interaction is modeled by a controlled unitary:

$$U: |i\rangle\_S \otimes |e_0\rangle\_E \mapsto |i\rangle\_S \otimes |e_i\rangle\_E$$

where $\{|e\_0\rangle, |e\_1\rangle\}$ are orthonormal environmental pointer states. After interaction:

$$|\Psi_1\rangle = \alpha|0\rangle|e_0\rangle + \beta|1\rangle|e_1\rangle$$

6.2 Checking the Commitment Conditions

Condition 1 — Distinguishability threshold.
The trace distance between the two branches of the system is:

$$D = 1/2\| |0\rangle\langle 0| - |1\rangle\langle 1| \|_1 = 1$$

which clearly exceeds δ_min for any reasonable $\delta\_min < 1$. Condition 1 is satisfied provided the state preparation produces outcomes sufficiently separated in the distinguishability measure.

Condition 2 — Environmental amplification.
Before interaction, the environmental state is pure: $S(\rho\_E^{(0)}) = 0$. After the controlled unitary, tracing over S:

$$\rho\_E = |\alpha|^2\ |e_0\rangle\langle e_0| + |\beta|^2\ |e_1\rangle\langle e_1|$$

The amplification measure is:

$$A = S(\rho\_E) = -|\alpha|^2 \log|\alpha|^2 - |\beta|^2 \log|\beta|^2 \geq 0$$

$A = 0$ when $|\alpha| = 1$ or $|\beta| = 1$ (system already in an eigenstate — no superposition to commit). A is maximized at $A = \ln 2$ (one bit) when $|\alpha|^2 = |\beta|^2 = 1/2$. The Entanglement Ledger increments by $\Delta L = A$.

The amplification condition requires $A \geq A\_min = k\_B \ln 2$. Note that A depends continuously on $|\alpha|^2$ and $|\beta|^2$, reaching ln 2 only at the balanced case. For the purposes of this schematic model, we treat A_min illustratively as the minimum amplification required for a one-bit commitment; a precise treatment would specify A_min as a function of the environmental coupling geometry rather than a universal threshold. With this caveat, the condition $A \geq A\_min$ is satisfied whenever both $|\alpha|^2$ and $|\beta|^2$ are sufficiently nonzero — i.e., whenever there is a genuine superposition to resolve. A system already in an eigenstate produces $A = 0$ and requires no commitment to produce a definite outcome; the outcome is already determined.

After the controlled unitary, the pointer states $|e\_0\rangle$ and $|e\_1\rangle$ are orthogonal by construction, representing correlation export into distinguishable environmental configurations. By the causal boundedness argument, once $|e\_0\rangle$ and $|e\_1\rangle$ have propagated across the environmental degrees of freedom beyond $J^-(P)$, no locally admissible operation can reverse the correlation structure. Condition 2 is satisfied.

Condition 3 — Capacity allocation.
The new committed record requires one unit of BCB capacity. If $N(\tau) < N\_BCB$, capacity is available and $C > 0$. Condition 3 is satisfied in the generic case.

6.3 The Commitment Event

All three conditions being satisfied, a commitment event occurs. The committed record is the stable distinction between outcomes $|0\rangle$ and $|1\rangle$, encoded in the environmental pointer states. VERSF time increments by $\Delta\tau = 1$. BCB capacity decrements by $\Delta N = 1$.

The system's reduced density matrix, post-commitment, is diagonal in the pointer basis:

$$\rho\_S\hat{\ }committed = |\alpha|^2\ |0\rangle\langle 0| + |\beta|^2\ |1\rangle\langle 1|$$

The off-diagonal terms have vanished — not because a collapse postulate was applied, but because the coherences are now encoded in the Entanglement Ledger, causally inaccessible to any local observer. This outcome is structurally identical to what standard decoherence theory gives: the reduced density matrix of the system becomes diagonal in the pointer basis after tracing over the environment. The VERSF account does not claim novelty here over Zurek's einselection (discussed further in Section 11); the commitment framework adds the threshold condition specifying *when* this diagonalization constitutes an irreversible fact, not a new mechanism for producing it.

6.4 Interpretation

This model makes explicit what the abstract commitment condition achieves. Within the present framework, the appearance of a definite outcome does not require a new physical postulate. The model proposes it requires: (a) a resolvable distinction, (b) propagation of that distinction into environmental degrees of freedom beyond local reversal, and (c) available substrate capacity for the resulting record. When these are satisfied, the commitment follows from the framework's structural architecture. The probabilities $|\alpha|^2$ and $|\beta|^2$ determine which outcome is recorded — a matter for the companion quantum foundations papers — but the *existence* of a definite outcome is, within this account, a consequence of commitment dynamics alone.

6.5 A Natural Normalisation for the Two-State Model

The two-state model permits an explicit identification of Φ that makes Equation (1) numerically tractable for this case. This is not a computation of Φ_c from substrate physics — that derivation remains outstanding — but a choice of natural normalisation that makes the threshold condition explicit and Φ calculable from the state amplitudes.

Define the local distinguishability driving force in terms of the amplification measure:

$$\mathbf{\Phi = (A)/(A_{min}) = (A)/(k_B \ln 2)}$$

where $A = S(\rho_E) = -|\alpha|^2 \log|\alpha|^2 - |\beta|^2 \log|\beta|^2$ is the environmental entropy increase after interaction. By this definition Φ is dimensionless, $\Phi \geq 0$, and $\Phi = 1$ precisely when $A = A_{min}$ — i.e., when the amplification condition is exactly at threshold.

Importantly, because the initial state is uncorrelated ($\rho_{SE} = \rho_S \otimes \rho_E$) and the coupling is unitary, Section 5.2 establishes that $\Delta S_E = I(S:E)$ exactly. Therefore $A = I(S:E)$ in this model, and the identification $\Phi = A/A_{min}$ is the same as $\Phi = I(S:E)/A_{min}$ from Equation (1a) — exactly, not as an approximation. The two-state model therefore implements the information-theoretic form of Section 5.6 without further assumption.

The commitment condition $A \geq A_{min}$ is then equivalent to $\Phi \geq 1$. This identifies:

$$\mathbf{\Phi_c = 1}$$

in this normalisation. To be precise: $\Phi_c = 1$ is not derived from BCB/TPB substrate parameters the way nucleation theory derives ΔF^* from surface tension and supersaturation — it is the value Φ_c must take *by construction* when Φ is defined as $I(S:E)/A_{min}$. The physical content is not in the value $\Phi_c = 1$ but in the fact that $\Phi = I(S:E)/A_{min}$ is a computable, state-dependent quantity.

With this normalisation, Equation (1a) becomes:

$\Gamma\_fact = R\_TPB \exp(-(A\_min)/(I(S:E))) (1 - (N(\tau))/(N\_BCB))$

The commitment rate increases monotonically with the mutual information exported by the system–environment interaction: as the superposition becomes more balanced ($|\alpha|^2 \to 1/2$, $|\beta|^2 \to 1/2$), I(S:E) → A_min and Φ → 1, so $e^{-1/\Phi} \to e^{-1} \approx 0.37$. As the superposition becomes more unequal ($|\alpha|^2 \to 0$ or 1), I(S:E) → 0 and Φ → 0, so $e^{-1/\Phi} \to 0$ and commitment is strongly suppressed. This is physically correct: a system already near an eigenstate produces negligible correlation with the environment and commits rarely.

The generalisation to arbitrary physical systems requires identifying I(S:E) and A_min in the local environmental context, and ultimately computing Φ_c from the BCB/TPB substrate parameters rather than defining it by convention — the outstanding work identified in Section 15.

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7. Near-Commitment Dynamics and the Commitment Boundary

Not every reversible distinction reaches the commitment threshold. Understanding what happens to distinctions that approach but fail to satisfy the commitment condition is essential for a complete theory of fact production.

7.1 The Commitment Boundary

The commitment boundary is the structural interface at which reversible distinctions transition into committed records. It is not a spatial surface but a condition boundary in the space of physical configurations: a transition occurs when all three components of $\mathcal{C}\_commit$ simultaneously evaluate to 1.

Geometrically, the commitment boundary can be represented as a surface in the (D, A, C) parameter space, separating the region $\{D \geq \delta\_min, A \geq A\_min, C > 0\}$ from its complement. Reversible dynamics move a distinction through this space. A commitment event occurs when the trajectory crosses the boundary into the commitment region and the resulting state is stabilized.

The fold structure of the VERSF programme — the detailed geometry and dynamics of this boundary — is developed in dedicated companion papers. At the architectural level of the present paper, three properties of the boundary are relevant:

1. **It is not sharp in coordinate time.** The amplification condition in particular develops over a timescale governed by the system-environment coupling strength and the structure of the environmental modes. The commitment boundary has a characteristic crossing timescale τ_cross that depends on the physical system.

2. **It is one-directional.** A distinction that has fully crossed the commitment boundary — satisfying all three conditions with A >> A_min — cannot return to the Void without thermodynamic cost. The causal irreversibility of the exported correlations (A2) ensures this. A distinction in the process of crossing, however, may retreat if the amplification condition is not fully satisfied.
3. **It is capacity-dependent.** As N(τ) → N_BCB, the commitment boundary effectively recedes: fewer distinctions can commit because Condition 3 fails. In high-saturation regimes, even distinctions that satisfy Conditions 1 and 2 may fail to commit because no capacity is available.

7.2 Near-Commitments

A near-commitment is a reversible distinction that satisfies Conditions 1 and 2 but fails Condition 3, or that satisfies Condition 1 but has not yet reached the amplification threshold.

Near-commitments have several important properties:

They produce entropy without producing facts. When Conditions 1 and 2 are satisfied but Condition 3 fails, correlation is exported into the environment (Entanglement Ledger increments) but no committed record forms. This corresponds to thermalization: the distinction is absorbed into the diffuse thermal background rather than forming a sharp factual record.

They may dephase into the Void. When Condition 1 is satisfied but Condition 2 has not yet been met, the distinction remains in the reversible substrate. If the environmental coupling is weak, the distinction may persist as a coherent superposition for an extended period. If the coupling is insufficient to drive A above A_min before decoherence disperses the superposition, the near-commitment fails and the distinction returns to undifferentiated Void dynamics. This is consistent with the unitarity of Void dynamics established in Section 3: dephasing into the Void refers specifically to cases where environmental coupling is too weak to bring A to A_min — the correlation that would be exported remains sub-threshold and the distinction returns to reversible superposition dynamics without completing an irreversible export. It is the incompleteness of the export that keeps the process within $\mathcal{V}$; any export that does satisfy A ≥ A_min constitutes an irreversible commitment and exits the Void.

They set the decoherence timescale. The rate at which near-commitments either cross the threshold or retreat determines the characteristic decoherence timescale of a system. Systems with strong environmental coupling cross quickly; systems in isolation can sustain near-commitments indefinitely. This connects commitment dynamics to observable quantum coherence times.

---

8. Capacity Constraints on Fact Production

Fact production occurs within a finite distinguishability substrate governed by the Bit Conservation and Balance (BCB) principle.

Let $N(\tau)$ denote the number of committed records at VERSF time τ. The BCB constraint is:

$$N(\tau) \leq N_{BCB}$$

where N_{BCB} is the effective distinguishability capacity of the relevant physical region, defined in the architecture companion paper as the maximum number of simultaneously stabilizable bit-conserving distinctions within the BCB structure of that region. This is a finite positive integer by A3. For orientation, motivated by holographic entropy bounds, one expects N_{BCB} to scale as a quantity of order $A/(4\ell_P^2)$ for a region with bounding area A, though the precise relationship between the BCB definition and the Bekenstein-Hawking area law is not established here — the architecture companion provides the operative definition, and the holographic scaling is cited as a plausible upper bound rather than a derivation.

The dynamics of record formation and dispersal obey:

$$dN(\tau)/d\tau = \Gamma_{form} - \Gamma_{disperse}$$

where Γ_{form} is the rate at which reversible distinctions satisfy the commitment condition and produce new records, and $\Gamma_{disperse}$ is the rate at which existing records become thermodynamically unresolvable and release capacity back into the Void substrate.

Several consequences follow:

Entropy is the cost of record maintenance. Maintaining a committed record requires ongoing thermodynamic expenditure — at minimum $k_BT \ln 2$ per bit per thermal relaxation time (Landauer's principle). Entropy production within the BCB framework therefore measures the ongoing cost of sustaining the committed record structure of the universe against thermal dispersal.

Capacity saturation drives dispersal. As $N(\tau) \to N_{BCB}$, the formation rate is suppressed (Condition 3 fails increasingly often) and the dispersal rate may increase as the thermodynamic cost of maintaining existing records becomes difficult to meet. This generates a natural equilibrium dynamic: in statistical equilibrium, $\Gamma_{form} = \Gamma_{disperse}$ and $N(\tau)$ is stationary.

The second law is a BCB consequence. Within the BCB framework, the statistical tendency of entropy to increase is a combinatorial consequence of finite capacity: states that disperse commitments and restore usable capacity vastly outnumber states that concentrate commitments. The second law is not an independent postulate but a reflection of the combinatorics of the BCB capacity structure.

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9. Rate of Fact Production and Admissibility

9.1 Commitment Rate

Fact production occurs at a finite rate bounded by the Ticks Per Bit (TPB) structure of the framework.

Let R(t) denote the total commitment rate in coordinate time. Then:

$$d\tau/dt = R(t)$$

Quantum speed limits impose an upper bound via the Margolus-Levitin theorem:

$$R(t) \leq (2E_{avail})/(\pi\hbar)$$

where E_{avail} is the available free energy of the system. Normalizing by BCB capacity gives the commitment rate per unit capacity:

$$R_{TPB} \equiv (R)/(N_{BCB}) \leq (2E_{avail})/(\pi\hbar\, N_{BCB})$$

This bound is saturated in maximally entropic systems (black holes, thermal equilibria at high temperature) and far below saturation in low-entropy ordered systems.

9.2 Admissibility Constraints

Not every reversible process that satisfies the commitment condition in the dynamical sense produces an admissible committed record. A commitment map $\mathcal{T}$ must also satisfy structural constraints that ensure the resulting committed record is consistent with the physical law structure:

- **(C1) Conservation**: all relevant conserved quantities are preserved across the commitment.
- **(C2) Causal consistency**: the commitment does not generate closed causal loops in the committed record structure.
- **(C3) BCB compatibility**: the resulting state satisfies $N(\tau) \leq N_{BCB}$.
- **(C4) TPB compatibility**: the commitment rate satisfies $R \leq R_{TPB}^{max} \cdot N_{BCB}$.

Physical law, in the VERSF interpretation, is the admissibility structure: the set of constraints any commitment must satisfy to become a stable physical fact. The Hamiltonian of a physical system encodes the dynamically permitted transition structure at the quantum level, subject to admissibility. The interaction Hamiltonian in the two-state model of Section 6, for example, is admissible precisely because it satisfies C1-C4.

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10. Time as Fact Accumulation

Within the VERSF framework, time is not a fundamental dimension of spacetime but an ordering variable defined by commitment events.

Define VERSF time τ as:

$$\tau = \int_0^T d\sigma_{irr}$$

where $d\sigma_{irr}$ is the differential count measure on irreversible commitment events. τ counts the total number of committed records that have formed up to a given stage of the universe's history.

Since each commitment event involves irreversible entropy production by A2, $d\tau$ and dS_{irr} increase together, though they are not proportional quantities — τ is a dimensionless count of committed records while S_{irr} carries units of k_B:

$$d\tau \sim dS_{irr} \geq 0$$

This inequality is not the second law — it is stronger. The second law is a statistical statement about ensembles. The monotonicity of τ is a structural consequence of the definition of commitment: a distinction is committed precisely when it cannot be reversed without thermodynamic cost, and τ counts commitments. τ is monotonically non-decreasing by construction.

Three temporal notions must be distinguished:

Symbol	Meaning
τ	Global dimensionless commitment count (ordering variable)
$\theta(x)$	Local coarse-grained time-depth field (spatially varying)
t	Emergent coordinate/clock time

Only τ is fundamental to the commitment architecture. $\theta(x)$ is a descendant quantity encoding local commitment depth. t is the emergent coordinate time defined by coarse-grained aggregation of local commitment events.

To make the distinction between τ and t concrete: consider two spacetime regions with identical coordinate-time duration Δt but different BCB saturation levels. The region with lower saturation has a higher Γ_{fact} and therefore accumulates more committed records — a larger $\Delta\tau$ — in the same Δt. The τ-count diverges between the two regions even when coordinate time does not, in principle making $\Delta\tau$ observable as a difference in the density of irreversible events per unit coordinate time between high- and low-entropy regions.

Fact production as event density. The notion of a "rate of fact production" can be misleading if taken to presuppose a background time against which events are counted. The more fundamental picture is formalized in Equation (1b) and the derivation path of the proper time limit below: the physical structure is a commitment density field $\chi(x)$ distributed across the spacetime manifold, with VERSF time defined by the worldline integral $\tau_{VERSF}[\gamma] = \int_\gamma \chi(x)\, d\tau_{proper}$. What observers call the "rate" of fact production is their coordinate description of this field, parameterized by their local clocks. This recasts the Lorentz concern into a scalar-density derivation problem: rather than asking whether Γ_{fact} transforms correctly as a rate, the question becomes whether $\chi(x)$ can be defined as a genuine scalar field on spacetime — which requires that all local quantities entering it ($T_{\mu\nu} u^\mu u^\nu$, the barrier factors Φ and Φ_c, and the proper fact density ρ_{fact} and proper capacity density ρ_{max} measured in the local rest frame of the commitment-supporting substrate) are each well-defined spacetime scalars. $T_{\mu\nu} u^\mu u^\nu$ is manifestly scalar once u^μ is fixed. Φ and Φ_c are taken as scalar control parameters by definition. The densities ρ_{fact} and ρ_{max} require specification as proper densities in the substrate rest frame rather than coordinate 3-densities; this is an additional assumption stated here explicitly. Under these specifications, $\chi(x)$ is a scalar, and the worldline integral is covariant regardless of how individual observers slice it. The outstanding work is then precisely identifying each of these scalars from the BCB/TPB substrate. Put simply: time is not what measures change; change is what generates time, and what we call its "rate" is a coordinate description of an underlying commitment density field.

Derivation path: proper time from accumulated commitment density. The correct approach is not to make the coordinate rate Γ_{fact} Lorentz-invariant, but to define VERSF time as a worldline integral of a scalar and show it recovers proper time in the appropriate limit.

Step 1: define the scalar commitment density. Rather than starting from the frame-dependent $d\tau/dt = \Gamma_{fact}$, define a local scalar commitment density $\chi(x)$ encoding the commitment-supporting conditions at each spacetime point. The natural definition, carrying the barrier and capacity structure of Equation (1), is:

$$\chi(x) = \chi_0(x) \exp(-\Phi_c(x)/\Phi(x)) \left(1 - \frac{\rho_{fact}(x)}{\rho_{max}(x)}\right)$$

where $\chi_0(x)$ is a scalar baseline commitment density discussed in Step 3 below.

Step 2: define VERSF time as a worldline integral over proper time. Emergent VERSF time along a timelike worldline γ is:

$$\tau_{VERSF}[\gamma] = \int_\gamma \chi(x)\, d\tau_{proper}$$

This form is parameterization-independent — $d\tau_{proper}$ is the invariant proper time element — and $\chi(x)$ is a scalar, so the integral is covariant. This is the same mathematical structure as proper time in general relativity (a worldline integral of a local scalar), with $\chi(x)$ playing the role of an accumulated-commitment weighting field rather than the metric integrand.

Step 3: derive the scalar baseline from BCB/TPB. The frame-dependent $R_{TPB} = 2E_{avail}/\pi\hbar$ is replaced by a covariant baseline whose form follows from the architecture rather than by stipulation.

In the non-covariant TPB formulation, the maximal commitment-attempt frequency scales as $E_{avail}/\hbar$ — the Margolus–Levitin principle that distinguishable dynamical updates are bounded by available energy divided by $\hbar$. In the covariant setting, the local replacement for E_{avail} is the rest-frame energy density measured by the subsystem whose commitment events are being tracked:

$$\varepsilon(x) \equiv T_{\mu\nu} u^\mu u^\nu$$

This is a scalar once u^μ is fixed by the physical subsystem. BCB then requires that commitments occur relative to a finite localization scale: facts cannot be packed arbitrarily finely, so the commitment attempt rate must be normalized by the characteristic scales of one commitment-supporting BCB cell. In the BCB architecture, distinguishable records must occupy finite localization cells whose degrees of freedom support the storage and propagation of correlations. More precisely, a BCB localization cell represents the minimal spacetime region capable of sustaining a stable distinguishable record — the smallest physical volume within which the three commitment conditions (distinguishability, amplification, and capacity) can be simultaneously satisfied. Such cells therefore carry a characteristic energy density ρ_* and volume V_*, *defining the energy scale* $E_* = \rho_* V_*$ associated with one commitment-supporting region. By the Margolus–Levitin principle, the characteristic commitment timescale of one such cell is $\tau_* \sim \hbar/E_* = \hbar/(\rho_* V_*)$. *The dimensionless loading* $\varepsilon/\rho_* = T_{\mu\nu} u^\mu u^\nu / \rho_*$ measures how strongly the local substrate is driven relative to one BCB cell's commitment capacity; dividing by the substrate timescale τ_* converts this loading into a commitment attempt frequency with units of 1/time. The natural covariant baseline is therefore:

$$\chi_0(x) = \alpha \frac{T_{\mu\nu} u^\mu u^\nu}{\rho_*} \cdot \frac{1}{\tau_*}, \quad \tau_* \sim \frac{\hbar}{\rho_* V_*}$$

where α is a dimensionless constant encoding the detailed BCB cell geometry. This form has unambiguous dimensions: $T_{\mu\nu} u^\mu u^\nu / \rho_*$ is dimensionless (energy density divided by energy density), and $1/\tau_*$ has units of 1/time, so χ_0 has units of 1/time — consistent with $\chi_0\, d\tau_{proper}$ giving a dimensionless commitment count per worldline segment. The $1/\hbar$ factor of earlier versions is recovered as $1/\tau_* \sim \rho_* V_*/\hbar \sim E_*/\hbar$, so the Margolus–Levitin quantum throughput scaling is preserved, but now carried by an explicit BCB substrate scale rather than $\hbar$ alone. This also reconciles the notation with Equation (1b), where α absorbs both ρ_* and τ_* into a single dimension-fixing coefficient. Identifying ρ_* and V_* from the BCB/TPB substrate parameters is the primary outstanding derivation.

Step 4: when κ becomes universal. Define the full local commitment-density factor:

$$\kappa(x) = \alpha \frac{T_{\mu\nu} u^\mu u^\nu}{\rho_*} \cdot \frac{1}{\tau_*} \exp\left(-\Phi_c(x)/\Phi(x)\right) \left(1 - \frac{\rho_{fact}(x)}{\rho_{max}(x)}\right)$$

Then $\tau_{VERSF}[\gamma] = \int_\gamma \kappa(x)\, d\tau_{proper}$. In general $\kappa(x)$ varies across spacetime and between physical subsystems; it is not microscopically universal. A universal κ_0 emerges only after coarse-graining over many commitment events in a regime satisfying all of the following conditions simultaneously:

(i) *Homogeneous substrate loading*: $T_{\mu\nu} u^\mu u^\nu$ is approximately constant across the worldlines under comparison — the coarse-grained background looks like a single effective medium (as in FLRW cosmology or a uniform laboratory environment).

(ii) *High-amplification regime*: $\Phi \gg \Phi_c$ throughout, so $\exp(-\Phi_c/\Phi) \to 1$. If some worldlines pass through near-threshold regions and others do not, the barrier factor is worldline-dependent and no universal κ exists.

(iii) *Low saturation*: $\rho_{fact} \ll \rho_{max}$, so the capacity factor approaches 1. Worldlines through differently saturated regions accumulate different commitment densities.

(iv) *Coarse-graining over many events*: each worldline segment must contain many microscopic commitment events, so that local fluctuations average out and $\kappa(x)$ is replaced by a smooth effective scalar field. This is a law-of-large-numbers condition: the coarse-graining scale L must satisfy $L \gg \ell_*$ where ℓ_* is the characteristic BCB cell length.

(v) *Universal clock coupling*: coarse-grained clock systems must sample the same commitment density field — i.e., the effective coupling to the BCB substrate is the same for all systems being compared. This is the analogue of the GR assumption that all ideal clocks measure the same proper time; in VERSF it requires that coarse-grained systems couple identically to the substrate or that α is universal after coarse-graining.

Under all five conditions, $\kappa(x) \approx \kappa_0$ throughout the region of interest and:

$$\tau_{VERSF}[\gamma] \approx \kappa_0 \int_\gamma d\tau_{proper} = \kappa_0 \, \tau_{proper}[\gamma]$$

Proper time is therefore proposed to arise as the geometric coarse-grained limit of accumulated irreversible fact production. Clocks tick more slowly in regions where local conditions support less commitment per worldline segment — high barrier suppression, high saturation, or lower rest-frame energy density — and the standard GR proper time is the limit in which all such variations are negligible.

The **coordinate rate of temporal progression** is given by the non-covariant form (Equation 1):

$$d\tau/dt = \Gamma_{fact} = R_{TPB} \exp(-\Phi_c/\Phi) \left(1 - \frac{N(\tau)}{N_{BCB}}\right)$$

Equation (1) is used throughout this paper for conceptual clarity and calculability; Equation (1b) is the more fundamental form. The coordinate expression should be read as the parameterization of the underlying four-volume density by a non-relativistic observer's clock — it is not an independent physical law but a derived expression valid where the covariant form reduces to a single time coordinate. All downstream uses of Equation (1) — including the GRW mapping, the decoherence conjecture, and the unification table — inherit this status: they are stated in coordinate form for clarity, and their covariant analogues are given by replacing R_{TPB} with $T_{\mu\nu} u^\mu u^\nu/\hbar$ and rates with four-volume densities. Time passes fastest in regions of high distinguishability driving force and low BCB saturation. Time slows when driving forces weaken, when free energy depletes, or when the committed record structure approaches saturation.

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11. Measurement as Fact Production

Quantum measurement is a measurement-specific realisation of the commitment dynamics defined in Section 4 and requires no new machinery. The four-stage hierarchy (decoherence →

amplification → commitment → outcome selection) maps directly onto the measurement process: Stage 1 is preparation of the superposition; Stage 2 is coupling to the apparatus, initiating amplification; Stage 3 is environmental propagation, driving $A(\rho_{SE})$ toward A_{min}; Stage 4 is commitment when $D \geq \delta_{min}$, $A \geq A_{min}$, and $C > 0$ are simultaneously satisfied — at which point the distinction becomes irreversibly encoded in the environment and a new fact enters the universe's record. There is no collapse postulate: the preferred basis is set by the pointer states of the interaction Hamiltonian (recovering Zurek's einselection result as a consequence of the amplification condition), and the commitment threshold specifies *when* a distinction in that basis becomes an irreversible fact — the condition einselection does not supply.

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12. Fact Production and the Origin of Quantum Probability

The preceding section describes the dynamical conditions under which commitment events occur. A complementary question is how probabilities are assigned to the different possible outcomes when such a commitment takes place.

12.1 The Double Square Rule

A companion derivation within the VERSF programme establishes that the Born probability rule

$$\mathbf{P(A) = |\psi_A|^2}$$

arises uniquely from the geometry of distinguishability in a discrete informational universe, as established in the companion paper on pairwise probability. The key insight of that derivation is that irreversible commitment events do not act on individual reversible trajectories but on **correlation structures between pairs of reversible paths**. Because correlations are inherently pairwise objects, the probability functional governing outcome selection must be bilinear in path contributions. The resulting probability rule is therefore quadratic in amplitudes — yielding the Born rule as the unique admissible probability law consistent with symmetry, normalization, and compositional factorization.

The present framework provides the dynamical complement to that result. The Double Square derivation establishes the *form* of the probability law. The fact-production dynamics developed here determine *when* the irreversible selection process occurs.

12.2 Why Fact Production Operates on Pairwise Correlations

Before developing the commitment-selection mechanism in detail, it is necessary to establish why irreversible fact-production events must act on pairwise path correlations rather than on individual reversible trajectories. This is not an arbitrary structural assumption — it follows from two independent arguments, one geometric and one thermodynamic.

The relational structure of distinguishability. Distinguishability is inherently relational: a state is not distinguishable in isolation but only relative to another state. This is expressed through the distinguishability metric $D(s_i, s_j)$, which measures the informational difference between pairs of states rather than properties of individual states. The same relational structure applies to reversible micro-paths: if two paths P and P' lead to the same macro-outcome A, their distinguishability is determined by the phase difference

$$\Delta\theta = \theta(P) - \theta(P')$$

which is a property of the *relationship* between paths, not of either path individually. Because distinguishability information resides in relations between alternatives, any irreversible selection mechanism that respects the geometry of the state space must act on correlation structures between paths rather than on individual paths.

The thermodynamic structure of measurement. The thermodynamic argument is independent and reaches the same conclusion. Irreversible measurement events involve the destruction of quantum coherences — the off-diagonal terms ρ_{ij} of the density matrix linking pairs of basis states. The thermodynamic cost of measurement, the entropy production associated with the commitment event, is therefore a functional of the set of pairwise correlations ρ_{ij} rather than of individual state amplitudes. Since each coherence element is constructed from pairs of reversible paths,

$$\rho_{ij} \sim \sum_{P\ i,\ P'\ j} e^{i}(\theta(P) - \theta(P'))$$

the entropy cost of commitment is inherently quadratic in path contributions. Consequently, the irreversible selection process associated with fact production must operate on pairwise path correlations. This thermodynamic argument is a direct consequence of the Entanglement Ledger structure: the correlation exported during a commitment event has the bilinear structure of quantum coherences, not the linear structure of individual amplitudes.

The impossibility of individual-path selection. These two arguments are reinforced by a third: selection mechanisms acting on individual paths lead to contradiction. If irreversible events selected individual paths with probabilities depending only on single-trajectory properties,

$$P(A) = \sum_{P}\ R_A\ f(\theta(P))$$

a three-line argument shows this is inadmissible. Under a global phase transformation $\theta(P) \rightarrow \theta(P) + \alpha$ for all paths P, the physical state is unchanged (global phase is unobservable), so P(A) must be invariant under this U(1) transformation. But the sum above transforms as $\Sigma\ f(\theta(P) + \alpha)$, which must equal $\Sigma\ f(\theta(P))$ for all α. That is, f must be a U(1)-invariant function of θ — a function satisfying $f(\theta + \alpha) = f(\theta)$ for all $\alpha \in \mathbb{R}$. A subtlety must be addressed: a function of the modulus $|e^{i\theta}| = 1$ is trivially U(1)-invariant and need not be constant, so the argument requires specifying that f depends on the phase θ itself rather than merely on the modulus of the complex amplitude. The geometric phase θ(P) defined in Section 12.1 is a real-valued phase angle, not a complex amplitude — f is stipulated to be a function of this real phase angle directly. This stipulation is physically motivated: a rule that depends only on $|e^{i\theta}| = 1$ is trivially constant on all paths and cannot produce interference effects; only rules that depend on θ itself — rather than its modulus — can exhibit the phase sensitivity that distinguishes quantum from classical probability. Stipulating $f(\theta)$ rather than $f(|e^{i\theta}|)$ is therefore equivalent to requiring that the selection rule be non-trivially quantum: that it have genuine sensitivity to the phase structure of the paths. Under this stipulation, for a continuous function $f: \mathbb{R} \to \mathbb{R}$ satisfying $f(\theta + \alpha) = f(\theta)$ for all $\alpha \in \mathbb{R}$, the only solutions are constants. (A function like $\cos^2(\theta/2)$ fails this: it is continuous but changes under $\theta \to \theta + \alpha$.) With f constant, the probability reduces to counting paths in R_A, which is classical path counting and destroys interference. Therefore any non-classical individual-path selection rule violates U(1) phase invariance, and any U(1)-invariant individual-path rule reduces to classical probability.

This rules out individual-path selection. The remaining question is whether selection on triple or higher-order correlations could replace pairwise selection. Consider a rule based on triple path correlations: $P(A) = \Sigma_{\{P,Q,R \in R_A\}}\, g(\theta(P), \theta(Q), \theta(R))$. For such a rule to be gauge-invariant under $\theta \to \theta + \alpha$, g must be invariant under simultaneous shift of all three arguments. Any such invariant must depend on phase differences alone. The group of gauge transformations $\theta \to \theta + \alpha$ acts on phase space by simultaneous translation; the minimal gauge-invariant triple correlations factor into products of pairwise phase differences $(\theta(P) - \theta(Q))$, since these are the building blocks invariant under global shift. A triple combination such as $e^{i(\theta(P)-\theta(Q))} + e^{i(\theta(Q)-\theta(R))} + e^{i(\theta(R)-\theta(P))}$ is gauge-invariant but is a sum of pairwise-difference terms, not a genuinely new structure. By the same reasoning, any gauge-invariant n-point function whose minimal invariants factor into pairwise differences implements selection on pairwise correlations rather than a distinct higher-order structure. The full algebraic argument — that the invariant ring is generated by pairwise differences and that higher correlations do not escape this decomposition — is developed in the companion paper on pairwise probability, which establishes the complete basis structure. Pairwise selection therefore emerges as the *minimal and unique admissible mechanism* compatible with interference, compositional stability, and probability normalization.

The physical picture that follows is simple: reversible dynamics generate a network of possible paths through distinguishability space. When a commitment event nucleates, the selection mechanism acts on the correlation structure among reversible paths — because that correlation structure is what distinguishability geometry requires, what thermodynamic cost is a functional of, and what the only admissible non-classical probability rule can be built from.

12.3 Commitment Events as Correlation Selection

Let R_A denote the set of reversible micro-paths leading to macro-outcome A. The companion paper on pairwise probability shows that the probability of selecting outcome A depends on the correlation structure of these paths:

$$\mathbf{P(A) = |\textstyle\sum_{P}\, R_A\, e^{i}\theta(P)|^2}$$

where θ(P) represents the geometric phase accumulated along path P. Within the fact-production framework, the selection of this correlation structure occurs precisely when a commitment event takes place — when a reversible distinction nucleates into a committed record according to the rate law:

$$\Gamma_{fact} = R_{TPB} \exp(-\Phi_c/\Phi) \left(1 - \frac{N(\tau)}{N_{BCB}}\right)$$

The three factors correspond to the three conditions that must be jointly satisfied for any commitment event to occur: the TPB throughput limit governs the maximum rate of irreversible commitments; the commitment barrier determines whether environmental amplification is sufficient to stabilize a distinction; and the capacity constraint ensures that distinguishable record space is available.

12.4 Division of Labour Across the Programme

The complete measurement process decomposes into two stages with distinct theoretical homes:

This paper — Fact Production. Reversible distinctions undergo stochastic nucleation into irreversible commitments at the rate governed by Equation (1). This paper answers: *when does a commitment event occur, and what physical conditions drive it?*

Companion paper on pairwise probability — Outcome Selection. When a commitment event occurs, the outcome follows the quadratic probability law determined by pairwise path correlations. That paper answers: *given that a commitment event has occurred, which outcome becomes the realized fact?*

Admissibility companion — Why this probability structure. A further companion paper argues that alternatives to the quadratic rule — linear, power-law, or otherwise — either reduce to classical probability, violate compositional stability, or fail normalization under reversible evolution. It establishes why this outcome structure is not merely convenient but physically required given A1–A3.

The division is clean and defensible: the present paper supplies the dynamical trigger, the companion paper on pairwise probability supplies the outcome statistics, and the admissibility companion explains why no other statistics are available.

12.5 The Unified Causal Chain

Combining the results across the VERSF programme yields the following causal chain from substrate to measurement statistics:

```
Void substrate
      ↓
reversible distinguishability dynamics
      ↓
commitment events  (fact production — this paper)
      ↓
pairwise correlation selection  (forced by relational geometry +
thermodynamic structure)
      ↓
```

```
Born-rule probabilities  (companion paper on pairwise probability)
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Each arrow is governed, within the present framework, by a structural constraint derived from A1–A3 rather than an independent postulate. The full microphysical derivation connecting these levels remains outstanding work.

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13. A Master Equation for Measurement as Fact Production

Section 12 established *when* commitment events occur (the rate Γ_fact) and *why* they must act on pairwise path correlations (producing Born-rule outcome statistics). This section writes down the combined dynamical equation.

13.1 Reversible Evolution and Stochastic Commitment

Let ρ denote the density operator describing the reversible quantum state of a system prior to measurement. Between commitment events, the system evolves unitarily:

$$d\rho/dt = -i/\hbar[H, \rho]$$

Fact-production dynamics introduce an additional stochastic component. Let {A_i} denote the possible measurement outcomes, with associated projectors {Π_i} on the system Hilbert space. A commitment event selecting outcome i transforms the state according to:

$$\rho \longrightarrow (\Pi_i\, \rho\, \Pi_i)/(\mathrm{Tr}(\Pi_i\, \rho))$$

with probability

$$P_i = \mathrm{Tr}(\Pi_i\, \rho) = |\psi_i|^2$$

which is precisely the quadratic probability law derived from pairwise path-correlation selection in Section 12.

13.2 The Master Equation

Combining reversible evolution with stochastic commitment jumps gives the full measurement master equation:

$$d\rho = -i/\hbar[H,\rho]\, dt + \sum_i ((\Pi_i\, \rho\, \Pi_i)/(\mathrm{Tr}(\Pi_i\, \rho)) - \rho)\, dN_i$$

Equation (2) — The Measurement Master Equation (effective stochastic unraveling)

Equation (2) should be read as an effective stochastic unraveling of the commitment process — not a derivation from the underlying VERSF substrate, but a dynamical equation whose structure is consistent with the fact-production picture and the pairwise probability rule, and which makes the combined dynamics precise enough to compare with existing quantum trajectory theories. The projectors {Π_i} are the pointer-basis projectors of the system Hilbert space: they are determined by the interaction Hamiltonian H_int via einselection (Zurek, 2003), as described in Section 11. Equation (2) does not specify {Π_i} independently — its basis-dependence is explicit, and a full derivation from the VERSF substrate would need to show how H_int selects the pointer basis and therefore determines which commitment projectors appear in the jump term.

where dN_i are stochastic counting processes satisfying:

$$\mathbb{E}[dN_i] = \Gamma\_fact \cdot P_i \, dt = \Gamma\_fact \cdot Tr(\Pi_i \, \rho) \, dt$$

The two terms in Equation (2) have distinct physical roles:

Term	Meaning
−(i/ℏ)[H,ρ] dt	Reversible unitary evolution within the Void
Σ_i (Π_i ρ Π_i / Tr(Π_i ρ) − ρ) dN_i	Stochastic commitment jumps at rate Γ_fact

Between commitment events the system evolves reversibly. When a commitment occurs — when the distinction nucleates across the barrier — the state undergoes a discontinuous projection corresponding to the formation of a physical fact. The Born rule probabilities govern which projection occurs. The commitment rate Γ_fact determines how frequently such events happen.

Normalization note. Standard quantum trajectory theory (Carmichael; Dalibard, Castin, & Mølmer) modifies the between-jump evolution with a non-Hermitian effective Hamiltonian H_eff = H − iℏ/2 Σ_i Γ_i Π_i†Π_i, which ensures that individual trajectory norms are maintained correctly between jumps — the non-Hermitian term exactly compensates the probability removed by jumps that haven't yet occurred. Equation (2) as written uses standard unitary evolution between jumps. The intended interpretation is as an Itô stochastic differential equation where the dN_i are independent Poisson increments; in this calculus Tr(𝔼[ρ]) = 1 is preserved, but individual stochastic realizations may drift from unit trace. Incorporating per-trajectory normalization would require adding the non-Hermitian correction −iℏ/2 Σ_i Γ_fact · Tr(Π_i ρ) · Π_i†Π_i dt to the between-jump evolution — essentially replacing H with H_eff where the effective decay rates are set by Γ_fact · P_i rather than by environmental coupling constants. This correction is not included in Equation (2) because it requires specifying how Γ_fact decomposes per outcome, which depends on the Lindblad-to-VERSF derivation that remains outstanding. Equation (2) is therefore presented as a mean-field-level effective equation; the per-trajectory version is the target of that derivation.

13.3 Relation to Existing Quantum Trajectory Theories

The structure of Equation (2) resembles the quantum jump equations used in open quantum system theory and quantum trajectory approaches. The formal similarity is deliberate but the physical interpretation is fundamentally different.

In standard quantum trajectory theory (Carmichael, Dalibard, Mølmer–Sørensen), stochastic jumps represent the effect of environmental monitoring — photon emissions, detector clicks, or other dissipative interactions. The jump rate is determined by the system-environment coupling strength, and the theory is derived from the Lindblad master equation by unravelling.

In the VERSF commitment framework, the jumps correspond to irreversible fact-production events — the nucleation of a committed record from the reversible Void substrate. The jump rate Γ_{fact} is *not* determined solely by environmental coupling but by the three structural conditions jointly:

$$\Gamma_{fact} = R_{TPB} \exp(-\Phi_c/\Phi) (1 - (N(\tau))/(N_{BCB}))$$

This means the commitment rate depends on distinguishability driving force Φ (which includes environmental coupling), on the commitment barrier Φ_c (which sets the minimum amplification required), and on BCB capacity (which suppresses commitment near saturation). Environmental coupling is one source of Φ but not the only one — the rate structure is richer than standard trajectory theory allows.

The key conceptual difference is that standard trajectory theory treats the jumps as effects of the environment on the system; the VERSF master equation treats the jumps as facts being produced by the universe. The environment is not acting on the system — the system-environment complex is collectively crossing the commitment boundary.

The jump structure is not the novel prediction. It must be acknowledged directly that piecewise-continuous coherence trajectories with discrete jumps are not a VERSF-specific prediction. Standard quantum trajectory theory — the Carmichael, Dalibard, and Mølmer–Sørensen unraveling formalism — already predicts exactly this structure for a single quantum trajectory under continuous monitoring. The smooth exponential decay $\rho_{ij}(t) = \rho_{ij}(0)\, e^{-\gamma t}$ appears only in the Lindblad master equation, which describes the average over an ensemble of trajectories. Any single unraveling already shows piecewise-continuous evolution punctuated by discrete jumps. The VERSF effective unraveling in Equation (2) is structurally identical in this respect, and presenting jump structure as a distinct VERSF prediction would be incorrect.

The genuinely distinct prediction. The novel VERSF prediction is not the jump structure but the rate at which jumps occur. In standard quantum trajectory theory, the jump rate is determined entirely by the system-environment coupling strength γ. In the VERSF framework, the commitment rate is:

$$\Gamma_{fact} = R_{TPB} \exp(-\Phi_c/\Phi) (1 - (N(\tau))/(N_{BCB}))$$

The capacity factor $(1 - N/N_{BCB})$ suppresses the commitment rate in high-entropy environments, independently of the coupling constant γ. This means the waiting-time distribution for commitment events is modified by a term that depends on environmental entropy density but not on coupling strength — a suppression that quantum trajectory theory does not predict and cannot produce. The specific prediction is:

- **Standard quantum trajectory theory**: waiting time T_c for a jump is exponentially distributed with rate γ, independent of environmental entropy density at fixed coupling.
- **VERSF prediction**: T_c is exponentially distributed with rate Γ_{fact}, which includes a capacity suppression $(1 - N/N_{BCB})$ that decreases independently of γ as the environmental entropy density increases.

Whether experimental platforms can cleanly separate $N_{BCB,env}$ from coupling strength is a genuine challenge, discussed in Section 13.3 above. But this capacity-dependent suppression is the testable distinction, not the jump morphology itself.

Comparison to GRW and CSL. The VERSF commitment framework should also be compared to spontaneous collapse models — specifically GRW (Ghirardi, Rimini, & Weber, 1986) and CSL (Continuous Spontaneous Localization; Ghirardi, Pearle, & Rimini, 1990) — which are the most directly relevant alternatives in quantum foundations. GRW introduces a stochastic collapse rate $\lambda \approx 10^{-16}$ s^{-1} per particle as a fundamental parameter not derived from environmental coupling. CSL adds a continuous stochastic driving term correlated with mass density, also parameterized by independent constants. Both share the logical structure of Equation (2): unitary Schrödinger evolution punctuated by stochastic collapses at a rate set by a new parameter.

The VERSF framework differs from GRW and CSL in a structurally important way: the commitment rate Γ_{fact} is not a primitive parameter but is derived from physical quantities — the distinguishability driving force Φ (which encodes environmental coupling), the commitment barrier Φ_c (set by A1 and A2), and the BCB capacity N_{BCB} (set by A3). The VERSF programme therefore proposes to *explain* the collapse rate rather than postulate it. GRW and CSL treat λ as a constant of nature to be measured; the VERSF framework treats the effective collapse rate as a function of the local physical state, environmental entropy density, and substrate capacity. If the BCB/TPB architecture can be shown to reproduce the effective GRW/CSL collapse rates in the appropriate regime, this would constitute a significant derivation of what GRW and CSL take as primitive. That derivation is not completed here — it requires first principles computation of Φ_c, identified as outstanding work in Section 15 — but the structural distinction from GRW/CSL is the paper's most important positioning claim and deserves explicit statement.

Dimensional mapping to GRW. Even without a full derivation, the dimensional structure of the correspondence can be sketched explicitly to show the mapping is coherent. Let V_{BCB} be the spatial volume of a BCB commitment region and n_p the particle number density. The number of particles in one BCB region is $N_p = n_p V_{BCB}$. If commitment events occur per BCB region at rate Γ_{fact}, the per-particle collapse rate is:

$$\lambda_{eff} \sim \frac{\Gamma_{fact}}{N_p} = \frac{\Gamma_{fact}}{n_p V_{BCB}}$$

In the regime where $\Phi \gg \Phi_c$ and the capacity factor is near unity, $\Gamma_{fact} \to R_{TPB}$, giving:

$$\lambda_{eff} \sim \frac{R_{TPB}}{n_p V_{BCB}}$$

The GRW constant $\lambda \approx 10^{-16}$ s^{-1} per particle therefore corresponds, in this mapping, to a specific value of R_TPB/(n_p V_BCB). This is not a derivation — it does not fix V_BCB or R_TPB from first principles — but it shows two things: (i) the dimensional correspondence is clean, and (ii) the GRW collapse rate is not a fundamental constant in this picture but an emergent ratio set by BCB region size and particle density. This scaling should be interpreted with R_TPB held fixed; if the available energy per BCB region varies with V_BCB, the effective dependence of λ_eff on region size may be modified. The programme to derive V_BCB from the BCB/TPB architecture and match the observed GRW rate is the concrete content of the outstanding derivation of Φ_c noted in Section 15.

One non-trivial step in this programme should be flagged: the mapping between VERSF commitment events — which are per-distinction and per-region — and the GRW per-particle collapse rate (which is spatially localized at a random position in space) is not immediate and requires explicit analysis of how BCB regions decompose into per-particle degrees of freedom; this is deferred to future work.

13.4 The Note on Decoherence in Section 14.1

The master equation also sharpens the decoherence conjecture developed in Section 14.1. The standard Caldeira-Leggett result governs the decay of off-diagonal density matrix elements under continuous environmental interaction. The VERSF master equation modifies this in two ways. First, decoherence without commitment — environmental coupling that increases A(ρ_SE) but does not satisfy all three commitment conditions — produces continuous decay of off-diagonal terms without generating discrete fact-production events. Second, once the commitment threshold is crossed, the jump term projects ρ onto a diagonal state, producing an instantaneous complete decoherence of the committed degree of freedom. The VERSF prediction is therefore not simply a modified decoherence rate but a qualitatively different dynamics: continuous partial decoherence punctuated by discrete complete projections at rate Γ_fact. Whether these discrete projection events are distinguishable from continuous Lindblad decay in current experimental regimes is a question the decoherence conjecture of Section 14.1 begins to address.

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14. Implications

14.1 Decoherence *(conjectural phenomenology)*

The material in this section is more speculative than the rest of the paper and should be read as framework-motivated phenomenology rather than derived theory.

Decoherence, within the present framework, is the dynamical process that drives the amplification condition toward satisfaction. It is a necessary but not sufficient condition for commitment: decoherence increases A(ρ_SE), but commitment requires A ≥ A_min, C > 0, and D ≥ δ_min simultaneously.

This reframing has a testable consequence. In standard Caldeira-Leggett environmental decoherence, the decoherence rate scales as $\gamma_{dec} \propto \lambda^2 T$ with no direct dependence on local entropy density at fixed coupling. The VERSF commitment framework predicts a modification: since $N_{BCB,env} \sim S_{local}/k_B$ (the number of distinguishable environmental recording channels scales with local entropy), the per-channel commitment rate is suppressed in high-entropy environments:

$$\boldsymbol{\gamma_{dec} \propto (E_{avail})/(S_{local} \cdot \hbar)}$$

at fixed coupling and temperature, where the proportionality constant depends on the system–environment coupling strength. A quantitative concern must be addressed: for a thermal bath, $S_{local} \sim k_B \ln \Omega(E)$ grows approximately as $k_B \ln(E/E_0)$ at high energy, and if $E_{avail} \sim k_B T$, then $E_{avail}/S_{local} \sim T/\ln(\Omega)$ — differing from the standard Caldeira-Leggett $\gamma_{dec} \propto T$ scaling only logarithmically. In typical experimental regimes $\ln(\Omega)$ varies slowly, so the predicted deviation may be too small to distinguish from standard results without precise control of the bath. The predicted suppression becomes parametrically large in engineered environments where entropy density can be varied independently of temperature and coupling strength — precisely the regime identified in the experimental protocol above. In such a system, the VERSF prediction is an $E_{avail}/(S_{local} \cdot \hbar)$ suppression that is independent of coupling strength, while the Caldeira-Leggett prediction is coupling-dependent but entropy-independent. This is, in principle, a resolvable distinction; without such a protocol the logarithmic difference may be observationally negligible. A significant experimental challenge should also be acknowledged: in most experiments, changing bath entropy density changes the bath itself — its temperature, mode density, or composition — simultaneously changing coupling strength, making the "fixed coupling" qualifier experimentally demanding.

14.2 Entropy

Entropy, in the BCB framework, measures two distinct but related things:

1. **The cost of record maintenance**: the thermodynamic energy required to sustain existing committed records against thermal dispersal.
2. **The dispersal structure of expired records**: the entropy increment produced when an existing committed record disperses and releases its BCB capacity back into the Void.

The second law of thermodynamics emerges as a combinatorial consequence of BCB dynamics rather than as an independent postulate. States that disperse records and restore capacity dominate the accessible state space; entropy therefore increases statistically as the universe evolves toward higher-occupancy BCB configurations.

14.3 The Arrow of Time

The arrow of time, within the commitment framework, has a structural explanation that is stronger than the standard statistical account — and it avoids circularity.

The standard account (Boltzmann) explains temporal asymmetry as a consequence of initial conditions: the universe began in a low-entropy state, and entropy increases because there are more high-entropy states than low-entropy states. This is a probabilistic explanation that applies to ensembles.

The VERSF structural account begins not with τ but with A2. Irreversible correlation export beyond $J^-(P)$ prevents reversal of commitment events by any locally admissible operation. This is a physical fact about causal structure, independent of any definition of time. Therefore the set of committed records can only grow: no locally admissible operation removes a committed record from the universe's history. τ simply counts the members of this monotonically growing set — it is a bookkeeping variable, not the explanation of temporal asymmetry. The explanation is A2; τ is the count of its consequences.

So the argument runs: A2 → irreversible commitment → the set of committed records is monotone → τ, which counts those records, is non-decreasing. The arrow of time is built into the causal structure of commitment itself, not into the definition of τ.

The statistical tendency of entropy to increase is then a separate, downstream consequence of BCB combinatorics. The two accounts are compatible and complementary: the structural account establishes why time has a direction at all; the statistical account establishes why entropy increases along that direction.

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15. Limitations and Outstanding Work

The framework developed in this paper is a theoretical proposal, not a completed derivation. Several important limitations should be stated explicitly.

The relativistic proper time limit is not derived. Section 10 establishes the derivation path and states the conditions under which it closes. VERSF time is defined as $\tau_{VERSF}[\gamma] = \int_\gamma \kappa(x)\, d\tau_{proper}$, *where* $\kappa(x)$ *encodes the local substrate loading, barrier suppression, and capacity suppression. The five universality conditions under which* $\kappa(x) \to \kappa_0$ *are stated in Section 10, Step 4; the proper-time limit is reached only in the coarse-grained regime where all five hold simultaneously. Two ingredients required to evaluate* $\kappa(x)$ *from first principles remain outstanding. First, the characteristic BCB energy-density scale* ρ^* has not been identified from the BCB/TPB substrate architecture; its derivation is equivalent to computing the effective BCB cell volume and is the primary outstanding computation. Second, the 4-velocity u^μ of the commitment-supporting substrate — specifically, whether it is identified with the quantum system, the apparatus, or a coarse-grained BCB medium field — requires the full substrate derivation to specify. Until both are determined, the recovery of proper time is a structural result with a well-defined derivation path rather than a completed calculation.

Equation (1) is not derived from first principles. The fact production rate law is a phenomenologically motivated equation whose nucleation-theoretic form is physically well-grounded, but whose parameters — Φ, Φ_c, and their relationship to the VERSF substrate —

have not been derived from the underlying BCB/TPB architecture. In particular, Φ_c has been characterised structurally (as the minimum driving force satisfying A1 and A2 jointly) but not computed from first principles for any specific physical system. This derivation — the analogue of computing the nucleation barrier from surface tension in classical nucleation theory — is identified as the natural next step in the programme.

Equation (2) is an effective stochastic equation, not a substrate derivation. The measurement master equation is constructed to be consistent with the fact-production picture and the pairwise probability rule, but it is not yet derived from the VERSF substrate by integrating out environmental degrees of freedom. As discussed in Section 13.2, per-trajectory normalization requires a non-Hermitian correction term whose decay rates are set by $\Gamma_{fact} \cdot P_i$ per outcome — a specification that depends on the full Lindblad-to-VERSF derivation. The standard route from a microscopic Hamiltonian to a Lindblad master equation, and from Lindblad to quantum trajectories, has not yet been replicated for the VERSF commitment architecture. A full derivation — including the per-trajectory non-Hermitian correction and the pointer-basis selection from H_{int} — remains outstanding.

The decoherence scaling conjecture is not derived. The prediction that the per-channel commitment rate scales as $\gamma_{dec} \propto E_{avail}/(S_{local} \cdot \hbar)$ at fixed coupling is a framework-motivated conjecture. A derivation would require a full master-equation treatment specifying how $N_{BCB,env}$ depends on local entropy density and how this enters the suppression of commitment rate. This is identified as a key target for experimental contact.

No complete empirical calibration. The framework makes qualitative predictions distinguishable from standard quantum mechanics — continuous Lindblad decoherence punctuated by discrete commitment projections; suppression of commitment in high-entropy environments; capacity saturation effects at cosmological scales — but no quantitative calibration of Φ_c against known experimental parameters has been performed. Such calibration would require identifying a physical system where the commitment rate is independently measurable and comparing the Arrhenius-form prediction of Equation (1) against observed decoherence and measurement timescales.

The geometric phase θ(P) in the pairwise probability framework is used in Section 12 but its connection to the Void substrate geometry has not been established within the VERSF architecture. This connection — relating θ(P) to the information-theoretic geometry of paths through distinguishability space — is deferred to the companion paper on pairwise probability.

These limitations do not undermine the conceptual unity of the framework, but they define the precise boundary between what has been proposed and what remains to be demonstrated.

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16. Conclusion

This paper has developed a structural theory of fact production within the Void Energy–Regulated Space Framework.

The central proposal is that physical reality emerges through a continuous process of commitment events, in which reversible distinctions nucleate across a commitment barrier and become irreversible records. The present framework casts this process in the mathematical language of nucleation theory: the framework proposes that physical facts nucleate when informational distinctions overcome the commitment barrier Φ_c, driven by distinguishability, amplified by environmental coupling, and constrained by finite BCB capacity.

Fact production is governed by three simultaneous dynamical conditions unified in Equation (1), and combined with Born-rule outcome selection in the effective stochastic unraveling of Equation (2). Within this account, time, entropy, the arrow of time, measurement outcomes, and decoherence are each consequences of a single underlying commitment-based architecture — not separate phenomena requiring separate explanations.

The present work does not claim to complete the full microphysical derivation of measurement, but proposes a unified dynamical framework in which fact formation, decoherence, and outcome selection can be treated within a single commitment-based architecture. The framework therefore reframes the emergence of physical reality as a dynamical process of irreversible record formation, governed by informational thresholds rather than by a separate collapse postulate.

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