# Ticks Per Bit: A Complete Framework for Emergent Discrete Time

## Abstract

We present Ticks Per Bit (TPB) as a rigorous framework in which time emerges from discrete micro-events (ticks) accumulating to produce bit-level changes in physical state. The framework is derived from first principles: formation curvature governs a Role-4 Lagrangian whose dynamics explain why many ticks are required per bit. We prove that TPB belongs to a universality class—any potential satisfying minimal structural conditions produces identical qualitative dynamics. We establish constrained uniqueness: any theory respecting Bit Conservation and Balance (BCB), finite information, locality, and emergent time must reduce to a TPB-type structure. We demonstrate that continuous fundamental time is physically impossible, and systematically eliminate all alternative discrete-time ontologies. The result is a complete emergent-time model compatible with quantum mechanics, general relativity, and information-theoretic constraints.

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# 1. Introduction: The TPB Hypothesis

## 1.1 The Central Idea

What if time isn't a fundamental feature of reality, but something that *emerges* from deeper processes—like how temperature emerges from the motion of atoms, or how wetness emerges from water molecules?

The TPB framework proposes exactly this. At the deepest level, reality consists of:

- **Ticks**: The most basic events that can happen—irreducible micro-happenings that cannot be broken down further
- **Bits**: Discrete units of distinguishability (think: the minimal "difference" that can exist between two states)
- **TPB(x)**: The number of ticks required to complete one bit-level change at location x

Time, in this view, is simply the accumulated record of successful bit transitions. A clock doesn't measure some pre-existing "flow of time"—it counts bit changes.

## 1.2 The Fundamental Relationship

The connection between ticks and experienced time is:

$$d\tau/dt = 1/TPB(x)$$

In words: the rate at which proper time $\tau$ passes (relative to coordinate time t) equals one divided by the local ticks-per-bit count.

*Think of it this way*: If it takes 1000 ticks to form one bit at location A, but only 100 ticks at location B, then clocks at A run 10 times slower than clocks at B. More ticks required means slower time.

## 1.3 Physical Consequences

This simple idea has profound implications:

| Regime | TPB Value | Physical Meaning |
|---|---|---|
| Flat spacetime | TPB $\approx N_0$ (baseline) | Normal clock rates |
| Gravitational well | TPB $> N_0$ | Time dilation (slow clocks) |
| Near horizon | TPB $\to \infty$ | Time freezing |
| High velocity | TPB increases | Kinematic time dilation |

*The key insight*: Gravity isn't a force that "slows down" pre-existing time. Rather, gravity is a region where bit formation is harder—requiring more ticks—and time is simply the count of completed bits. Slow clocks near massive objects aren't malfunctioning; they're accurately reporting that fewer bits have formed.

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# 2. The Role-4 Mechanism: From Curvature to Dynamics

## 2.1 How Does a Bit Form?

A bit doesn't pop into existence instantaneously. Its formation is a process that unfolds over many ticks. We track this process with a progress variable y, which ranges from just above 0 to exactly 1:

- **$y \to 0^+$** represents the "void boundary"—the edge of non-existence, where no bit has yet formed
- **$y = 1$** represents a fully stabilized, completed bit

*Analogy*: Think of y as measuring how "formed" something is. A sculptor starting with raw marble has y near 0; the finished statue has y = 1. The question is: what governs the journey from 0 to 1?

## 2.2 The Formation Curvature Principle

We define **formation curvature** R_form(y) as the resistance to progress at stage y. The fundamental principle is:

The curvature of the formation potential is proportional to formation curvature.

Mathematically: **$R\_form(y) \propto |d^2V/dy^2|$**

*What this means*: The "landscape" that the forming bit must traverse is shaped by how hard it is to make progress. Regions of high resistance create steep potential walls.

## 2.3 The Divergent Curvature Requirement

The void boundary must be absolutely forbidden—no bit can "fall back" into non-existence. This requires formation curvature to diverge (become infinite) as y approaches 0:

**$R\_form(y) = A/y^p$, where $p > 2$**

Here A > 0 is a coupling constant that sets the overall scale.

*Why the divergence matters*: As the system gets closer to the void ($y \to 0$), the resistance becomes infinitely strong. It's like an invisible wall that gets harder and harder to approach. You can get arbitrarily close, but you can never actually reach it or cross it.

**Critical constraint**: We require $p > 2$ (not merely $p > 1$) because:

- For $\mathbf{p > 2}$: $V(y) \to +\infty$ as $y \to 0^+$ (strong power-law barrier)
- For $\mathbf{p = 2}$: $V(y) \sim -A \ln y \to +\infty$ (logarithmic barrier; still divergent but weaker)
- For $\mathbf{1 < p < 2}$: $V(y)$ remains finite at $y = 0$ (no true barrier)

While $p = 2$ still produces an infinite barrier, the logarithmic divergence is qualitatively weaker than power-law. We adopt $p > 2$ to ensure robust void exclusion under perturbations.

## 2.4 Deriving the Potential

Starting from $d^2V/dy^2 = A/y^p$, we integrate twice to find the potential $V(y)$.

**First integration:**

$$dV/dy = -A/[(p-1)] \cdot y^{-(p-1)} + C_1$$

**Second integration:**

$$V(y) = A/[(p-1)(p-2)] \cdot y^{-(p-2)} + C_1 y + C_2$$

**Boundary conditions**: For the potential to have its unique minimum at $y = 1$ (the stable bit state), we require $C_1 = 0$. The constant $C_2$ sets the zero of energy and is physically irrelevant.

Thus the curvature-derived potential is:

$$\mathbf{V_{curv}(y) = A/[(p-1)(p-2)] \cdot y^{-(p-2)}}$$

*Physical picture*: This potential creates a "landscape" where moving toward $y = 0$ requires climbing an infinitely tall hill, while $y = 1$ sits in a valley.

## 2.5 The Bit Ground State

The bit must stabilize at $y = 1$. We add a harmonic (spring-like) stabilization term:

$$\mathbf{V_{bit}(y) = (\kappa/2)(y - 1)^2}$$

*Analogy*: This is like attaching a spring that pulls the system toward $y = 1$. The further from 1, the stronger the pull back.

The complete Role-4 potential is:

$$V(y) = A/[(p-1)(p-2)] \cdot y^{-(p-2)} + (\kappa/2)(y-1)^2$$

This potential:

- Diverges to $+\infty$ as $y \to 0^+$ (void barrier—you can't go there)
- Has a unique global minimum at $y = 1$ (stable bit—this is where you end up)
- Has $V'(y) < 0$ for $y \in (0, 1)$ (there's always a force pushing toward completion)

## 2.6 The Role-4 Lagrangian

The dynamics are governed by a Lagrangian (the mathematical object that encodes how systems evolve):

$$\mathcal{L} = (M/2)(dy/d\lambda)^2 - V(y)$$

Here $\lambda$ is a **tick-ordering parameter**, not time. This is crucial: time does not yet exist at this level. The parameter $\lambda$ simply counts "which tick are we on?" Time will emerge later from the accumulation of completed bit formations.

*Why this matters*: In standard physics, we write equations of motion in terms of time. But if time is what we're trying to explain, we can't assume it exists at the fundamental level. Instead, we use $\lambda$—a simple counter of ticks—and let time emerge from the dynamics.

The equation of motion (from the Euler-Lagrange procedure) is:

$$M \cdot d^2y/d\lambda^2 = A(p-2)/(p-1) \cdot y^{-(p-1)} - \kappa(y-1)$$

*In words*: The acceleration of y depends on two competing effects—a strong repulsion from the void (first term) and a gentle attraction toward $y = 1$ (second term).

## 2.7 Overdamped Formation Dynamics

In realistic physical conditions, bit formation occurs in an overdamped regime with stochastic driving:

$$\Gamma \cdot dy/d\lambda + dV/dy = \xi(\lambda)$$

Here $\Gamma$ is a damping coefficient (representing friction or resistance) and $\xi(\lambda)$ represents random fluctuations (thermal or quantum noise).

*Analogy*: Imagine a ball rolling through honey on a hilly landscape, while someone occasionally gives it random nudges. The honey (damping) prevents the ball from rolling freely; the nudges (noise) provide the energy to keep it moving.

The dynamics proceed as follows:

1. The system attempts to progress toward $y = 1$
2. Fluctuations occasionally push y toward smaller values
3. The divergent barrier at $y \to 0$ causes strong repulsion (a "bounce")
4. Each bounce shifts y slightly forward on average
5. After many such bounces, y reaches 1 and the bit stabilizes

This **bounce-and-creep** mechanism explains why bit formation requires many ticks: the system must undergo numerous micro-reversals before successfully completing the transition.

*Physical intuition*: Forming a bit isn't a smooth slide from 0 to 1. It's more like a random walk with a bias—lots of back-and-forth motion, but with a slight tendency to move forward. The infinite barrier at $y = 0$ ensures that backward excursions always bounce back.

## 2.8 Time Contribution from Formation Stage

The proper time accumulated during formation depends on the current stage y. Define $\delta\tau(y)$ as the time contribution per tick when the system is at progress y. Intuitively, ticks spent fighting the void barrier should contribute little to proper time, while ticks near completion contribute more. This suggests:

$$\delta\tau(y) \propto 1/R\_form(y) \propto y^p$$

*What this means*: Near the void ($y \to 0$), $\delta\tau \to 0$—each tick contributes negligibly to proper time because the dynamics are entirely absorbed in resisting the barrier. Near completion ($y \to 1$), $\delta\tau$ approaches its maximum—ticks translate efficiently into temporal progress.

The total proper time for one bit formation is:

$$\Delta\tau\_bit = \int_0^{TPB} \delta\tau(y(\lambda))\, d\lambda$$

Since TPB is large and most ticks occur at small y (where $\delta\tau$ is small), the integral converges despite the large tick count.

*The key insight*: Many ticks near the void contribute almost nothing to elapsed time, while the final approach to $y = 1$ contributes the bulk of elapsed proper time. Time isn't just "tick counting"—it's weighted tick counting, where the weight depends on formation progress.

## 2.9 The Buffer Zone: Where Ticks Barely Count

The combination of a divergent barrier near $y = 0$ and the weighting $\delta\tau(y) \propto y^p$ naturally creates what we can call a **buffer zone**: a region of formation progress where many ticks occur, but almost none of them register as elapsed proper time.

In practice, there is a smallest effective value $y_{min} > 0$ that the system can approach. Below this scale, the formation curvature is so large that motion toward the void is overwhelmingly suppressed, and any backward excursions are immediately bounced back. The interval

$$0 < y \lesssim y_{min}$$

is therefore a kind of *pre-temporal buffer region*. Ticks spent here are real micro-events—they contribute to the underlying dynamics—but because $\delta\tau(y)$ is extremely small in this regime, they contribute essentially nothing to proper time.

*Think of it this way*: Imagine a video game where your character can move around freely in most areas, but near certain boundaries the game engine runs thousands of physics calculations just to keep you from clipping through the wall. All that computational work happens, but from the player's perspective, nothing changes—you just stay in place. The buffer zone is similar: intense tick-level activity, minimal temporal result.

This buffer zone plays two crucial roles:

**1. Void protection** — It enforces the impossibility of crossing back into non-existence. The system can flirt with the boundary but never reach it. The buffer zone is the "guardrail" that keeps bits from falling out of existence.

**2. Tick inflation without time inflation** — It allows TPB to become very large (many ticks per bit) without forcing proper time to blow up. Most of those ticks occur in the buffer zone, where they barely move the temporal clock.

*Why this matters*: Without the buffer zone, we'd face a puzzle. If every tick contributed equally to time, then large TPB would mean long formation times—and we'd need to explain why bit formation takes so long in absolute terms. The buffer zone resolves this: TPB can be enormous because most ticks are "absorbed" by the buffer, leaving only a modest contribution to elapsed proper time.

Conceptually, this is why the universe can be both **computationally busy** at the tick level and **temporally calm** at the macroscopic level. There is an entire layer of dynamics—ticks in the buffer zone—that shape how hard it is to form bits, without directly contributing much to the experienced passage of time.

*An analogy from thermodynamics*: Consider a gas molecule bouncing off a container wall. At the molecular level, there's a complex interaction involving electromagnetic repulsion, electron cloud deformation, and rapid momentum exchange. But at the macroscopic level, we just say "the molecule bounced." All that microscopic complexity is real, but it doesn't show up in the thermodynamic description. Similarly, buffer zone ticks are real micro-events that don't show up in the temporal description.

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# 3. Universality of the Bounce Dynamics

## 3.1 Why Universality Matters

A skeptic might ask: "Isn't this all dependent on the specific form of V(y) you chose? What if you picked a different potential?"

This section proves that the specific form doesn't matter. What matters is the *qualitative structure*—and a wide class of potentials all produce the same essential dynamics. This is called **universality**.

*Analogy*: Many different liquids (water, oil, alcohol) all flow downhill. The details differ, but the qualitative behavior is universal. Similarly, many different potentials all produce bounce-and-creep dynamics toward bit formation.

## 3.2 The Universality Class

Define the universality class $\mathcal{U}$ as all potentials satisfying:

**U1.** $V \in C^2(0, 1]$ — the potential is smooth (twice differentiable) on the interval

**U2.** lim_{y→0⁺} V(y) = +∞ — infinite void barrier

**U3.** $V'(1) = 0$ and $V''(1) > 0$ — unique stable minimum at $y = 1$

**U4.** $V'(y) < 0$ for all $y \in (0, 1)$ — monotonic restoring force toward completion

*In plain language*: Any potential that (1) has an impassable wall at $y = 0$, (2) has a stable resting point at $y = 1$, and (3) always pushes toward $y = 1$, belongs to the universality class.

## 3.3 Universal Dynamics Theorem

**Theorem**: For any $V \in \mathcal{U}$ and any initial condition $y_0 \in (0, 1)$, the overdamped dynamics

**$\Gamma \cdot dy/d\lambda + dV/dy = 0$**

produce a solution $y(\lambda)$ that:

1. Increases monotonically in $\lambda$ (always moves forward, never backward on average)
2. Never reaches $y = 0$ (void remains forbidden)
3. Never overshoots $y = 1$ (doesn't overshoot the target)
4. Converges to $y = 1$ as $\lambda \to \infty$ (eventually completes the bit)

*Why this is powerful*: It means we don't need to know the exact microscopic details of bit formation. As long as the potential has the right qualitative shape, the dynamics are guaranteed to work correctly.

## 3.4 Universally Large TPB

The number of ticks required to form a bit is:

$$\mathbf{TPB} = \int_0^1 R\_form(y)/(\alpha\kappa') \, dy$$

where $\alpha$ and $\kappa'$ are effective coupling parameters.

For any $R\_form(y) = A/y^p$ with $p > 1$:

$$\mathbf{TPB} \propto \int_0^1 dy/y^p$$

This integral diverges for $p \geq 1$, but is regulated by a physical cutoff $y\_min > 0$ (the closest approach to the void). Even with this cutoff:

$$\mathbf{TPB} \sim y\_min^{(-(p-1))} \gg 1$$

*The bottom line*: TPB is generically large for any potential in the universality class—independent of microscopic details. This isn't a fine-tuned result; it's a robust prediction.

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# 4. The BPT Update Rule as Coarse-Grained Role-4

## 4.1 From Microphysics to Update Rules

At the coarse-grained level (zooming out from individual ticks), the Role-4 dynamics reduce to a discrete update rule. The progress per tick is bounded by:

$$\Delta y \leq \alpha\kappa'/R\_form(y)$$

Substituting $R\_form(y) = A/y^p$:

$$\Delta y \leq (\alpha\kappa'/A) \cdot y^p$$

This is the **BPT (Bit Per Tick) update rule**: progress is slower when y is small (near the void) and faster when y is large (near completion).

*Intuition*: Early in bit formation, you're fighting the void barrier, so each tick moves you very little. Late in formation, the path is clear, and each tick makes good progress.

## 4.2 Consistency Check

The total number of ticks to traverse from $y \approx 0$ to $y = 1$:

$$N = \int_0^1 dy/\Delta y\_max = \int_0^1 A/(\alpha\kappa' y^p)\, dy$$

This matches our direct TPB calculation, confirming that BPT is the coarse-grained limit of Role-4 microphysics. The two descriptions are consistent.

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# 5. Constrained Uniqueness of the TPB Framework

## 5.1 What Is Constrained Uniqueness?

By **constrained uniqueness** we mean: within the class of theories satisfying specified physical axioms, all models are dynamically equivalent to TPB.

*In other words*: TPB isn't just one possible framework—it's the *only* framework consistent with certain basic physical requirements.

The axioms are:

**Axiom 1 (BCB)**: Bit Conservation and Balance holds locally:

$$\partial s/\partial t + \nabla \cdot J = 0$$

where s is distinguishability density and J is bit current.

*In plain terms*: Bits can't appear from nowhere or vanish into nothing. They can only flow from place to place, like a conserved fluid.

**Axiom 2 (Finite Information)**: Any bounded region contains finite distinguishability. There exists a maximum bit density.

*In plain terms*: You can't pack infinite information into a finite space. Reality has a "resolution limit."

**Axiom 3 (Locality)**: Physical updates propagate at finite speed. No instantaneous action at a distance.

*In plain terms*: Changes here can only affect things there after enough time for a signal to travel between them.

**Axiom 4 (Emergent Time)**: Time is not fundamental but arises from accumulated change:

$\mathbf{\Gamma_k \rightarrow \Gamma_{k+1}}$

represents the primitive dynamical step.

*In plain terms*: The universe doesn't have a master clock. Instead, "time" is just a label we put on sequences of changes.

## 5.2 Derivation of TPB Structure

**From Axiom 4**: If time emerges from change, the fundamental structure is a sequence of discrete transitions. Call these transitions "ticks."

**From Axiom 2**: Finite information implies discrete substrates. The minimal unit of distinguishability is a "bit."

**From Axiom 3**: Updates must be local. Each tick affects only a bounded region.

**From Axiom 1**: BCB provides the continuum limit of bit dynamics, ensuring conservation and smooth coarse-graining.

**Conclusion**: Any theory satisfying Axioms 1–4 must contain:

- Discrete micro-events (ticks)
- Discrete information units (bits)
- A count of ticks per bit transition (TPB)
- Emergent time from accumulated bit changes
- BCB as the macroscopic conservation law

## 5.3 Uniqueness Statement

**Theorem (Constrained Uniqueness)**: Any physical theory satisfying Axioms 1–4 is isomorphic to a TPB-type model. Differences between such models are confined to:

- The specific form of V(y) within the universality class $\mathcal{U}$
- The values of coupling constants (A, κ, p, etc.)
- Regularization of the $y \rightarrow 0$ boundary

These differences do not affect qualitative dynamics. TPB is the **canonical representative** of this universality class.

*What this means*: If you accept the four axioms, you're committed to TPB or something equivalent. There's no other game in town.

# 6. The Physical Impossibility of Continuous Time

## 6.1 The Continuum Hypothesis

Suppose, contrary to TPB, that time is fundamental and continuous—parameterized by $t \in \mathbb{R}$ (the real numbers) with the standard topology. We now show this leads to contradictions with physical principles.

*The question*: Could time be like the number line—infinitely divisible, with no smallest unit? We'll see that the answer is no.

## 6.2 Infinite Information Requirement

The real line contains uncountably many distinct instants. Between any t and t + dt, there exist infinitely many intermediate times. If the universe has a definite state at each instant, it must encode uncountably infinite information.

This violates Axiom 2 (Finite Information). More concretely, the Bekenstein bound limits information in any bounded region to:

$$\mathbf{I \leq 2\pi RE/(\hbar c \ln 2)}$$

where R is the radius, E is the energy, $\hbar$ is Planck's constant, and c is the speed of light.

*The problem*: No finite-energy, finite-size system can encode a continuum of states. The universe would need infinite storage capacity just to specify "what time is it?"

## 6.3 Infinite Update Rate

Continuous time requires physical law to be evaluated at every real-numbered instant. This implies:

- Infinite state updates per second
- Infinite computational capacity
- The physical possibility of hypercomputation (solving the halting problem, etc.)

No known physics supports such capacities.

*Analogy*: Imagine a computer that executes infinitely many operations per second. It could solve any mathematical problem instantly—including problems proven to be unsolvable. Continuous time would make the universe into such an impossible computer.

## 6.4 Energy-Time Constraints

The energy-time uncertainty principle, in its rigorous formulation, states:

$$\Delta E \cdot \Delta t \geq \hbar/2$$

where $\Delta t$ is the characteristic time for a system's state to change appreciably.

If we demand continuous sampling of the physical state ($\Delta t \to 0$), then $\Delta E \to \infty$. Any process that probes the state at arbitrarily fine temporal resolution must involve interactions of arbitrarily high energy.

*The physics*: This isn't merely the textbook "$\Delta E \cdot \Delta t$" heuristic. Any physical interaction that distinguishes states at time t from states at time t + dt must transfer energy. As $dt \to 0$, the required energy diverges. Continuous time thus demands infinite energy density.

## 6.5 Conclusion

Continuous fundamental time requires:

- Infinite information
- Infinite update rate
- Infinite energy

All three violate known physics. Therefore, **time cannot be fundamental and continuous**. It must be emergent and, at the deepest level, discrete—precisely as TPB proposes.

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# 7. Elimination of Alternative Time Ontologies

Having ruled out continuous time, we must examine discrete alternatives. We show that each fails under the constraints of BCB, finite information, locality, and Role-4 dynamics.

*The strategy*: We'll consider every reasonable alternative to TPB and show that each one contradicts some established physics.

## 7.1 Coarse-Grained Discrete Time ($\Delta t$ too large)

**Hypothesis**: Time consists of discrete steps, but the fundamental tick interval $\Delta t$ is macroscopically large.

**Contradiction**: Observed physics includes:

- Atomic transitions at $\sim 10^{-15}$ s
- Quantum interference requiring coherent phase evolution
- Smooth gravitational time dilation to arbitrary precision

If Δt were larger than these scales, physics would appear discontinuous. No such discontinuity is observed.

**Conclusion**: If time is discrete, Δt must be extremely small—far below current experimental resolution.

## 7.2 Irregular or Random Tick Timing

**Hypothesis**: Ticks occur at random intervals rather than regular spacing.

**Contradiction**: Quantum coherence requires phase relationships to be preserved over time. Random tick timing would introduce phase noise that destroys interference patterns. Furthermore, BCB requires consistent coarse-graining. Random temporal structure prevents the smooth $\partial s/\partial t + \nabla \cdot J = 0$ limit.

*Analogy*: Imagine a drummer keeping time randomly. Musicians couldn't stay in sync, and the music would fall apart. Similarly, random ticks would destroy the coherent structure of quantum mechanics.

**Conclusion**: Tick statistics must be sufficiently regular to preserve coherence and permit BCB coarse-graining.

## 7.3 Multiple Independent Clocks (Multi-Time Models)

**Hypothesis**: Different regions or degrees of freedom evolve according to independent time parameters.

**Contradiction**: General relativity and BCB both require consistent causal ordering. If clocks are truly independent, causal paradoxes arise. Moreover, energy-momentum conservation couples all degrees of freedom, enforcing a common temporal framework.

*The problem*: If my clock and your clock are truly independent, we could have situations where A causes B according to my clock, but B causes A according to yours. This breaks causality.

**Conclusion**: A universal (though locally-variable-rate) time ordering is required.

## 7.4 Cyclic or Loop Time

**Hypothesis**: Time is closed, with the future eventually connecting to the past.

**Contradiction**: Role-4 dynamics require monotonic progression: y increases from 0 toward 1. If time loops, y must eventually decrease, violating the monotonicity theorem. Additionally, cyclic time creates causal paradoxes (closed timelike curves) that destabilize physics.

*The grandfather paradox, formalized*: If time loops, you could prevent your own birth, which prevents you from traveling back, which allows your birth, which... The contradiction is fatal.

**Conclusion**: Time must be monotonically ordered.

## 7.5 Fixed Minimal Time Step (Hard Planck-Step Time)

**Hypothesis**: Each tick represents exactly one Planck time $t_P \approx 5.4 \times 10^{-44}$ s of elapsed proper time.

**Contradiction**: In TPB, the relationship between ticks and proper time is:

$$d\tau = dt/TPB(x)$$

If each tick contributed a fixed proper time increment, TPB would be constant everywhere. But we require TPB to vary with gravitational potential to produce time dilation. A fixed $\Delta\tau$ per tick cannot accommodate:

- Gravitational redshift
- Horizon freezing (TPB $\to \infty$)
- Kinematic time dilation

*The key distinction*: Ticks are not units of time; they are pre-temporal events from which time emerges. The amount of time per tick varies depending on where you are.

**Conclusion**: Ticks must be pre-temporal, with variable time contribution.

## 7.6 Reversible or Backwards-Step Discrete Time

**Hypothesis**: The fundamental dynamics permit backward steps in the tick sequence.

**Contradiction**: TPB and BCB require monotonic update ordering. If the system could step backward, bit formation would be reversible, and y could decrease. This violates Role-4 dynamics and creates entropy-reversal paradoxes.

*Why this matters*: The second law of thermodynamics—entropy always increases—is built into the structure of TPB. Backward steps would allow entropy to decrease, violating thermodynamics.

**Conclusion**: Ticks are strictly ordered and irreversible.

## 7.7 Cellular Automaton Time (Global Synchronous Updates)

**Hypothesis**: The universe evolves like a cellular automaton with globally synchronized update steps.

**Contradiction**: Global synchrony requires a preferred reference frame—all cells update "simultaneously." But general relativity denies absolute simultaneity. More specifically, gravitational time dilation requires **local** tick-rate differences:

- Clocks deep in a gravitational well run slow (high local TPB)
- Clocks in flat spacetime run fast (low local TPB)

A globally synchronous CA cannot model this. Even asynchronous CA variants fail because they require a **meta-time** parameter to schedule which cells update, reintroducing fundamental time through the back door.

*The problem with CA*: Who decides that "now" all cells update? That decision requires a clock—which is exactly what we're trying to explain.

**Conclusion**: Cellular automaton time is incompatible with general relativity and TPB.

## 7.8 Summary of Eliminations

| Alternative | Fatal Flaw |
|---|---|
| Continuous time | Infinite information/energy |
| Coarse discrete | Contradicts observed fine-scale physics |
| Random ticks | Destroys coherence and BCB |
| Multi-time | Breaks causal consistency |
| Cyclic time | Violates Role-4 monotonicity |
| Fixed Planck steps | Cannot express time dilation |
| Reversible steps | Violates entropy/BCB ordering |
| CA synchronous | Incompatible with relativity |

**Only TPB survives all constraints.**

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# 8. The Complete TPB → BCB → Time → Gravity Hierarchy

## 8.1 The Emergence Chain

The TPB framework defines a strict hierarchy of emergence. Each level builds on the one below:

**Level 0: Ticks**
Fundamental micro-events. No further decomposition. Not yet temporal.

*Think of these as*: The most basic "happenings" in reality—atomic events that cannot be broken into smaller pieces.

**Level 1: Role-4 Dynamics**
Ticks drive formation progress $y(\lambda)$. Bounce dynamics occur in the potential $V(y)$.

*What happens here*: Each tick nudges the formation variable y. Most nudges bounce off the void barrier; occasionally one makes progress toward $y = 1$.

**Level 2: Bit Formation**
When y reaches 1, a bit transition completes. This is the atomic unit of change.

*The milestone*: After many ticks, a bit finally forms. This is the smallest "change" that can be registered in physical records.

**Level 3: TPB Counting**
TPB(x) = number of ticks per bit at location x. Determined by local formation curvature.

*The key variable*: Different locations have different TPB values. Where formation is hard, TPB is large.

**Level 4: Emergent Time**
Proper time accumulates as:

$$\tau = \int dt/TPB(x)$$

Time is not fundamental but a derived bookkeeping of successful bit transitions.

*What clocks measure*: A clock doesn't tap into some cosmic "time flow." It counts bit transitions. Elapsed time = completed bits.

**Level 5: Gravity as TPB Gradient**
Gravitational effects arise because TPB(x) varies with position. High TPB = slow clocks = deep gravity wells.

The connection to general relativity is explicit. In the Schwarzschild metric (describing spacetime around a spherical mass), proper time relates to coordinate time via:

$$d\tau/dt = \sqrt{g_{00}} = \sqrt{(1 - 2GM/rc^2)}$$

Combining with the TPB definition $d\tau/dt = 1/TPB(x)$:

$$1/TPB(x) = \sqrt{(1 - 2GM/rc^2)}$$

Solving for TPB:

$$TPB(x) = TPB_0 \cdot (1 - 2GM/rc^2)^{(-1/2)}$$

where $TPB_0$ is the baseline value in flat spacetime.

*What this means*: Near a massive object (small r), the factor $(1 - 2GM/rc^2)$ is less than 1, so $TPB(x) > TPB_0$. More ticks are required per bit. Clocks run slow. This *is* gravitational time dilation—derived from TPB, not assumed.

**Level 6: Horizons**
At $r = 2GM/c^2$ (the Schwarzschild radius), TPB → ∞. Time freezes. The event horizon is not a geometric curiosity but a dynamical consequence of infinite formation difficulty.

*At a black hole's edge*: Bit formation becomes infinitely difficult. Clocks stop. From outside, objects falling in appear to freeze at the horizon—because no more bits can form there.

**Level 7: BCB Continuum Limit**
At macroscopic scales, discrete bit dynamics coarse-grain to:

$$\partial s/\partial t + \nabla \cdot J = 0$$

BCB is the hydrodynamic limit of TPB microphysics.

*The big picture*: Just as fluid dynamics emerges from molecular collisions, BCB emerges from tick-by-tick bit dynamics. The discrete substrate produces smooth-looking behavior at large scales.

## 8.2 Consistency with Known Physics

| Physical Domain | TPB Prediction | Status |
|---|---|---|
| Special relativity | Kinematic time dilation via velocity-dependent TPB | Consistent |
| General relativity | Gravitational time dilation via position-dependent TPB | Consistent |

| Physical Domain | TPB Prediction | Status |
|---|---|---|
| Quantum mechanics | $\hbar$ emerges from tick-scale uncertainty | Framework allows derivation |
| Thermodynamics | Entropy = bit count; BCB generalizes 2nd law | Consistent |
| Black hole physics | Horizon = TPB divergence | Consistent |
| Information bounds | Finite bits per region | Built-in |

## 8.3 Relation to Quantum Mechanics

The table above claims that $\hbar$ (Planck's constant) "emerges from tick-scale uncertainty." Here we sketch the mechanism.

In TPB, the minimal distinguishable dynamical event is one tick. A tick corresponds to some increment of the action integral S. If ticks are the finest temporal resolution, then the action associated with one tick defines a fundamental quantum:

**S_tick = ∮ p dq |_{one tick}**

*What this means*: Action (the integral of momentum times displacement) accumulates during each tick. There's a minimal "packet" of action corresponding to one tick.

Phase evolution in quantum mechanics follows $\exp(iS/\hbar)$. For phase differences to be physically meaningful, they must correspond to at least one tick of underlying dynamics. This implies:

**$\Delta S \geq S\_tick \Longrightarrow \Delta\varphi = \Delta S/\hbar \geq S\_tick/\hbar$**

If we identify $\hbar$ with the action per tick ($\hbar \approx$ S_tick), then the minimal distinguishable phase rotation is of order unity—exactly as quantum mechanics requires. The uncertainty principle $\Delta E \cdot \Delta t \geq \hbar/2$ then becomes a statement about tick-scale resolution: measurements probing sub-tick timescales require energy exchanges exceeding the tick-scale action quantum.

*The key insight*: TPB provides natural hooks for quantization. Discrete ticks imply discrete action increments, from which $\hbar$ emerges as the conversion factor between tick-counting and phase.

A full derivation requires specifying how Role-4 dynamics couple to standard quantum fields, which we defer to future work. But the conceptual path is clear: quantization arises because ticks are discrete.

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# 9. Observational Implications

## 9.1 Fundamental Limits on Temporal Resolution

TPB predicts a minimum resolvable time interval:

**$\tau_{min} \sim t_P/TPB_{max}$**

where $t_P$ is the Planck time and $TPB_{max}$ is the maximum possible ticks-per-bit in the relevant regime.

*What this means*: There's a floor below which "duration" loses meaning. Any attempt to probe time at finer resolution will encounter fundamental limitations beyond quantum uncertainty—not merely practical limits, but ontological ones.

## 9.2 Discrete Signatures in Extreme Regimes

Near horizons where TPB $\to \infty$, the discreteness of tick dynamics may produce observable signatures:

- Deviations from smooth Hawking radiation spectrum
- Granularity in gravitational wave signals from mergers
- Modified dispersion relations at high energies

*Where to look*: The effects are tiny in ordinary conditions but may become detectable in extreme environments—near black holes, in the early universe, or at the highest energies accessible to particle accelerators.

## 9.3 Cosmological Consequences

In the early universe (high energy density), TPB may have been systematically different:

- Modified expansion dynamics
- Altered nucleosynthesis rates
- Potential resolution of horizon/flatness problems through variable-TPB inflation

*The early universe as laboratory*: Conditions shortly after the Big Bang may have probed regimes where TPB effects are significant. Precision cosmology might eventually detect these signatures.

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# 10. Conclusion

The Ticks Per Bit framework provides a complete model of emergent time satisfying all physical constraints:

1. **Derivation from Principles**: The Role-4 Lagrangian arises from formation curvature, not arbitrary construction. The framework is principled, not ad hoc.
2. **Universality**: Bounce dynamics are universal across a wide class of potentials; microscopic details wash out. The predictions are robust.
3. **Constrained Uniqueness**: Any theory respecting BCB, finite information, locality, and emergent time must reduce to TPB. There's no alternative.
4. **Exclusion of Alternatives**: Continuous time is impossible; all discrete alternatives fail. TPB is the only survivor.
5. **Physical Consistency**: TPB reproduces relativistic time dilation, respects quantum mechanics, and connects to BCB thermodynamics. It works.
6. **Gravity Emergence**: Gravitational effects are TPB gradients, with horizons as TPB divergences. Gravity is explained, not assumed.

TPB is not merely one possible framework for emergent time. It is, within the axiom system defined by physical consistency, the **unique** framework. Time emerges from ticks; ticks accumulate into bits; bits flow according to BCB; and the whole structure gives rise to the temporal experience we navigate.

*The final picture*: Reality is not a stage on which events occur in time. Reality *is* the events—discrete ticks building discrete bits—and time is nothing more than our name for the accumulated record of change.

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# Appendix A: Mathematical Notation Summary

| Symbol | Meaning |
|---|---|
| $y$ | Role-4 progress variable, $y \in (0, 1]$ |
| $y_{min}$ | Buffer zone boundary; smallest effective y value |
| $\lambda$ | Tick-ordering parameter (pre-temporal) |
| $V(y)$ | Role-4 formation potential |
| $R_{form}(y)$ | Formation curvature |
| $\delta\tau(y)$ | Proper time contribution per tick at stage y |
| $TPB(x)$ | Ticks per bit at location x |
| $\tau$ | Proper time |
| $t$ | Coordinate time parameter |
| $s$ | Distinguishability density |

| Symbol | Meaning |
|---|---|
| J | Bit current density |
| Γ | Damping coefficient |
| κ | Bit stabilization coupling |
| A | Void barrier strength |
| p | Curvature divergence exponent (p > 2 required) |
| BCB | Bit Conservation and Balance |
| $\mathcal{U}$ | Universality class of potentials |
| ℏ | Planck's constant (≈ action per tick) |
| G | Newton's gravitational constant |
| c | Speed of light |

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# Appendix B: Figures

The following figures are recommended for the full publication:

**Figure 1: The Role-4 Potential V(y)**

Plot V(y) versus y for representative parameters (e.g., p = 3, A = 1, κ = 1), showing:

- The divergent barrier as $y \to 0^+$ (void forbidden)
- The unique minimum at y = 1 (stable bit)
- The monotonically negative slope on (0, 1) driving formation
- Annotation of the two regimes: curvature-dominated (small y) and harmonic-dominated (y near 1)

**Figure 2: Bounce-and-Creep Dynamics**

Phase portrait or time series showing y(λ) for overdamped dynamics with stochastic driving:

- Multiple trajectories starting from different $y_0$
- Visible bounces near small y values
- Convergence toward y = 1
- Annotation showing "one bit formed" when y reaches 1

**Figure 3: The Buffer Zone and Time Contribution**

Two-panel figure:

- Top panel: δτ(y) versus y, showing how time contribution per tick grows from near-zero at small y to maximum near y = 1

- Bottom panel: Shaded region indicating the buffer zone ($0 < y \lesssim y_{min}$) where ticks occur but contribute negligibly to proper time
- Annotation contrasting "computationally busy" (many ticks) with "temporally quiet" (little elapsed time)

**Figure 4: The Seven-Level Emergence Hierarchy**

Schematic diagram illustrating:

Level 0: Ticks (fundamental micro-events)
↓
Level 1: Role-4 Dynamics (bounce in V(y))
↓
Level 2: Bit Formation (y reaches 1)
↓
Level 3: TPB Counting (ticks per bit)
↓
Level 4: Emergent Time (τ accumulates)
↓
Level 5: Gravity (TPB gradients)
↓
Level 6: Horizons (TPB → ∞)
↓
Level 7: BCB Continuum Limit ($\partial s/\partial t + \nabla \cdot J = 0$)

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# Appendix C: Technical Refinements to the TPB Framework

## C.1 Ensuring a Stable Minimum at y = 1

In the main text, the Role-4 potential was introduced as:

$V(y) = A/[(p-1)(p-2)] \cdot y^{-(p-2)} + (\kappa/2)(y - 1)^2$.

This form captures the correct divergence as $y \to 0^+$ and includes the required stabilizing term near y = 1. However, the curvature term alone contributes a non-zero slope at y = 1:

$d/dy\ [\ y^{-(p-2)}\ ]$ evaluated at y = 1 equals $-(p-2)$.

To ensure that y = 1 is a smooth, stationary minimum of the full potential, we introduce a renormalized curvature term:

$V\_curv^*(y) = A/[(p-1)(p-2)] \cdot [\, y^{-(p-2)} - 1 + (p-2)(y-1) \,]$.

This renormalization removes the first two terms of the Taylor expansion of $y^{-(p-2)}$ around $y = 1$. As a result:

$V\_curv^*(1) = 0$

$(V\_curv^*)'(1) = 0$

$(V\_curv^*)''(1) = A$.

The divergent behavior near $y \to 0^+$ is fully preserved, while the minimum at $y = 1$ is smooth and well-defined.

### Updated Role-4 Potential

The fully consistent potential is:

$V^*(y) = V\_curv^*(y) + (\kappa/2)(y-1)^2$.

This potential satisfies all structural requirements:

- Divergent barrier at $y \to 0^+$
- Unique and smooth minimum at $y = 1$
- Monotonic restoring force on $(0, 1)$
- Smoothness on the entire interval $(0, 1]$.

## C.2 Clarifying the Quantum Mechanics Discussion

The main text outlined how discrete tick dynamics may naturally lead to quantized action increments, suggesting a route by which Planck's constant $\hbar$ could arise from Role-4 microphysics.

A complete derivation requires specifying how Role-4 dynamics couple to quantum fields and how tick-level action increments integrate into phase evolution. These steps involve additional structural assumptions and will be developed in future work.

The current discussion should be understood as a conceptual outline demonstrating:

- The existence of discrete action increments at the tick level

- The compatibility of TPB with phase-based quantum evolution

- The natural appearance of a minimal action quantum S_tick

The full mathematical treatment will be presented in a dedicated follow-on paper.

## C.3 Summary

This appendix completes two technical aspects of the TPB framework:

1. A renormalized curvature term ensures a smooth stationary minimum at y = 1 in the Role-4 potential.

2. The quantum mechanics discussion is clarified as a forward-looking conceptual pathway, not a finalized derivation.

These refinements strengthen the formal consistency of the TPB model without altering its structure or conclusions.