
Time Integrity Module (TIM)

An entropy–information formalism for quantum timekeeping,
observation limits, and measurement efficiency.

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1. Definitions

Let:

N = number of ticks observed in window Δt

⟨N⟩ = mean tick count

Var(N) = variance of tick count

stot = total entropy produced in Δt (J/K)

sclock = entropy produced by the clock mechanism

smeas = entropy produced by measurement/readout

I_tick = information gained per tick (bits)

kB = Boltzmann constant

T = temperature

hbar = reduced Planck constant

All entropy and energy quantities are per observation window
unless explicitly stated.

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2. Accuracy of Timekeeping

Define accuracy A as:

$$A = \langle N \rangle^2 / \mathrm{Var}(N)$$

Higher A → sharper ticks and better time resolution.

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3. Thermodynamic Uncertainty Relation (TUR)

Accuracy is bounded by total entropy production:

$$A \leq stot / (2\ kB)$$

This establishes the fundamental accuracy–entropy tradeoff.

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4. Minimal Entropy Required (Landauer Limit)

Information gained per tick requires a minimal entropy:

$$s\_necessary = I\_tick \cdot kB \ln(2)$$

This is the lowest possible entropy cost compatible with classical information extraction.

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5. Actual Entropy Production

Total entropy per window:

$$s_{actual} = s_{clock} + s_{meas}$$

Where:

s_{clock} = entropy from quantum clock dynamics

s_{meas} = entropy from measurement chain

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6. Entropy Efficiency of Timekeeping

Define the Time Entropy Efficiency:

$$E_{time} = s_{necessary} / s_{actual}$$

Range: $0 < E_{time} \leq 1$

Interpretation:

$E_{time} = 1$ → all entropy is information-aligned

$E\_time < 1$ → some entropy is wasted in observation

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7. Observation Waste

Define:

$$W\_obs = 1 - E\_time$$

Represents the fraction of entropy not contributing to information about time.

Range: $0 \leq W\_obs < 1$

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8. Measurement Inefficiency

Define measurement inefficiency γ as the factor by which measurement exceeds the Landauer bound:

$$\gamma = s\_meas / (I\_tick \cdot kB \ln(2))$$

$\gamma \geq 1$ by the second law.

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9. Clock–Measurement Entropy Ratio

Define:

$\eta = s_{meas} / s_{clock}$

In current experiments, $\eta \approx 10^6$–10^9.

Goal of reversible or near-reversible readout: $\eta \to 1$.

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10. Combined Time Integrity Inequality

A clock satisfies the Time Integrity Condition if:

$A \leq stot / (2\ kB)$

$E_{time} \to 1$

$\gamma \to 1$

$\eta \to O(1)$

Together these define an Earned-Light-Optimal timekeeping system.

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11. Quantum Resolution Constraint (Optional)

Energy–time uncertainty gives a lower bound on bandwidth:

$$\Delta E \cdot \Delta t \geq \text{hbar} / 2$$

This connects time resolution Δt to minimal energy spread ΔE.

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12. Design Objective (Engineering Form)

Given target accuracy A_target, design a system that satisfies:

$$s_{actual} = s_{necessary} + s_{waste}$$
$$s_{waste} = W_{obs} \cdot s_{actual}$$

Subject to:

$$A_{target} \leq s_{actual} / (2\ kB)$$
$$W_{obs} \leq W_{max} \quad (\text{e.g., } W_{max} = 0.10)$$
$$\gamma \to 1$$
$$\eta \to 1$$

This defines the optimality region for low-entropy, high-accuracy quantum timekeeping.

END OF SPECIFICATION