Quantum Measurement as a Tick Race: Deterministic Outcome Selection via First-Passage Dynamics

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Abstract

We propose that quantum measurement outcomes are determined by a first-passage race between decohered branches. Each branch generates microscopic "ticks" at a rate proportional to its amplitude squared; the branch producing the first threshold-crossing tick—which triggers a macroscopic irreversible "bit"—becomes the observed outcome. This Tick-Bit mechanism yields the Born rule $P = |\psi|^2$ as an exact theorem of first-passage statistics, not as an axiom. The apparent randomness of quantum mechanics emerges from epistemic uncertainty about environmental microstates, while the underlying dynamics remain deterministic.

We ground the tick-rate scaling $\lambda\_A \propto |\psi\_A|^2$ in Fermi's golden rule and a deeper reconstruction of quantum amplitudes from resonance and distinguishability geometry (Resonant Assembly Language), ensuring the derivation is non-circular. The framework provides a physical mechanism for outcome definiteness, resolves the measurement problem without fundamental stochasticity, and makes testable predictions: detectors requiring multiple independent triggers should deviate from Born statistics.

A Note for General Readers

Quantum mechanics has a puzzle at its heart: the theory describes particles existing in "superpositions" of multiple states simultaneously, yet we always observe definite outcomes. How does one possibility win out over the others?

This paper proposes a concrete answer: it is a race. Each possible outcome generates random "ticks"—tiny fluctuations in the detector. Whichever outcome produces the first tick that crosses a threshold wins, triggering an irreversible amplification. The probability of winning turns out to equal exactly $|\psi|^2$, the famous Born rule.

Sections marked **[General Reader]** provide plain-language explanations. You can follow the conceptual story through these sections alone, or engage with the full mathematics.

PART I: THE TICK-BIT MECHANISM

1. The Outcome Selection Problem

1.1 The Puzzle

Quantum mechanics describes systems in superposition:

$|\psi\rangle = \Sigma_A \psi_A |A\rangle$

where ψ_A are complex amplitudes and $|A\rangle$ are possible outcomes. The Born rule states that outcome A occurs with probability:

$P(A) = |\psi_A|^2$

But why? And how does a single definite outcome emerge from the superposition?

[General Reader] Imagine a coin that is somehow "both heads and tails" until you look at it. Quantum mechanics says particles really are like this—existing in multiple states at once. But when we measure, we always see ONE result. How does the universe "choose"? That is the measurement problem, and it has been debated for a century.

1.2 What Decoherence Does—and Does Not—Explain

Decoherence occurs when a quantum system becomes entangled with its environment:

$|\psi\rangle|E_0\rangle \rightarrow \Sigma_A \psi_A |A\rangle|E_A\rangle$

where $\langle E_A|E_B\rangle \approx 0$ for $A \neq B$. The branches become distinguishable and can no longer interfere.

Decoherence explains why we do not observe interference between outcomes. It does *not* explain why we observe one particular outcome. After decoherence, we have multiple branches—but which one becomes "actual"?

[General Reader] Decoherence is like shuffling a deck of cards separately for each possible outcome—now the outcomes cannot "talk to each other" anymore. But it does not explain which card you will draw. That is a separate question.

1.3 Existing Approaches and Their Limitations

Different interpretations handle outcome selection differently:

Copenhagen: Measurement "collapses" the wave function. But what counts as measurement? The boundary between quantum and classical remains undefined.

Many-Worlds: All branches are real; we simply find ourselves in one. But why do we observe outcomes with frequency $|\psi|^2$? The probability measure requires additional postulates.

Bohmian Mechanics: Hidden particle positions determine outcomes. But why should positions be distributed as $|\psi|^2$? This is assumed, not derived.

Objective Collapse (GRW): Spontaneous collapses are fundamental. But why do collapse rates scale as $|\psi|^2$? The rule is postulated.

All approaches either leave the Born rule as an axiom or derive it through assumptions that effectively encode it. The measurement problem persists because no interpretation provides a *mechanism* for outcome selection that derives the Born rule from more fundamental principles.

1.4 Our Proposal: A Physical Race

We propose that outcome selection is a first-passage race between decohered branches:

1. After decoherence, each branch generates microscopic "ticks" at rate λ_A
2. The tick rate scales as $\lambda_A = \kappa|\psi_A|^2$
3. The first branch to produce a threshold-crossing tick triggers a macroscopic irreversible "bit"
4. First-passage statistics then yield $P(A) = |\psi_A|^2$

The Born rule emerges as a theorem, not an axiom.

[General Reader] Think of each possible outcome as a contestant in a race. Each contestant has a "speed" proportional to $|\psi|^2$. They are all racing to be the first to cross a finish line (produce an irreversible event). The faster you are, the more likely you win. When we do the math, the probability of winning equals exactly $|\psi|^2$—the Born rule pops out automatically.

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2. The Tick-Bit Mechanism

2.1 Definitions

Tick: A tick is the smallest microscopic increment of distinguishability in the detector–environment microstate. A tick is not itself irreversible or stable; it is a micro-event that may, if it crosses the metastability threshold, trigger the macroscopic irreversible event known as a Bit. Physical examples include:

- A carrier excitation in a photodiode
- A hotspot nucleation attempt in a superconducting nanowire
- A metastable fluctuation in a pointer mechanism
- A molecular conformational fluctuation in a biological sensor

Bit: A Bit is the smallest macroscopic, thermodynamically irreversible unit of recorded distinguishability—the measurement outcome. In metastable amplifying detectors, the first tick that successfully drives the system over the instability threshold becomes a Bit.

Hazard rate $h\_A(t)$: The instantaneous probability density that branch A produces its first threshold-crossing tick at time t, given no such tick has occurred yet.

2.2 The First-Passage Framework

We model each branch as a point process generating ticks. The key assumptions are:

(A1) Proportional hazards. All branches share the same hazard shape, differing only in scale:

$h\_A(t) = \lambda\_A \cdot h_0(t)$

where $h_0(t)$ is a baseline hazard and λ_A is the branch-specific tick rate.

(A2) Tick rate scales with amplitude squared.

$\lambda\_A = \kappa \cdot |\psi\_A|^2$

where κ is a constant depending on the apparatus.

(A3) First-tick selection. The outcome is determined by the first branch to produce a threshold-crossing tick (which becomes the Bit).

[General Reader] These assumptions say: (1) all branches "tick" in the same general pattern, just at different speeds; (2) the speed is proportional to $|\psi|^2$; (3) first one to tick wins. These are physically reasonable for real detectors, as we discuss below.

2.3 Strengthened Constraints: From Assumptions to Physical Necessities

The assumptions (A1)–(A3) can be recast in a more rigorous form grounded in general physical principles. None are arbitrary; each is a structural consequence of quantum dynamics, decoherence, and detector physics. We denote the strengthened versions as (A1′)–(A3′).

(A3′) First-tick selection (k = 1) is forced by metastability and thermodynamic irreversibility

Any macroscopic detector capable of amplifying a quantum input must operate as a metastable system near an instability threshold. In such systems, the first microscopic event that crosses the barrier triggers deterministic relaxation to a macroscopic outcome. This is a universal feature of metastable amplification:

- A metastable system near an instability point has a single escape pathway (Arrhenius barrier)
- As soon as one microscopic fluctuation crosses the barrier, the system undergoes rapid, deterministic relaxation into one macrostate
- Subsequent fluctuations occur after the macrostate has been irreversibly determined

This principle spans supercooled nucleation (a single nucleus triggers crystallization), avalanche photodiodes (one carrier triggers breakdown), photomultipliers (one photoelectron triggers the cascade), superconducting nanowires (one hotspot triggers the voltage pulse), Geiger-Müller tubes (one ionization triggers the discharge), and chemical ignition (one radical triggers the reaction).

Thus k = 1 is not a modeling assumption but a *thermodynamic necessity* for any single-quantum-sensitive detector. Tick-Bit does not assume k = 1—physics forces k = 1.

(A2′) Tick rates must scale as $|\psi_A|^2$ by unitarity, symmetry, and perturbation theory

Transition amplitudes evolve linearly under the Schrödinger equation:

$$d\psi/dt = -(i/\hbar)\, H\, \psi$$

Physical transition rates must be non-negative, gauge-invariant, and phase-covariant quadratic forms of the amplitudes. The only such functional is $|\psi_A|^2$. Any other choice would break phase covariance, violate linearity of quantum response, break local tomography, or violate energy conservation in perturbation theory.

Time-dependent perturbation theory (Fermi's golden rule) confirms this scaling as a dynamical fact about amplitude-squared flow rates, independent of any probabilistic interpretation. We develop this further in Section 4.

Therefore $\lambda_A \propto |\psi_A|^2$ is forced by linear quantum dynamics and U(1) symmetry, not postulated. This is a representation-theoretic necessity.

(A1′) Proportional hazards arise from detector branch-blindness

After decoherence, each branch A interacts with the detector via the same Hamiltonian H_{int}; the apparatus cannot condition its response on which branch it is coupled to. The detector Hamiltonian is the same operator acting on $|A\rangle|P_0\rangle|E_A\rangle$ regardless of A. This implies that the hazard functions share the same time-shape $h_0(t)$, differing only by scale factors λ_A determined by branch-dependent microstructure.

This is exactly the proportional hazards structure of the Cox model, emerging from the branch-blindness of the detector Hamiltonian. Branch-specific environmental microstates affect λ_A (the scale), but not $h_0(t)$ (the shape).

Even if two physical detectors differ slightly, those differences enter λ_A, not $h_0(t)$. Corrections to proportional hazards are second-order and yield small perturbative corrections to Born statistics—exactly as the theory predicts for any realistic physical system.

Summary: Why These Constraints Are Ironclad

With (A1′)–(A3′) reframed this way, the constraints become physically necessary, not modeling choices:

- (A3′) gives irreversibility and outcome definiteness from thermodynamics
- (A2′) gives Born weights at the rate level from unitarity and symmetry
- (A1′) gives the proportional hazards structure from detector branch-blindness

Once (A1′)–(A3′) hold, the Born rule $P(A) = |\psi_A|^2$ is forced. No alternative functional form survives all three constraints. Tick-Bit is not "a mechanism that happens to work"—it is the unique mechanism consistent with unitary dynamics, decoherence, metastable amplification, and amplitude-squared transition rates.

2.4 Survival Functions and First-Passage Probability

Let T_A be the waiting time for the first tick in branch A. The survival function (probability no tick by time t) is:

$$S_A(t) = \exp(-\lambda_A \cdot H_0(t))$$

where $H_0(t) = \int_0^t h_0(s)ds$ is the cumulative baseline hazard.

The probability density for first tick at time t is:

$$f_A(t) = h_A(t) \cdot S_A(t) = \lambda_A \cdot h_0(t) \cdot \exp(-\lambda_A \cdot H_0(t))$$

For competing processes, the probability that branch A fires first is:

$$P(A \text{ first}) = \int_0^\infty f_A(t) \cdot \prod_{B\neq A} S_B(t)\, dt$$

2.5 The First-Passage Born Rule Theorem

Theorem 2.1 (First-Passage Born Rule). Under constraints (A1′)–(A3′), the probability that branch A produces the first threshold-crossing tick (the Bit) is:

$$P(A) = |\psi_A|^2 / \Sigma_B |\psi_B|^2$$

Proof. With proportional hazards $h_A(t) = \lambda_A \cdot h_0(t)$:

$$P(A \text{ first}) = \int_0^\infty \lambda_A \cdot h_0(t) \cdot \exp(-\Sigma_C \lambda_C \cdot H_0(t))\, dt$$

Let $u = H_0(t)$, so $du = h_0(t)dt$:

$$P(A \text{ first}) = \int_0^\infty \lambda_A \cdot \exp(-\Sigma_C \lambda_C \cdot u)\, du = \lambda_A / \Sigma_C \lambda_C$$

Substituting $\lambda_A = \kappa \cdot |\psi_A|^2$:

$$P(A) = \kappa \cdot |\psi_A|^2 / \Sigma_C \kappa \cdot |\psi_C|^2 = |\psi_A|^2 / \Sigma_B |\psi_B|^2 \blacksquare$$

Lemma 2.2 (Uniqueness of Linear Probability Assignment). Let P: $\{\lambda_A\} \to [0,1]$ be a probability assignment satisfying: (i) *Normalization:* $\Sigma_A P(A) = 1$ (ii) *Symmetry:* P is invariant under permutation of branch labels (iii) *Homogeneity:* $P(A; \{c\lambda_B\}) = P(A; \{\lambda_B\})$ for any $c > 0$ (iv) *Continuity:* P depends continuously on $\{\lambda_A\}$

Then $P(A) = \lambda_A / \Sigma_B \lambda_B$.

Proof sketch. By (ii) and (iv), $P(A) = f(\lambda_A, \Sigma_B \lambda_B)$ for some continuous symmetric function f. By (iii), f is homogeneous of degree zero in its arguments, so $f(\lambda_A, \Sigma\lambda_B) = g(\lambda_A / \Sigma\lambda_B)$ for some function g. By (i), $\Sigma_A g(\lambda_A / \Sigma\lambda_B) = 1$ for all configurations. The only continuous solution is $g(x) = x$, giving $P(A) = \lambda_A / \Sigma_B \lambda_B$. ■

This lemma confirms that the proportional hazards structure (A1′) combined with first-passage dynamics uniquely determines the probability assignment. There is no freedom to choose a different functional form.

[General Reader] The math confirms our intuition: when contestants race with speeds proportional to $|\psi|^2$, the probability of winning is exactly $|\psi|^2$ (after normalizing). The Born rule is not a mystery—it is the inevitable outcome of a fair race with these speeds.

A note on the "race" metaphor: The race is not a dynamical interaction between branches—after decoherence, branches evolve independently and do not "communicate." Rather, the race is a counterfactual comparison: each branch's microstate configuration determines a threshold-crossing time T_A, and the winner is simply the branch whose configuration happens to produce the earliest such time. This is structurally identical to Bohmian mechanics, where particle positions determine outcomes but different branches never interact. The mathematics of competing point processes captures this comparison without requiring any inter-branch dynamics.

2.6 Technical Details: First-Tick Selection and the k > 1 Prediction

As established in (A3′), the $k = 1$ structure is thermodynamically forced for metastable amplifying systems. Here we develop the technical consequences and the testable prediction that follows.

The mechanism reproduces the Born rule only if the outcome is determined by the first tick ($k = 1$). If $k > 1$ independent ticks were required, waiting times would follow a $\text{Gamma}(k, \lambda_A)$ distribution, yielding different statistics.

For concreteness, consider the specific detector parameters:

Avalanche photodiodes: Electric field tuned just below breakdown; a single carrier ionization event initiates multiplicative gain of 10^5–10^6.

Photomultipliers: Each dynode stage multiplies by ~4–10×, yielding total gains of 10^6–10^8 from a single initial electron.

Superconducting nanowire detectors: A single photon breaks Cooper pairs locally, creating a resistive hotspot that diverts current and produces a measurable signal within picoseconds.

These numbers are not incidental—they reflect the thermodynamic requirement that single-quantum sensitivity demands first-crossing amplification.

Prediction: Detectors engineered to require $k \gg 1$ independent events (e.g., multi-photon coincidence counters with truly independent channels) should show deviations from Born statistics. This is testable, though challenging to implement cleanly. See Section 10 and Appendix B for quantitative predictions.

2.7 Robustness: Deviations from the Constraints Produce Deviations from Born

The constraints (A1′)–(A3′) are not only sufficient for deriving the Born rule; they are also necessary in a strong sense. Small or systematic violations of any one of them generically produce calculable deviations from $P(A) = |\psi_A|^2$. This section summarizes the robustness analysis.

2.7.1 Violating (A2′): Wrong Exponent in λ_A

Suppose we keep (A1′) and (A3′)—proportional hazards and $k = 1$—but relax (A2′) by allowing the tick rates to scale as a different power of the amplitude:

$\lambda\_A = \kappa \cdot |\psi\_A|^\alpha, \alpha \neq 2$

The first-passage result still gives:

$P(A) = \lambda\_A / \Sigma\_B \lambda\_B = |\psi\_A|^\alpha / \Sigma\_B |\psi\_B|^\alpha$

Thus, the outcome probabilities directly inherit the wrong exponent α. For a simple two-branch system with $|\psi_1|^2 = 2|\psi_2|^2$, we have $|\psi_1| = \sqrt{2}\, |\psi_2|$. Then:

Born rule (α = 2):

$P_1 = |\psi_1|^2 / (|\psi_1|^2 + |\psi_2|^2) = 2/3 \approx 0.667$

Sublinear case (α = 1):

$P_1 = |\psi_1| / (|\psi_1| + |\psi_2|) = \sqrt{2} / (\sqrt{2} + 1) \approx 0.586$

Superquadratic case (α = 4):

$P_1 = |\psi_1|^4 / (|\psi_1|^4 + |\psi_2|^4) = 4/5 = 0.800$

These deviations (≈0.586 vs 0.667 vs 0.800) are large and would have been detected long ago in interference and polarization experiments. Decades of quantum optics and spin measurements are consistent with $P \propto |\psi|^2$ to very high precision. Thus α = 2 is not just convenient—it is empirically forced.

2.7.2 Violating (A1′): Non-Proportional Hazards

Now keep (A2′) and (A3′) but relax (A1′). Suppose the hazard functions have slightly different shapes across branches:

$h\_A(t) = \lambda\_A \cdot h_0(t) + \varepsilon\_A \cdot g(t)$

with small parameters ε_A and some perturbing shape g(t). The survival and first-passage integrals no longer simplify exactly to λ_A / Σλ_C. To first order in ε_A:

$P(A) = P^0(A) + \delta P(A)$

where $P^0(A) = \lambda\_A / \Sigma\_C \lambda\_C$ is the ideal proportional-hazards result and δP(A) is a correction term of order ε.

Two points are clear:

Generic deviations: For generic g(t) and nonzero ε_A, δP(A) ≠ 0. Non-proportional hazards generically produce departures from the simple λ_A/Σλ_C rule.

Suppression by scale separation: In realistic detectors, microscopic variations in response shape $g(t)$ occur on timescales τ_{micro} (carrier scattering, phonon relaxation), while the macroscopic avalanche unfolds on timescales $\tau_{macro} \gg \tau_{micro}$. The correction integral is typically suppressed by $\tau_{micro}/\tau_{macro}$. This explains why Born statistics are extremely accurate in practice even though no real detector is perfectly branch-blind microscopically.

2.7.3 Violating (A3′): Multi-Tick Requirements (k > 1)

As shown in Appendix B, when (A1′) and (A2′) are retained but (A3′) is violated by requiring $k > 1$ independent ticks, the waiting-time distribution becomes Gamma(k, λ_A) and the first-passage probability deviates from $\lambda_A / \Sigma\lambda_C$. For two branches with $\lambda_1 = 2\lambda_2$:

- $k = 1$: $P_1 = 2/3 \approx 0.667$
- $k = 2$: $P_1 = 20/27 \approx 0.741$

2.7.4 Summary: Tick-Bit as a Robust Fixed Point

Taken together, these robustness results show that:

- Violating (A2′) (wrong exponent) leads directly to $P(A) \propto |\psi_A|^\alpha$, $\alpha \neq 2$, which is empirically ruled out
- Violating (A1′) (non-proportional hazards) produces calculable corrections that are generically nonzero but suppressed by microscopic/macroscopic scale separation
- Violating (A3′) ($k > 1$) yields Gamma-distributed waiting times and explicit deviations from the $\lambda_A/\Sigma\lambda_C$ rule

The Tick-Bit mechanism is not merely *a* mechanism that reproduces the Born rule; it is the **robust fixed point** in the space of detector-layer outcome-selection models satisfying physical constraints. Small deviations from (A1′)–(A3′) produce correspondingly small, calculable deviations from Born statistics, while large deviations (e.g., $\alpha \neq 2$ or $k \gg 1$) are already experimentally excluded.

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3. Is Tick-Bit Just an Ad Hoc Fit to the Born Rule?

One natural worry is that Tick-Bit is "just something we made up that happens to reproduce the Born rule." In other words, given that $|\psi|^2$ already appears everywhere in quantum mechanics, one might suspect that any model can be reverse-engineered to match it, with no real explanatory gain.

There are three reasons this objection does not apply.

3.1 Strong Constraints, Not a Free Choice

The Tick-Bit mechanism is not an arbitrary story bolted onto quantum theory; it is the result of imposing physically necessary constraints (A1′–A3′):

- Decoherence produces effectively independent branches with amplitudes ψ_A
- Transition rates must scale as $|\psi_A|^2$ by unitarity, U(1) symmetry, and perturbation theory (A2′)
- Metastable amplifying detectors are thermodynamically forced to trigger on the first supercritical event (A3′)
- The detector Hamiltonian is branch-blind, forcing proportional hazards structure (A1′)
- The distinguishability functional must satisfy additivity, symmetry, phase covariance, and mild regularity, which uniquely forces $D(A) = |\psi_A|^2$

Given these ingredients, a proportional-hazards race with $\lambda_A \propto |\psi_A|^2$ is not an arbitrary choice; it is the unique way to combine decohered branches, amplitude-squared transition rates, and threshold detection into a concrete outcome-selection mechanism.

3.2 Sensitivity to Modifications

The mechanism is not "under-constrained" in the sense that anything goes. On the contrary, small changes destroy key features:

- If we change the distinguishability functional away from $|\psi|^2$, we lose additivity and interference consistency
- If we require $k > 1$ independent ticks, the first-passage probabilities deviate from $|\psi|^2$
- If we abandon proportional hazards, the simple $\lambda_A/\Sigma\lambda_C$ structure is lost and the Born rule no longer follows as a theorem

These failures are not cosmetic; they are calculable and, in principle, testable. Section 2.7 provides a detailed robustness analysis showing that deviations from each constraint (A1′)–(A3′) produce specific, quantifiable departures from Born statistics. The Tick-Bit framework is therefore falsifiable under controlled changes of its assumptions.

3.3 Additional Explanatory and Predictive Content

Finally, Tick-Bit does more than reproduce $|\psi|^2$. It offers:

- A detector-level, first-passage mechanism for outcome definiteness, rather than a bare collapse postulate
- A deterministic microdynamics with epistemic probabilities, resolving how apparent randomness can arise from unitary evolution plus inaccessible microstructure
- A quantitative prediction that detectors engineered with $k \gg 1$ independent triggers should show observable deviations from Born statistics

- A natural link between outcome selection, irreversibility, and emergent time in the TPB framework

These are additional structural and conceptual payoffs that go beyond merely "fitting" the Born rule.

For these reasons, Tick-Bit should not be viewed as an unconstrained just-so story. It is a specific, tightly constrained mechanism that (i) respects known quantum dynamics, (ii) fails in calculable ways when its assumptions are altered, and (iii) yields new conceptual clarity and potential empirical signatures.

To put it plainly: Tick-Bit is not "one arbitrary story among many." It is what you get if you take decoherence, golden-rule transition rates, and single-quantum threshold detectors seriously, then ask: "What concrete mechanism could connect these to definite outcomes and the Born rule?" Within that space, the first-passage tick race really is the thing that fits the bill.

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4. Grounding $\lambda_A \propto |\psi_A|^2$: Why Tick Rates Scale with Amplitude Squared

4.1 The Circularity Question

A potential objection: "You assumed $\lambda_A \propto |\psi_A|^2$. Is that not just assuming the Born rule?"

This objection conflates two distinct uses of $|\psi|^2$:

- **Born rule (outcome statistics):** $P(A) = |\psi_A|^2$ for measurement outcomes
- **Fermi's golden rule (transition dynamics):** $\Gamma \propto |\langle f|V|i\rangle|^2$ for transition rates

The second is a statement about *dynamics*—how fast quantum systems transition between states—not about outcome probabilities. It is derived from time-dependent perturbation theory using only the Schrödinger equation and the structure of Hilbert space, without invoking the Born rule for measurement outcomes.

The logical structure is:

1. Time-dependent perturbation theory → transition rates scale as |matrix element|^2
2. Measurement interactions have matrix elements proportional to system amplitudes
3. Therefore tick rates scale as $|\psi_A|^2$
4. First-passage statistics → $P(A) = |\psi_A|^2$

At no point do we assume $P(A) = |\psi_A|^2$. The outcome probability emerges from the race dynamics.

To be fully explicit: in Tick-Bit, the quantities Γ_A and λ_A are interpreted as rates of amplitude-squared flow toward macroscopic distinguishability—currents in amplitude space, not probabilities per se. These rates describe how fast each branch accumulates the microscopic preconditions for a threshold-crossing event. The probabilistic meaning arises only after the first-passage competition resolves: the race converts deterministic rate differences into outcome probabilities. The Born rule emerges from the competition, not from the rate equation itself.

4.2 Derivation from Fermi's Golden Rule

Consider a measurement described by an interaction Hamiltonian:

$$H\_int = \Sigma\_A |A\rangle\langle A| \otimes \hat{V}\_A$$

where $|A\rangle$ are system outcome states and $\hat{V}\_A$ acts on the pointer and environment.

For a system in state $|\psi\rangle = \Sigma\_A \psi\_A |A\rangle$, the initial joint state is:

$$|\Psi_0\rangle = |\psi\rangle \otimes |P_0\rangle \otimes |E_0\rangle$$

where $|P_0\rangle$ and $|E_0\rangle$ are initial pointer and environment states.

By Fermi's golden rule, the transition rate into pointer channel A is:

$$\Gamma\_A = (2\pi/\hbar) \cdot |\psi\_A|^2 \cdot \Sigma\_f |\langle f\_A|\langle P\_A| \hat{V}\_A |P_0\rangle|E_0\rangle|^2 \cdot \delta(E\_f - E\_i)$$

The key point: Γ_A factorizes as:

$$\Gamma\_A = |\psi\_A|^2 \cdot \kappa\_A$$

where κ_A depends only on apparatus matrix elements, not on the system amplitudes.

[General Reader] Fermi's golden rule is a standard result in quantum mechanics from the 1920s: the rate of quantum transitions is proportional to the square of the relevant amplitude. This is already part of quantum theory—we are not adding anything new. We are just applying it to the measurement process.

4.3 Addressing Deeper Circularity Concerns

One might object that Fermi's golden rule is itself derived using probabilistic reasoning that implicitly assumes $|\psi|^2$ weighting. This concern can be addressed at two levels:

Operational level: Fermi's golden rule can be derived purely from the Schrödinger equation by computing the time evolution of state amplitudes under perturbation. The $|\text{matrix element}|^2$ dependence emerges from the mathematical structure of complex amplitudes—specifically, from the fact that transition amplitudes are complex numbers and physical rates must be real and non-negative. The simplest real, non-negative, phase-invariant function of a complex amplitude a is $|a|^2$.

Foundational level: The Resonant Assembly Language (RAL) framework in Part II derives the $|\psi|^2$ structure from physical first principles—resonance geometry and distinguishability requirements—without presupposing quantum mechanics. This provides a non-circular foundation for the amplitude-squared scaling.

4.4 The Complete Logical Chain

The full derivation follows this chain:

1. **Resonance geometry** → complex amplitudes naturally describe oscillatory systems (Section 13)
2. **Distinguishability structure** → bilinear form $D(A) = |\psi\_A|^2$ is uniquely determined (Section 14)
3. **Time-dependent perturbation theory** → transition rates scale as $|\text{matrix element}|^2$
4. **Measurement interaction structure** → $\Gamma\_A = |\psi\_A|^2 \cdot$ (apparatus factors)
5. **Tick rate identification** → $\lambda\_A = \kappa|\psi\_A|^2$
6. **First-passage statistics** → $P(A) = |\psi\_A|^2$

At no point do we assume $P(A) = |\psi\_A|^2$. The probability emerges from the race dynamics operating on independently-grounded rate scaling.

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5. Worked Example: Stern-Gerlach Measurement

We trace through a complete Stern-Gerlach measurement to illustrate the mechanism.

5.1 State Preparation

A spin-½ particle is prepared in the $|+x\rangle$ state:

$$|\psi\_in\rangle = (1/\sqrt{2})(|+z\rangle + |-z\rangle)$$

Including apparatus and environment:

$$|\Psi_0\rangle = |\psi\_in\rangle \otimes |D_0\rangle \otimes |E_0\rangle$$

[General Reader] We start with an electron spinning "sideways" (in the x-direction). Quantum mechanically, this equals a 50-50 superposition of spinning "up" and "down" in the z-direction.

5.2 Stern-Gerlach Separation

The inhomogeneous magnetic field separates spin components spatially:

$|\Psi_1\rangle = (1/\sqrt{2})(|+z\rangle|path\_\uparrow\rangle + |-z\rangle|path\_\downarrow\rangle) \otimes |D_0\rangle \otimes |E_0\rangle$

The spin states are now correlated with spatial paths.

5.3 Decoherence

Interaction with detectors and environment produces:

$|\Psi_2\rangle = (1/\sqrt{2})(|+z\rangle|path\_\uparrow\rangle|D\_\uparrow\rangle|E\_\uparrow\rangle + |-z\rangle|path\_\downarrow\rangle|D\_\downarrow\rangle|E\_\downarrow\rangle)$

where $\langle E\_\uparrow|E\_\downarrow\rangle \approx 0$. The branches are now distinguishable and cannot interfere.

[General Reader] The two paths become entangled with different detector states and different environmental states (air molecules, thermal radiation, etc.). Once this happens, the paths cannot interfere anymore—they are "decohered."

5.4 Branch Amplitudes and Tick Rates

We have two branches $A \in \{\uparrow, \downarrow\}$ with amplitudes:

$\psi\_\uparrow = 1/\sqrt{2}$, $\psi\_\downarrow = 1/\sqrt{2}$

Distinguishability weights:

$D(\uparrow) = |\psi\_\uparrow|^2 = 1/2$, $D(\downarrow) = |\psi\_\downarrow|^2 = 1/2$

Tick rates:

$\lambda\_\uparrow = \kappa \cdot |\psi\_\uparrow|^2 = \kappa/2$, $\lambda\_\downarrow = \kappa \cdot |\psi\_\downarrow|^2 = \kappa/2$

5.5 First-Passage Race

Both branches generate ticks at equal rates. The race is symmetric.

By Theorem 2.1:

$P(\uparrow) = \lambda\_\uparrow / (\lambda\_\uparrow + \lambda\_\downarrow) = (\kappa/2) / (\kappa/2 + \kappa/2) = 1/2$

$P(\downarrow) = \lambda\_\downarrow / (\lambda\_\uparrow + \lambda\_\downarrow) = 1/2$

This matches the Born rule prediction.

5.6 Physical Interpretation

Within each branch, the detector undergoes microscopic fluctuations. Each branch is racing to produce its first irreversible event—an avalanche trigger, a photon emission, a chemical reaction.

The branch that wins this race—say, ↑—produces a macroscopic, irreversible signal. Amplification and further decoherence then stabilize this outcome. The other branch (↓) becomes counterfactual.

[General Reader] Both possible outcomes are "trying" to happen—both detectors are fluctuating, ready to trigger. Whichever detector triggers first, wins. Since both have equal $|\psi|^2$, both have equal chances. We see spin-up or spin-down, each 50% of the time.

5.7 Unequal Amplitudes

Now consider $|\psi\_in\rangle$ prepared at angle θ from the z-axis:

$|\psi\_in\rangle = \cos(\theta/2)|+z\rangle + \sin(\theta/2)|-z\rangle$

Amplitudes:

$\psi\_\uparrow = \cos(\theta/2)$, $\psi\_\downarrow = \sin(\theta/2)$

Tick rates:

$\lambda\_\uparrow = \kappa \cdot \cos^2(\theta/2)$, $\lambda\_\downarrow = \kappa \cdot \sin^2(\theta/2)$

First-passage probabilities:

$P(\uparrow) = \cos^2(\theta/2) / (\cos^2(\theta/2) + \sin^2(\theta/2)) = \cos^2(\theta/2)$

$P(\downarrow) = \sin^2(\theta/2)$

Again matching the Born rule exactly.

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6. Determinism, Epistemic Probability, and the Nature of Quantum Randomness

6.1 Determinism at the Microlevel

A profound implication of Tick-Bit: the outcome is deterministic in principle.

After decoherence, each branch A has a specific environmental microstate configuration {m_i^(A)}. These microstates determine the exact times at which ticks occur:

T_A = T_A({m_i^(A)})

Given complete microstate information, the first-passage time T_A is fixed for each branch. The outcome is:

Outcome = argmin_A T_A

In the Tick-Bit picture, the microdynamics are deterministic in principle; the outcome is fixed by the microstate configuration, not by any fundamental stochastic process.

[General Reader] Here is the claim: quantum randomness might not be fundamental. If you knew EVERY detail about the detector, the air molecules, every particle involved—you could in principle calculate exactly which outcome would occur. The "randomness" exists because we CANNOT know all that information, not necessarily because the universe is inherently random.

6.2 Practical Inaccessibility

Why can we not know the microstates? Several fundamental barriers:

Exponential complexity: Environmental degrees of freedom diverge exponentially after decoherence. A detector interacting with ~10^{23} air molecules generates untraceable correlations in femtoseconds.

Chaotic sensitivity: Microscopic dynamics are chaotic. Tiny uncertainties in initial conditions amplify exponentially with Lyapunov exponents on the order of thermal collision rates.

Thermodynamic irreversibility: Decoherence is thermodynamically irreversible. Information about the pre-decoherence state is lost to heat—it is not merely hidden but genuinely dispersed.

No-cloning theorem: Quantum mechanics forbids copying unknown quantum states. We cannot measure microstates without disturbing them, and we cannot duplicate them for non-destructive analysis.

6.3 Epistemic vs. Ontic Probability

This bears on a long-standing debate:

Ontic probability: Randomness is fundamental; the universe genuinely "rolls dice."

Epistemic probability: Randomness reflects our ignorance; underlying dynamics are deterministic.

Tick-Bit is naturally interpreted as supporting epistemic probability: the Born rule emerges as the optimal prediction given our necessary ignorance of microstates. This interpretation is suggested by the framework's structure, though the empirical predictions remain identical regardless of which metaphysical stance one adopts.

[General Reader] When you flip a coin, the outcome is determined by physics—air currents, your thumb's force, the coin's spin. You call it "random" because you cannot track all those details. Quantum mechanics might be the same: deterministic underneath, but with details so complex that probability is the best we can do.

6.4 Comparison with Classical Statistical Mechanics

This parallels classical statistical mechanics:

Aspect	Classical Stat Mech	Tick-Bit QM
Underlying dynamics	Deterministic (Newton)	Deterministic (unitary + tick race)
Source of probability	Ignorance of microstates	Ignorance of microstates
Emergent law	Boltzmann distribution	Born rule
Fundamental randomness	No	No

The analogy is precise: just as thermodynamics emerges from deterministic mechanics plus epistemic uncertainty, the Born rule emerges from deterministic tick dynamics plus epistemic uncertainty.

6.5 What About "True Randomness" in QM?

Standard quantum mechanics is often said to involve "true" or "irreducible" randomness. Tick-Bit challenges this:

The appearance of true randomness arises because:

1. Microstates are inaccessible in practice and in principle
2. The best prediction is probabilistic
3. No pattern in outcomes can be exploited (by us)

But this does not require fundamental randomness—only fundamental unpredictability from our epistemic position.

[General Reader] "True randomness" might be an illusion created by our necessary ignorance. The universe could be a perfectly deterministic clockwork—but a clockwork so complex that we can never see all its gears. For all practical purposes, it is random to us. But "random to us" is not the same as "fundamentally random."

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7. Entanglement, Bell Correlations, and Nonlocality

7.1 The Challenge

Bell's theorem proves that no local hidden-variable theory can reproduce quantum correlations. Any deterministic mechanism reproducing quantum predictions must be nonlocal.

How does Tick-Bit handle this?

7.2 Entangled State Setup

Consider two qubits in the singlet state:

$|\Psi\rangle = (1/\sqrt{2})(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B)$

Alice measures along axis **a**; Bob along axis **b**. After decoherence, four branches exist with joint outcomes $(A, B) \in \{(+,+), (+,-), (-,+), (-,-)\}$.

The amplitudes depend on both settings:

$|\psi_{++}(\mathbf{a},\mathbf{b})|^2 = |\psi_{--}(\mathbf{a},\mathbf{b})|^2 = (1 - \mathbf{a}\cdot\mathbf{b})/4$

$|\psi_{+-}(\mathbf{a},\mathbf{b})|^2 = |\psi_{-+}(\mathbf{a},\mathbf{b})|^2 = (1 + \mathbf{a}\cdot\mathbf{b})/4$

7.3 Tick Rates for Joint Branches

Tick-Bit assigns tick rates to global branches in configuration space:

$\lambda_{AB}(\mathbf{a},\mathbf{b}) = \kappa \cdot |\psi_{AB}(\mathbf{a},\mathbf{b})|^2$

The tick rate for branch (A,B) depends on both Alice's setting **a** and Bob's setting **b**.

7.4 Nonlocality

This is explicitly nonlocal: the tick rate for a joint outcome depends on the measurement settings at both locations, even if Alice and Bob are light-years apart.

The key point: nonlocality resides in the configuration-space structure of tick rates, not in any signal propagation. Just as Bohmian mechanics has particle velocities that depend nonlocally on the full configuration via the wave function, Tick-Bit has tick intensities that depend nonlocally on the full measurement configuration via $|\psi|^2$. The wave function mediates nonlocal correlations in both frameworks—through guidance in Bohm, through rate-setting in Tick-Bit.

[General Reader] Bell proved that any hidden-variable theory matching quantum predictions must involve "spooky action at a distance." Tick-Bit is no exception: the tick rate for a joint outcome (Alice sees +, Bob sees −) depends on what BOTH Alice and Bob chose to measure. This is strange but unavoidable—Bell's theorem leaves no alternative.

7.5 No-Signaling Is Preserved

Despite nonlocality, no information can be transmitted faster than light:

$$\Sigma_B \lambda_{AB}(\mathbf{a},\mathbf{b}) = \kappa \cdot \Sigma_B |\psi_{AB}|^2 = \kappa \cdot |\psi_A|^2$$

Alice's marginal outcome distribution depends only on her setting **a** and the reduced state, not on Bob's setting **b**. The correlations only appear when Alice and Bob compare results—which requires ordinary subluminal communication.

7.6 No Superdeterminism or Retrocausality

Some hidden-variable approaches invoke:

Superdeterminism: Measurement choices are correlated with hidden variables, eliminating free choice.

Retrocausality: Effects propagate backward in time.

Tick-Bit requires neither. Nonlocal dependence of λ_{AB} on joint settings is sufficient, exactly as in Bohmian mechanics. The price of determinism is nonlocality, but not conspiracy or time-reversal.

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8. Ontological Status of Competing Branches

8.1 The Question

A natural question arises: after decoherence but before the race concludes, what is the ontological status of the competing branches? Do they all "exist"? In what sense do they "race"?

8.2 Three Interpretive Options

Tick-Bit is compatible with several ontological stances:

Option 1: Single-branch realism. Only one branch is ever real; the tick race determines which one actualizes from an initial superposition. The other branches are mathematical fictions representing unrealized possibilities. This resembles modal interpretations.

Option 2: Transient multi-branch realism. All branches exist temporarily during the race, but the losing branches are annihilated when the winner is determined. This resembles objective collapse but with a physical mechanism.

Option 3: Configuration-space realism. The fundamental arena is configuration space, where the wave function and its associated tick-rate field are real. "Branches" are features of this space. The first-passage event selects which configuration-space region becomes correlated with stable macroscopic records. This resembles Bohmian mechanics without committed particle ontology.

8.3 What Tick-Bit Adds

Tick-Bit does not resolve the interpretive question—no physical theory does. But it provides something the other interpretations lack: a *mechanism*.

In Many-Worlds, branches simply exist and the probability measure is postulated. In Copenhagen, collapse is a black box. In Tick-Bit, outcome selection has a physical story: micro-events race, and the first one to cross the threshold triggers an irreversible Bit. This mechanism constrains interpretation even if it does not uniquely determine it.

8.4 The Race as Physical Process

Crucially, the "race" is not metaphorical. Each branch, via its environmental microstate, has a definite (if unknowable) first-tick time. These times are physical quantities determined by the microscopic configuration. The race is as real as any thermodynamic process—it is the entropic evolution of the measurement apparatus toward a distinguishable macrostate.

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9. Comparison with Bohmian Mechanics

9.1 Structural Parallels

Bohmian mechanics (BM) is the best-known deterministic hidden-variable theory. Tick-Bit shares key features:

Feature	Bohmian Mechanics	Tick-Bit
Determinism	Yes	Yes
Hidden variables	Particle positions	Environmental microstates
Probability type	Epistemic	Epistemic
Reproduces Born rule	Yes	Yes
Nonlocality	Yes (guidance equation)	Yes (tick rates)

9.2 Key Differences

Aspect	Bohmian Mechanics	Tick-Bit
Ontology	Particles with definite positions	No commitment to particle trajectories
Dynamics	Guidance equation for velocities	First-passage statistics for outcomes
Wave function role	Real guiding field	Determines tick intensities via
Measurement	Particle position determines outcome	First threshold-crossing tick (Bit) determines outcome
Level of description	Modifies microscopic dynamics	Adds structure at measurement level

9.3 What Tick-Bit Adds

Non-circular derivation of $|\psi|^2$: The RAL framework reconstructs the amplitude structure from physical principles. BM assumes Hilbert space and uses the Born rule for the initial distribution.

No particle ontology: Tick-Bit does not commit to particles having trajectories. This avoids difficulties with relativistic extensions and quantum field theories, where particle number is not conserved.

Detector-level mechanism: Tick-Bit directly addresses how measurement apparatus produces outcomes, rather than relying on particle positions to determine pointer readings.

Connection to emergent time: Integration with the TPB (Ticks-Per-Bit) framework grounds time itself in irreversible change.

9.4 Complementarity

Tick-Bit and Bohmian mechanics are not mutually exclusive. One could adopt Bohmian particle ontology while using Tick-Bit to explain how particle positions become registered in detectors. They address different aspects of the measurement process.

[General Reader] Bohmian mechanics says particles have hidden positions that determine outcomes. Tick-Bit says the environment has hidden details that determine which detector triggers first. Both are deterministic; both match quantum predictions; both require nonlocality. They are different stories about "what is really going on," but they are compatible—you could believe both.

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10. Predictions and Experimental Signatures

10.1 Empirical Equivalence for Standard Measurements

For standard measurements with $k = 1$ threshold detectors, Tick-Bit reproduces all quantum predictions exactly. No existing experiment can distinguish it from standard quantum mechanics.

This is not a weakness. Any interpretation of quantum mechanics must reproduce the empirical success of the theory. The question is whether it offers additional predictions or explanatory power.

10.2 Predicted Deviation: k > 1 Detectors

If a detector requires $k > 1$ independent triggers, the waiting-time distribution becomes Gamma(k, λ_A) rather than exponential. First-passage probabilities then deviate from $|\psi|^2$.

Specific prediction: For $k = 2$ (two independent triggers required) and two branches with rates $\lambda_1 = 2\lambda_2$:

- $k = 1$: P(1 first) = $2/3 \approx 0.667$
- $k = 2$: P(1 first) = $20/27 \approx 0.741$

The deviation is substantial and measurable.

[General Reader] Here is a testable prediction: if you built a detector that only "clicks" after TWO independent quantum events (not just one), the probabilities would NOT follow the Born rule. This is genuinely new physics—though building such detectors is challenging.

10.3 Experimental Challenges

Testing the $k > 1$ prediction requires:

1. **True independence:** The k triggers must be causally independent, not merely sequential stages of a single amplification chain.
2. **Known k:** The number of required triggers must be precisely characterized.
3. **Sufficient statistics:** Deviations from Born statistics require many trials to distinguish from statistical fluctuation.

Distinguishing k > 1 from k = 1: The critical distinction is between *independent* triggers and *amplification stages*. A photomultiplier has many dynode stages, but these form a single causal chain initiated by one photoelectron—this is $k = 1$. A true $k = 2$ system would require two *separate* quantum absorption events, neither causing the other, both required before the detector registers.

Candidate experimental setups:

- *Two-photon coincidence detectors* with independent absorption sites, where both sites must fire within a coincidence window for registration. The challenge is ensuring the two absorptions are genuinely independent quantum events rather than correlated through shared optical modes.
- *Molecular switches* requiring two independent photoisomerization events to trigger a conformational change that produces the signal.
- *Dual-threshold superconducting detectors* engineered to require hotspot formation at two separate locations.

Statistical requirements: For the two-branch case with $\lambda_1 = 2\lambda_2$, the predicted probabilities are $P_1 = 0.667$ ($k = 1$) vs $P_1 = 0.741$ ($k = 2$). To distinguish these at 3σ confidence requires:

$$N \geq 9 / (0.741 - 0.667)^2 \approx 1{,}600 \text{ trials}$$

This is experimentally feasible if a clean $k = 2$ system can be constructed.

Existing datasets: We are not aware of existing experiments designed to test $k > 1$ statistics. Standard quantum optics experiments use $k = 1$ detectors by design. However, some multi-photon absorption spectroscopy data might be reanalyzable if the detection chain can be characterized precisely.

10.4 Timing Correlations

In principle, the tick-rate structure might produce subtle timing correlations in measurement events. Measurements with higher $|\psi|^2$ might show systematically shorter detection times.

For a single-branch detection with rate $\lambda = \kappa|\psi|^2$, the mean detection time is:

$\langle T \rangle = 1/\lambda = 1/(\kappa|\psi|^2)$

Higher amplitude means faster expected detection. This is in principle testable but requires extremely precise timing across many trials.

10.5 Current Experimental Status

No deviations from quantum mechanics have been observed. This is consistent with Tick-Bit, since:

1. Standard detectors are $k = 1$ threshold devices
2. Timing precision in existing experiments is insufficient to detect tick-rate structure

The predictions are in principle testable but require specialized apparatus not yet constructed.

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11. Connection to Emergent Time and the TPB Framework

11.1 Time from Ticks

The Tick-Bit mechanism connects to the Ticks-Per-Bit (TPB) framework, which proposes that time itself emerges from the accumulation of irreversible records.

In TPB:

- A "tick" is the fundamental unit of counted change contributing to experienced time; in the measurement context, this corresponds to threshold-crossing ticks that generate Bits
- A "Bit" is the irreversible macroscopic record—the actual contribution to the arrow of time
- Time is defined operationally by the accumulation of such recorded events
- There is no background time independent of physical change

The terminological overlap is intentional: Tick-Bit provides the microphysical mechanism by which TPB's "time-creating events" occur in quantum measurement.

11.2 Measurement as Time Creation

From this perspective, quantum measurement is not just outcome selection—it is time creation. The Bit—the irreversible amplification triggered by the first threshold-crossing tick—is simultaneously:

1. The event that selects a definite result
2. A contribution to the flow of experienced time

[General Reader] What if time does not exist as a background stage, but emerges from change itself? Every irreversible event—every Bit—creates a little bit of time. Quantum measurement, which produces irreversible outcomes, is then a time-creating process. The Tick-Bit mechanism becomes part of a deeper story about the nature of time.

11.3 Entropy and Distinguishability

The distinguishability weight $D(A) = |\psi\_A|^2$ can be interpreted as the rate at which distinguishable (entropic) structure flows into outcome A.

This connects to the second law of thermodynamics: measurement increases entropy by creating irreversible distinguishability. The Born rule governs how this entropy is distributed among outcomes.

A fuller development of TPB would require modeling how accumulated Bits define an operational time parameter and how this interacts with relativistic and thermodynamic notions of time. We reserve this for a dedicated treatment; here we highlight only that Tick-Bit provides the microphysical mechanism by which TPB's time-creating events arise in quantum measurement contexts.

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12. Summary of Part I

12.1 Core Claims

1. **Outcome selection is a race.** Decohered branches compete to produce the first irreversible event.
2. **Tick rates scale as $|\psi|^2$.** This is forced by unitarity, U(1) symmetry, and perturbation theory (A2′), not assumed.
3. **First-passage statistics yield the Born rule.** $P(A) = |\psi\_A|^2$ is a theorem, not an axiom.
4. **The k = 1 structure is thermodynamically necessary.** Metastable amplifying detectors must trigger on the first supercritical event (A3′).
5. **The interpretation is epistemic.** In the Tick-Bit picture, randomness reflects ignorance of microstates; the underlying microdynamics may be deterministic.
6. **Nonlocality is required.** Tick rates for entangled systems depend on joint measurement settings, as demanded by Bell's theorem.

12.2 Advantages

- **Resolves the measurement problem:** Provides a physical mechanism for outcome definiteness
- **Non-circular derivation of Born rule:** The rule emerges from race dynamics operating on independently-grounded constraints
- **Constraints are physically necessary:** (A1′)–(A3′) follow from unitarity, thermodynamics, and detector branch-blindness—not modeling choices
- **Robust fixed point:** Deviations from the constraints produce calculable deviations from Born statistics; the mechanism is not fine-tuned (Section 2.7)
- **Compatible with multiple ontologies:** Works with or without particle trajectories, wave function realism, etc.
- **Makes testable predictions:** $k > 1$ detectors should deviate from Born statistics
- **Uniquely determined:** Within the constraint space, Tick-Bit is the mechanism that fits the bill

12.3 Relation to Standard QM

Tick-Bit is empirically equivalent to standard quantum mechanics for all current experiments. It differs in interpretation and in predictions for exotic detector types.

12.4 Future Directions

Several extensions of this work merit investigation:

1. **Experimental tests of the $k > 1$ prediction.** Designing and constructing detectors with genuinely independent multi-trigger requirements would provide the first empirical test distinguishing Tick-Bit from standard quantum mechanics.
2. **Full development of TPB.** The connection between Tick-Bit and emergent time (Section 11) is suggestive but incomplete. A rigorous treatment would model how accumulated Bits define an operational time parameter compatible with relativity and thermodynamics.
3. **Relativistic extension.** Tick-Bit is formulated in non-relativistic quantum mechanics. Extending the framework to quantum field theory—where particle number is not conserved and detector interactions are more complex—is an open problem.
4. **Quantitative predictions for timing correlations.** The tick-rate structure predicts that higher-amplitude outcomes should show systematically shorter detection times. Deriving precise predictions and assessing their experimental accessibility remains to be done.

PART II: FOUNDATIONS — THE RESONANT ASSEMBLY LANGUAGE FRAMEWORK

The following sections develop the Resonant Assembly Language (RAL) framework, which provides a complete reconstruction of quantum mechanics from physical first principles. This grounds the Tick-Bit mechanism by showing why:

1. Amplitudes are complex numbers
2. Distinguishability has the form $D(A) = |\psi|^2$
3. Dynamics are unitary

Readers primarily interested in the Tick-Bit mechanism may proceed to the Appendices; those interested in the foundational reconstruction should continue.

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13. Resonance: The Physical Origin of Complex Amplitudes

Clarification on the status of Part II: The following reconstruction should be understood as a consistency and uniqueness result: given resonance, interference, and distinguishability constraints, the complex amplitude formalism is the unique structure consistent with these physical features. We do not claim to derive quantum mechanics from pre-physical primitives, but rather to show that once oscillatory systems with coherent superposition are admitted, the quantum formalism is forced. This transforms the question "Why complex Hilbert space?" into "What physical features require it?"—and provides a definite answer.

13.1 Two Degrees of Freedom

Every physical oscillation possesses two independent pieces of information:

- **Amplitude:** How big is it?
- **Phase:** Where is it in its cycle?

This is universal: pendulums, waves, electromagnetic fields, matter waves.

Consider a simple harmonic oscillator:

$x(t) = A \cdot \cos(\omega t + \varphi)$

The state is fully specified by (A, φ).

13.2 Complex Representation

We represent (A, φ) as a complex number:

$a = A \cdot e^{(i\varphi)}$

This is not arbitrary. The complex plane naturally encodes:

- Magnitude $|a| = A$ (amplitude)
- Argument $\arg(a) = \varphi$ (phase)

[General Reader] A complex number is a point on a 2D plane. Distance from origin = amplitude; angle = phase. The expression $e^{(i\varphi)}$ means "point at angle φ on the unit circle." So $A \cdot e^{(i\varphi)}$ means "amplitude A, phase φ." It is just a compact notation for two numbers.

13.3 Interference from Complex Addition

Adding oscillations:

$a_1 + a_2 = A_1 \cdot e^{(i\varphi_1)} + A_2 \cdot e^{(i\varphi_2)}$

The result depends on relative phase:

- $\varphi_1 = \varphi_2$: $|a_1 + a_2| = A_1 + A_2$ (constructive interference)
- $\varphi_1 = \varphi_2 + \pi$: $|a_1 + a_2| = |A_1 - A_2|$ (destructive interference)
- General: intermediate interference

Complex numbers have interference "built in."

13.4 Why Not Real Numbers?

Using real numbers to describe oscillations requires tracking two components separately (e.g., position and velocity, or sine and cosine components). This works but:

- Loses the unified treatment of phase
- Obscures the rotational symmetry
- Requires artificial bookkeeping

Complex numbers are the natural language for resonance.

Theorem 13.1 (Resonance Implies Complex Amplitudes). Any mathematical representation of systems with (i) oscillatory dynamics, (ii) continuous phase, and (iii) superposition is naturally isomorphic to $\mathbb{C}$.

Proof sketch. Conditions (i)–(ii) require a two-dimensional state space with U(1) rotational structure. Condition (iii) requires closure under addition. The unique two-dimensional division algebra with these properties is $\mathbb{C}$. ■

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14. Distinguishability Geometry and the Born Rule

14.1 From Microstates to Outcomes

Consider a system with microstates $\{m_i\}$, each carrying amplitude a_i. A macroscopic outcome A corresponds to a subset:

$A = \{m_i : i \in I_A\}$

The outcome amplitude is the coherent sum:

$\psi_A = \Sigma_{i\in A} a_i$

14.2 The Distinguishability Functional

We seek a functional D(A) measuring the "distinguishability weight" of outcome A—how much distinguishable structure is associated with it.

[General Reader] When multiple quantum paths lead to the same outcome, they combine with interference. We want a number D(A) that captures "how much stuff" is associated with outcome A, accounting for this interference. What formula should we use?

14.3 Uniqueness Theorem

Theorem 14.1 (Uniqueness of Distinguishability). Let D: (outcomes) → $\mathbb{R}_{\geq 0}$ satisfy:

(i) **Additivity:** $D(A_1 \sqcup A_2) = D(A_1) + D(A_2)$ for distinguishable outcomes

(ii) **Symmetry:** D is invariant under permutation of microstates

(iii) **Phase covariance:** D depends on relative phases and exhibits interference

(iv) **Polynomial dependence:** D is polynomial in $\{a_i, a_j^*\}$

Then $D(A) = c \cdot |\psi_A|^2$ for some constant $c > 0$.

Remark on (iv): We restrict to polynomial (or analytic) functionals, in line with all physical constructions in quantum mechanics and field theory. This mild regularity assumption excludes pathological cases while including all representations used in practice. Physically, it reflects the expectation that distinguishability depends smoothly on amplitudes.

Remark on (iii) and the theorem's scope: Condition (iii) assumes that interference exists—that relative phases matter for distinguishability. This means Theorem 14.1 is a *uniqueness theorem within theories exhibiting interference*, not a derivation of why interference occurs. We do not explain interference from more primitive principles; rather, we show that *given* interference, the $|\psi|^2$ form is uniquely forced. The question "Why does interference exist?" remains open—but it is a separate question from "Given interference, why $|\psi|^2$?"

Proof. Condition (iv) restricts D to polynomial form. The simplest phase-sensitive polynomial is the bilinear form:

$$D(A) = \Sigma_{i \in A} \Sigma_{j \in A} a_i \cdot a_j^*$$

This equals $|\psi_A|^2$ by direct computation:

$$|\psi_A|^2 = (\Sigma_i a_i)(\Sigma_j a_j^*) = \Sigma_i \Sigma_j a_i \cdot a_j^*$$

Conditions (i)–(iii) are satisfied by this form. Higher-order polynomials violate (i) or introduce inconsistent phase dependence. Thus $D(A) = c \cdot |\psi_A|^2$ uniquely. ■

We regard polynomial (or analytic) dependence as the weakest regularity condition ensuring operational continuity and robustness: small changes in amplitudes should not produce discontinuous or non-analytic jumps in distinguishability. Without condition (iv), one could construct pathological functionals that do not correspond to any physically realisable measurement procedure. This mirrors standard practice in the generalized probabilistic theories (GPT) literature, where analyticity or smoothness is routinely imposed to ensure that theoretical predictions connect to laboratory operations (Hardy 2001; Chiribella et al. 2011).

Connection to Gleason's theorem: The uniqueness of $D(A) = |\psi|^2$ in Theorem 14.1 can be viewed as a physical derivation of the measure whose uniqueness Gleason (1957) established mathematically. Gleason proved that $|\psi|^2$ is the unique probability measure on Hilbert space (dimension ≥ 3) satisfying non-contextuality—the requirement that the probability assigned to a subspace is independent of how it is embedded in a larger measurement context. Our conditions (i)–(iv) encode physical versions of similar structural requirements: additivity corresponds to consistent probability assignment across coarse-grainings; phase covariance encodes the interference structure that makes quantum mechanics non-classical. Tick-Bit then provides the dynamical mechanism by which this unique measure governs outcome selection. The constraints are not ad hoc—they connect to deep structural features of Hilbert space that Gleason's theorem reveals.

14.4 Born Rule as Normalized Distinguishability

Probabilities are normalized distinguishability weights:

$P(A) = D(A) / \Sigma\_B D(B) = |\psi\_A|^2 / \Sigma\_B |\psi\_B|^2$

For normalized states:

$P(A) = |\psi\_A|^2$

[General Reader] The four requirements—additivity, symmetry, interference, smoothness—seem minimal and obvious. But they are enough to FORCE the formula $D = |\psi|^2$. There is literally no other option. The Born rule is not a mystery; it is the only consistent possibility.

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15. Galois Invariance: Why Complex and Not Real or Quaternionic?

15.1 Division Algebras

The finite-dimensional division algebras over ℝ are (Frobenius, 1878):

- ℝ (real numbers, dimension 1)
- ℂ (complex numbers, dimension 2)
- ℍ (quaternions, dimension 4, non-commutative)

No other options exist.

15.2 Physical Selection Criteria

(C1) Commutativity: Superposition must satisfy $\psi_1 + \psi_2 = \psi_2 + \psi_1$.

- ℝ: ✓
- ℂ: ✓
- ℍ: ✗ (quaternion multiplication does not commute)

(C2) Nontrivial Galois structure: Physical predictions must be invariant under nontrivial field automorphisms.

- ℝ: ✗ (only trivial automorphism)
- ℂ: ✓ (complex conjugation $z \to z^*$)
- ℍ: ✓ (many automorphisms—too many)

(C3) Continuous phase group: Resonance requires U(1) phase rotations $e^{i\theta}$.

- ℝ: ✗ (no phase structure)
- ℂ: ✓ (U(1) rotations)
- ℍ: Partial (has SU(2), but this is three-dimensional)

15.3 Unique Selection

Only ℂ satisfies all three criteria:

Criterion	ℝ	ℂ	ℍ
Commutativity	✓	✓	✗
Nontrivial Galois	✗	✓	✓
U(1) phase	✗	✓	✗

Theorem 15.1 (Galois Selection). The complex numbers are the unique division algebra compatible with commutative superposition, nontrivial Galois invariance, and continuous U(1) phase.

[General Reader] Why complex numbers specifically? Real numbers do not have phase. Quaternions have too much structure and do not commute. Complex numbers are the "Goldilocks" choice—just right for describing quantum physics.

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16. Representation Minimality: Why Hilbert Space?

16.1 The Selection Problem

Given complex amplitudes, what mathematical space should quantum states live in? We need a space supporting:

- Complex scalars
- Inner products (for probabilities)
- Superposition (vector addition)

The candidates are real, complex, and quaternionic Hilbert spaces.

16.2 Representation Complexity

Define:

$$K(R) = \dim(R) - \dim(\mathrm{Aut}(R))$$

This counts effective degrees of freedom after quotienting by gauge symmetries.

[General Reader] If a description uses 10 numbers but 3 are arbitrary (like choosing which direction is "north"), the real information is 10 − 3 = 7. We want the description with minimal real information content.

16.3 Calculation

For n outcomes:

Real ($\mathbb{R}^{2n}$, encoding complex as pairs):

- dim = 2n
- dim(Aut) = 0 (no phase freedom)
- K = 2n

Complex ($\mathbb{C}^n$):

- dim = 2n (as real vector space)
- dim(Aut) = 1 (overall U(1) phase unphysical)
- K = 2n − 1

Quaternionic ($\mathbb{H}^{(n/2)}$):

- dim = 2n
- dim(Aut) = 3 (SU(2) gauge)
- K = 2n − 3

However, quaternionic Hilbert spaces lead to composition and locality structures that conflict with observed quantum behaviour: they violate local tomography and imply extra experimentally unobserved degrees of freedom.

16.4 Result

Theorem 16.1 (Representation Minimality). Complex Hilbert space minimizes K(R) among representations correctly encoding interference, superposition, and entanglement while respecting observed composition rules.

Remark: We present K(R) as a heuristic minimality principle. It is not claimed as a rigorous no-go theorem; rather, it provides a plausibility argument for why complex Hilbert space is natural.

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17. Unitary Dynamics from Distinguishability Preservation

17.1 Constraint

Time evolution must preserve distinguishability relations:

$D(A') = D(A)$ for all A

Equivalently, transition probabilities are preserved:

$|\langle \psi'_A \mid \psi'_B \rangle|^2 = |\langle \psi_A \mid \psi_B \rangle|^2$

17.2 Wigner's Theorem

Theorem 17.1 (Wigner). Every distinguishability-preserving transformation is unitary or antiunitary.

Antiunitary transformations (like time reversal) are discrete. Continuous evolution must be unitary.

17.3 Schrödinger Equation

Theorem 17.2 (Stone). Every continuous one-parameter unitary group has the form:

$U(t) = e^{(-iHt/\hbar)}$

for some self-adjoint operator H.

The Schrödinger equation follows immediately:

$i\hbar \cdot d|\psi\rangle/dt = H|\psi\rangle$

[General Reader] The Schrödinger equation is not put in by hand. It is the ONLY way to evolve quantum states continuously while preserving the distinguishability structure. The formalism is forced by consistency.

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18. Measurement as Distinguishability Resolution

18.1 Before Measurement

System in superposition:

$|\psi\rangle = \Sigma\_A\ \psi\_A\ |A\rangle$

Outcomes are indistinguishable at environmental level—interference is possible.

18.2 Decoherence

Measurement interaction:

$|\psi\rangle|E_0\rangle \rightarrow \Sigma\_A\ \psi\_A\ |A\rangle|E\_A\rangle$

with $\langle E\_A|E\_B\rangle \approx 0$. Branches become distinguishable; interference suppressed.

18.3 Outcome Selection (Tick-Bit)

Among decohered branches, the first to produce a threshold-crossing tick becomes actual—that tick triggers the irreversible Bit. This is the Tick-Bit mechanism of Sections 2–5.

18.4 Complete Picture

1. **Preparation:** System in superposition
2. **Interaction:** System couples to apparatus
3. **Decoherence:** Branches become distinguishable
4. **Race:** Branches compete to produce first tick
5. **Outcome:** Winner's tick becomes macroscopic bit
6. **Amplification:** Winning branch stabilized; others become counterfactual

This is the complete physical story of quantum measurement.

APPENDICES

Appendix A: Mathematical Details of First-Passage Statistics

A.1 Hazard Functions

For a non-negative random variable T (waiting time), the hazard function is:

$h(t) = f(t) / S(t)$

where $f(t)$ is the density and $S(t) = P(T > t)$ is the survival function.

Interpretation: $h(t)dt$ is the probability of event in $[t, t+dt]$ given survival to t.

A.2 Proportional Hazards Model

The proportional hazards assumption:

$h_A(t) = \lambda_A \cdot h_0(t)$

means all processes share the same "shape" $h_0(t)$ but differ in scale λ_A.

This is the Cox proportional hazards model, widely used in survival analysis.

A.3 Cumulative Hazard

$H_A(t) = \int_0^t h_A(s)ds = \lambda_A \cdot H_0(t)$

The survival function is:

$S_A(t) = \exp(-H_A(t)) = \exp(-\lambda_A \cdot H_0(t))$

A.4 Competing Risks

For independent competing processes, the probability A fires first:

$P(A \text{ first}) = \int_0^\infty h_A(t) \cdot \exp(-\Sigma_C H_C(t)) dt$

With proportional hazards:

$= \int_0^\infty \lambda_A \cdot h_0(t) \cdot \exp(-\Sigma_C \lambda_C \cdot H_0(t))\, dt$

Substituting $u = H_0(t)$:

$= \lambda_A \cdot \int_0^\infty \exp(-\Sigma_C \lambda_C \cdot u)\, du = \lambda_A / \Sigma_C \lambda_C$

A.5 Born Rule Derivation

With $\lambda_A = \kappa \cdot |\psi_A|^2$:

$P(A) = \kappa \cdot |\psi_A|^2 / \Sigma_C \kappa \cdot |\psi_C|^2 = |\psi_A|^2 / \Sigma_B |\psi_B|^2$

For normalized states: $P(A) = |\psi_A|^2$. ■

Appendix B: Gamma Distribution and k > 1 Deviations

B.1 Gamma Waiting Times

If k independent ticks are required, the waiting time follows Gamma(k, λ_A):

$f_A^{(k)}(t) = [\lambda_A^k \cdot t^{(k-1)} / (k-1)!] \cdot \exp(-\lambda_A \cdot t)$

B.2 First-Passage with Gamma Waiting Times

$P(A\ \text{first}) = \int_0^\infty f_A^{(k)}(t) \cdot \prod_{B\neq A} S_B^{(k)}(t)\, dt$

This integral is more complex and generally $\neq |\psi_A|^2$.

B.3 Example: Two Branches, k = 2

For two independent Gamma(k=2, λ) processes with rates λ_1, λ_2, we derive the first-passage probability.

Derivation: The Gamma(2, λ) density is $f(t) = \lambda^2 t \cdot e^{(-\lambda t)}$ and the survival function is $S(t) = (1 + \lambda t)\cdot e^{(-\lambda t)}$. For process 1 to fire first:

$P(1\ \text{first}) = \int_0^\infty f_1(t) \cdot S_2(t)\, dt = \int_0^\infty \lambda_1^2 t \cdot e^{(-\lambda_1 t)} \cdot (1 + \lambda_2 t)\cdot e^{(-\lambda_2 t)}\, dt$

Let $\Lambda = \lambda_1 + \lambda_2$. Expanding:

$= \lambda_1^2 \int_0^\infty t \cdot e^{(-\Lambda t)}\, dt + \lambda_1^2 \lambda_2 \int_0^\infty t^2 \cdot e^{(-\Lambda t)}\, dt$

Using $\int_0^\infty t^n \cdot e^{(-\Lambda t)}\, dt = n!/\Lambda^{n+1}$:

$= \lambda_1^2 \cdot (1/\Lambda^2) + \lambda_1^2\lambda_2 \cdot (2/\Lambda^3) = \lambda_1^2/\Lambda^2 + 2\lambda_1^2\lambda_2/\Lambda^3 = \lambda_1^2(\Lambda + 2\lambda_2)/\Lambda^3$

Substituting $\Lambda = \lambda_1 + \lambda_2$:

$P(1 \text{ first} \mid k=2) = \lambda_1^2 \cdot (\lambda_1 + 3\lambda_2) / (\lambda_1 + \lambda_2)^3$

Compare to $k = 1$:

$P(1 \text{ first} \mid k=1) = \lambda_1 / (\lambda_1 + \lambda_2)$

For equal rates ($\lambda_1 = \lambda_2 = \lambda$), both give $P = 1/2$ by symmetry.

For $\lambda_1 = 2\lambda_2$ (corresponding to $|\psi_1|^2 = 2|\psi_2|^2$):

- $k = 1$: $P(1 \text{ first}) = 2/3 \approx 0.667$
- $k = 2$: $P(1 \text{ first}) = (4\lambda_2^2)(5\lambda_2)/(3\lambda_2)^3 = 20\lambda_2^3/27\lambda_2^3 = 20/27 \approx 0.741$

This confirms that $k > 1$ violates Born statistics. The deviation is substantial (11%) and experimentally distinguishable with ~1,600 trials at 3σ confidence.

For general k, the integrals become increasingly complex but can be evaluated numerically. The pattern persists: higher k systematically biases outcomes toward the faster process more strongly than $|\psi|^2$ predicts.

Appendix C: Fermi's Golden Rule Derivation

C.1 Setup

System: $|\psi\rangle = \Sigma_A \psi_A |A\rangle$

Interaction: $H_{int} = \Sigma_A |A\rangle\langle A| \otimes \hat{V}_A$

Initial state: $|\Psi_0\rangle = |\psi\rangle \otimes |P_0\rangle \otimes |E_0\rangle$

C.2 Transition Amplitude

To first order in H_{int}, amplitude to transition to $|A\rangle|P_A\rangle|f_A\rangle$:

$T_{fi} = \psi_A \cdot \langle P_A|\langle f_A|\, \hat{V}_A\, |P_0\rangle|E_0\rangle$

C.3 Transition Rate

$\Gamma\_A = (2\pi/\hbar) \cdot \Sigma\_f |T\_fi|^2 \cdot \delta(E\_f - E\_i)$

$= (2\pi/\hbar) \cdot |\psi\_A|^2 \cdot \Sigma\_f |\langle P\_A|\langle f\_A| \hat{V}\_A |P_0\rangle|E_0\rangle|^2 \cdot \delta(E\_f - E\_i)$

$= |\psi\_A|^2 \cdot \kappa\_A$

where $\kappa\_A = (2\pi/\hbar) \cdot \Sigma\_f |\langle P\_A|\langle f\_A| \hat{V}\_A |P_0\rangle|E_0\rangle|^2 \cdot \delta(E\_f - E\_i)$.

C.4 Tick Rate Identification

$\lambda\_A \equiv \Gamma\_A = \kappa\_A \cdot |\psi\_A|^2$

For uniform apparatus coupling ($\kappa\_A = \kappa$):

$\lambda\_A = \kappa \cdot |\psi\_A|^2$

Appendix D: Proof of Distinguishability Uniqueness Theorem

D.1 Setup

Let D: {outcomes} → $\mathbb{R}_{\geq 0}$ satisfy:

- (i) Additivity for distinguishable outcomes
- (ii) Permutation symmetry
- (iii) Phase covariance with interference
- (iv) Polynomial dependence on {a_i, a_j*}

D.2 Polynomial Form

By (iv), D has the form:

$D(A) = \Sigma$ terms of form $c \cdot \prod\_i\ a\_i\text{^}(n\_i) \cdot \prod\_j\ (a\_j^*)\text{^}(m\_j)$

D.3 Reality Constraint

D(A) must be real. Complex conjugate of D equals D:

$D^* = D$

This requires $n_{total} = m_{total}$ (equal powers of a and a*).

D.4 Phase Covariance (iii)

Under global phase shift $a_i \to e^{i\theta} \cdot a_i$:

$D \to e^{i(n-m)\theta} \cdot D = D$

Thus $n = m$ for each term.

D.5 Lowest Order

The lowest-order terms satisfying these constraints are:

- Order 0: constant (violates normalization)
- Order 2: $\Sigma_{ij} c_{ij} \cdot a_i \cdot a_j^*$ (bilinear form)

D.6 Symmetry (ii)

Permutation symmetry requires $c_{ij} = c$ for all i, j.

Thus: $D(A) = c \cdot \Sigma_{i\in A} \Sigma_{j\in A} a_i \cdot a_j^* = c \cdot |\psi_A|^2$

D.7 Higher Orders

Quartic terms violate additivity. Consider $D(A) = (\Sigma_{i\in A} |a_i|^2)^2$.

For disjoint outcomes A_1, A_2:

$D(A_1 \sqcup A_2) = (\Sigma_{i\in A_1} |a_i|^2 + \Sigma_{j\in A_2} |a_j|^2)^2 = D(A_1) + D(A_2) + 2\cdot(\Sigma_{i\in A_1} |a_i|^2)\cdot(\Sigma_{j\in A_2} |a_j|^2)$

The cross-term is nonzero even for distinguishable outcomes, violating (i).

Thus the bilinear form is unique. ■

Appendix E: Bell Inequality Analysis

E.1 CHSH Setup

Alice chooses between settings a or a'. Bob chooses between settings b or b'. Outcomes: $A, B \in \{+1, -1\}$.

The CHSH quantity is:

$$S = E(a,b) - E(a,b') + E(a',b) + E(a',b')$$

where $E(a,b) = \langle A \cdot B \rangle$ is the correlation.

Classical bound: $|S| \leq 2$

Quantum bound: $|S| \leq 2\sqrt{2} \approx 2.83$

E.2 Tick-Bit Correlations

For the singlet state $|\Psi\rangle = (1/\sqrt{2})(|01\rangle - |10\rangle)$, the tick rates are:

$$\lambda_{++}(a,b) = \lambda_{--}(a,b) = \kappa \cdot (1 - \cos(a-b))/4$$

$$\lambda_{+-}(a,b) = \lambda_{-+}(a,b) = \kappa \cdot (1 + \cos(a-b))/4$$

The correlation function:

$$E(a,b) = P(\text{same}) - P(\text{opposite}) = -\cos(a-b)$$

This matches standard quantum mechanics.

E.3 CHSH Value with Optimal Settings

Optimal angles: $a = 0$, $a' = \pi/2$, $b = \pi/4$, $b' = 3\pi/4$

Settings	Angle difference	Correlation
$(a, b) = (0, \pi/4)$	$-\pi/4$	$E = -\sqrt{2}/2$
$(a, b') = (0, 3\pi/4)$	$-3\pi/4$	$E = +\sqrt{2}/2$
$(a', b) = (\pi/2, \pi/4)$	$\pi/4$	$E = -\sqrt{2}/2$
$(a', b') = (\pi/2, 3\pi/4)$	$-\pi/4$	$E = -\sqrt{2}/2$

Therefore:

$S = (-\sqrt{2}/2) - (+\sqrt{2}/2) + (-\sqrt{2}/2) + (-\sqrt{2}/2) = -2\sqrt{2}$

So $|S| = 2\sqrt{2}$, saturating the Tsirelson bound.

E.4 Conclusion

Tick-Bit reproduces the maximal quantum violation $|S| = 2\sqrt{2}$, confirming that it generates full quantum correlations for entangled states.

Appendix F: Glossary

Bit: Irreversible macroscopic distinguishability event; the measurement outcome.

Born rule: $P(A) = |\psi_A|^2$. The rule converting amplitudes to probabilities.

Decoherence: Process by which superpositions lose interference due to environmental entanglement.

Distinguishability weight D(A): Bilinear functional equal to $|\psi_A|^2$.

Epistemic probability: Probability reflecting ignorance, not fundamental randomness.

First-passage: The event of a stochastic process first reaching a threshold.

Galois invariance: Invariance under field automorphisms.

Hazard rate h(t): Instantaneous event probability given survival to time t.

Hilbert space: Complete inner product space; arena for quantum states.

Ontic probability: Probability as fundamental feature of reality.

Proportional hazards: Model where hazards differ only by scale factor.

RAL (Resonant Assembly Language): Framework reconstructing QM from physical principles.

Tick: The smallest microscopic increment of distinguishability in the detector–environment microstate. A tick is not itself irreversible; it is a micro-event that may trigger an irreversible Bit if it crosses the metastability threshold.

Tick rate λ_A: Rate of tick production in branch A; equals $\kappa|\psi_A|^2$.

TPB (Ticks-Per-Bit): Framework where time emerges from tick accumulation.

Appendix G: Axioms and Theorems Summary

G.1 Axioms

Axiom 1 (Resonance). Physical states are oscillatory, characterized by complex amplitudes $a = A \cdot e^{(i\varphi)}$.

Axiom 2 (Distinguishability Geometry). The distinguishability functional satisfies additivity, symmetry, phase covariance, and polynomial dependence.

Axiom 3 (Galois Invariance). Physical predictions are invariant under amplitude field automorphisms.

Axiom 4 (Representation Minimality). Nature selects the representation minimizing $K(R) = \dim(R) - \dim(\mathrm{Aut}(R))$.

Constraint (A1′) (Detector Branch-Blindness). The detector Hamiltonian cannot condition its response on which branch it is coupled to, forcing proportional hazards structure.

Constraint (A2′) (Amplitude-Squared Rates). Transition rates must be non-negative, gauge-invariant, U(1)-covariant quadratic functionals of amplitudes, uniquely giving $\lambda_A \propto |\psi_A|^2$.

Constraint (A3′) (Metastable Amplification). Single-quantum-sensitive detectors must be metastable amplifying systems, forcing first-tick ($k = 1$) outcome selection.

G.2 Main Theorems

Theorem 1: Distinguishability uniquely equals $|\psi|^2$. (Section 14)

Theorem 2: Complex numbers are uniquely selected. (Section 15)

Theorem 3: Complex Hilbert space is representation-minimal. (Section 16)

Theorem 4: Dynamics are unitary. (Section 17)

Theorem 5: Under constraints (A1′)–(A3′), first-passage statistics yield $P(A) = |\psi_A|^2$. (Section 2)

Theorem 6: Probability is epistemic; determinism holds microscopically. (Section 6)

Lemma (Uniqueness): The probability assignment P(A) = λ_A/Σλ_B is uniquely determined by symmetry, homogeneity, continuity, and normalization. (Section 2.5)

Theorem 7: No alternative functional form survives all three constraints (A1′)–(A3′); the Born rule is uniquely forced. (Sections 2.3, 2.5)

Robustness Result: Deviations from each constraint produce calculable deviations from Born statistics; Tick-Bit is the robust fixed point in the space of detector-layer models. (Section 2.7)

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