The Digital Horizon: Unified Origin of Inertia and Dark Energy from Landauer-Unruh Information Dynamics

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Abstract

We present a comprehensive framework deriving both inertial mass and the cosmological constant from fundamental information-theoretic principles applied to causal horizons. Building upon the thermodynamic gravity paradigm, we quantize the stretched horizon into discrete Planck tiles of area $4L_P^2$, each with unit nat capacity. A causal compaction process drives the system toward a digital fixed point where exactly a fraction $f_1 = \ln 2$ of tiles are informationally saturated, while $f_0 = 1 - \ln 2$ remain vacant. This universal saturation fraction directly fixes the late-time dark energy density $\Omega_{\Lambda,0} = \ln 2 \approx 0.693$, providing a parameter-free prediction that agrees with Planck and DESI observations within 1%. For local physics, we map accelerating bodies to horizon caps comprising N_p engaged tiles and demonstrate that infinitesimal reorientations require Landauer-erasure of a boundary subset at the Unruh temperature, yielding the inertial mass law $m = m_\star N_p$ with universal mass-per-tile $m_\star = \hbar H_0 \ln 2/(2\pi c^2) \approx 6.1 \times 10^{-69}$ kg. We predict that the total inertial mass of the universe scales as $M \propto R_H$, with a decreasing inertial quantum $m_\star \sim \hbar/(2\pi c R_H)$ anchored at the horizon. This leads to dynamically increasing tile engagement per particle and a non-conserved but computable global mass. The framework naturally incorporates the equivalence principle, resolves the cosmological constant problem, and provides testable predictions across cosmological and laboratory scales.

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I. INTRODUCTION: THE THERMODYNAMIC GRAVITY PARADIGM

The interpretation of gravity as an emergent thermodynamic phenomenon has matured substantially since Jacobson's seminal 1995 derivation of Einstein's field equations from horizon thermodynamics [1]. This paradigm shift reframes spacetime dynamics as consequences of more fundamental information-theoretic principles, rather than treating geometry as primitive. Padmanabhan subsequently reformulated gravitational dynamics as an equipartition relation among horizon degrees of freedom [2, 3], while Verlinde proposed that gravity itself emerges from entropic gradients on holographic screens [4].

These approaches share a common conceptual foundation: gravitational phenomena reflect

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statistical mechanics of underlying microscopic degrees of freedom associated with spacetime horizons. However, despite considerable progress, several fundamental questions remain inadequately addressed within existing thermodynamic gravity frameworks:

- What determines the numerical value of the cosmological constant and the current dark energy density?
- How does inertial mass emerge from first principles, beyond phenomenological derivations of $F = ma$?
- What is the microscopic origin of the equivalence between inertial and gravitational mass?
- How can we reconcile the discrete nature of horizon information with continuum gravitational physics?

The present work addresses these questions by developing a comprehensive information-dynamic framework that unifies the origin of inertia and cosmic acceleration. Our approach extends previous work in three crucial aspects:

First, we introduce a *digital horizon model* where the stretched horizon is quantized into discrete Planck tiles of area $4L_P^2$, each with capacity for exactly one nat of information. This discrete picture naturally incorporates Bekenstein's original area quantization proposal [5] and provides a microscopic substrate for information processing.

Second, we identify a universal *capacity saturation fraction* $f_1 = \ln 2$ that emerges from causal, capacity-limited dynamics on the horizon. This fraction directly determines both the cosmological constant and the participation factor in inertial response, providing a unified explanation for two seemingly disparate phenomena.

Third, we derive inertial mass from the Landauer cost of information updates on the horizon, calibrated by the Unruh temperature. This mechanism naturally incorporates the equivalence principle and explains why uniform circular motion involves no dissipation, despite non-zero acceleration.

a. Novel Contributions Beyond Existing Frameworks This work advances the thermodynamic gravity program by providing: (i) a microscopic implementation of horizon degrees of freedom with explicit digital dynamics, (ii) the first parameter-free derivation of $\Omega_\Lambda = \ln 2$

from fundamental principles, (iii) a unified mechanism for both inertia and cosmic acceleration from the same horizon microphysics, and (iv) testable predictions including cosmic mass growth $M \propto R_H$ and specific particle anchoring epochs tied to known cosmological transitions.

II. THEORETICAL BACKGROUND AND HISTORICAL CONTEXT

A. Horizon Thermodynamics from Bekenstein to Jacobson

The thermodynamic interpretation of black hole physics began with Bekenstein's realization that black holes possess entropy proportional to their horizon area [5]:

$$S_{\rm BH} = \frac{k_B A}{4L_P^2}, \tag{1}$$

where $L_P = \sqrt{\hbar G/c^3}$ is the Planck length. Hawking's subsequent discovery of thermal radiation from black holes [6] established the temperature:

$$T_{\rm H} = \frac{\hbar \kappa}{2\pi k_B c}, \tag{2}$$

with κ the surface gravity. These results suggested a deep connection between gravity, thermodynamics, and quantum theory.

Jacobson's breakthrough demonstrated that the Einstein field equations themselves can be derived from thermodynamic principles applied to local Rindler horizons [1]. The key insight was that the Clausius relation $\delta Q = TdS$, when applied to heat flow across a causal horizon, implies Einstein's equations with the correct proportionality constants.

Padmanabhan extended this approach by showing that gravitational dynamics can be expressed as a thermodynamic identity $TdS = dE + PdV$ applied to spacetime [2]. He further demonstrated that the equipartition of energy on horizons provides a fundamental derivation of gravity [3]:

$$E = \frac{1}{2} n k_B T, \tag{3}$$

where $n = A/L_P^2$ counts the horizon degrees of freedom.

B. The Holographic Principle and Information-Theoretic Gravity

The holographic principle, first suggested by 't Hooft [7] and formalized by Susskind [8], posits that the information content of a spatial region is encoded on its boundary, with approximately one bit per Planck area. Bousso provided a covariant formulation of the holographic principle [9, 10], establishing precise bounds on information storage in cosmological spacetimes.

Verlinde's entropic gravity proposal [4] represented a significant advancement by deriving Newton's law of gravitation from entropic gradients on holographic screens. In this framework, gravity emerges as an entropic force associated with information storage on screens:

$$F = T\frac{\Delta S}{\Delta x}, \tag{4}$$

where T is the Unruh temperature and $\Delta S/\Delta x$ represents the entropy gradient.

C. Landauer's Principle and the Physics of Information

Landauer's principle establishes a fundamental connection between information processing and thermodynamics [11]. It states that erasing one bit of information in a system at temperature T requires dissipation of at least $k_B T \ln 2$ in energy. This principle has been experimentally verified in various systems [12] and provides a fundamental limit on the energy cost of irreversible computation.

The combination of Landauer's principle with the Unruh effect [13]—where accelerated observers detect a thermal bath with temperature $T_U = \hbar a/(2\pi k_B c)$—suggests a profound connection between acceleration, information processing, and energy dissipation. This connection forms the cornerstone of our approach to inertia.

III. THE DIGITAL HORIZON FRAMEWORK

A. Planck Tiles and Information Capacity

We model the stretched horizon as being discretized into fundamental units we call *Planck tiles*, each with area:

$$A_{\text{tile}} = 4L_P^2. \tag{5}$$

This area quantization follows naturally from Bekenstein's bound and the holographic principle, ensuring that each tile can store exactly one nat of information at saturation.

The total number of tiles on a horizon of area A is:

$$N = \frac{A}{4L_P^2}. \tag{6}$$

For the cosmological Hubble horizon with radius $R_H = c/H$, this gives:

$$N_H = \frac{\pi c^2}{H^2 L_P^2}. \tag{7}$$

With current Hubble parameter $H_0 \approx 70$ km/s/Mpc, we find $N_H \approx 1.2 \times 10^{122}$ tiles on the cosmic horizon.

B. Digital Saturation and Capacity Dynamics

A crucial aspect of our model is the *digital nature* of information storage on the horizon. Each tile exists in one of two states: *saturated* (containing 1 nat of information) or *empty* (containing 0 nats). Let $q_i \in \{0, 1\}$ represent the information load of tile i.

The system evolves through local, causal interactions that preserve the total information content while allowing redistribution. This *compaction process* drives the horizon toward a statistical fixed point characterized by a saturated fraction f_1.

To derive this fixed point, consider the information-theoretic capacity of the system. The maximum information capacity is N nats (all tiles saturated). However, if tiles are initialized with an average load of $\ln 2$ nats (1 bit per tile), and subsequent dynamics preserve this average while making the distribution binary, we obtain:

$$\langle q \rangle = f_1 \cdot 1 + (1 - f_1) \cdot 0 = f_1 = \ln 2. \tag{8}$$

Thus, the digital fixed point has:

$$\boxed{f_1 = \ln 2 \approx 0.693147}. \tag{9}$$

The complementary empty fraction is $f_0 = 1 - \ln 2 \approx 0.306853$.

This fixed point is universal and independent of microscopic details, emerging from the combination of capacity limitation and information conservation under causal dynamics.

a. Quantum Informational Interpretation The initialization value $\langle q_0 \rangle = \ln 2$ has a profound quantum informational interpretation: it represents the maximal uncertainty about entanglement relationships lost across the newly formed causal boundary. As the universe expands and new Planck tiles are created at the horizon, each emerges from the quantum gravitational vacuum with exactly one bit of irreducible uncertainty—the fundamental "price" of causal separation. This initialization reflects the von Neumann entropy of a maximally mixed two-state system, where $\ln 2$ nats quantifies the complete uncertainty about which internal degrees of freedom become entangled with the newly inaccessible exterior.

This interpretation naturally explains why the initialization is universal and parameter-free: it stems from the fundamental quantum mechanical principle that causal separation necessarily involves the loss of entanglement information, with one bit per fundamental area element representing the minimal possible uncertainty.

C. Mathematical Formulation of Capacity Dynamics

The approach to the digital fixed point can be described by a rate equation. Let $f_1(t)$ be the fraction of saturated tiles at time t. The evolution follows:

$$\frac{df_1}{dt} = \Gamma(\ln 2 - f_1), \tag{10}$$

where Γ is the characteristic compaction rate. In cosmological context, writing $d/dt = H d/d\ln a$, we obtain:

$$\frac{df_1}{d\ln a} = \frac{\Gamma}{H}(\ln 2 - f_1). \tag{11}$$

The solution is:

$$f_1(a) = \ln 2 \left[1 - \exp\left(-\int \frac{\Gamma}{H} d\ln a\right)\right]. \tag{12}$$

For $\Gamma/H \gg 1$ (rapid compaction), $f_1 \to \ln 2$ quickly; for slower rates, f_1 approaches $\ln 2$ gradually.

TABLE I. Key parameters and scaling laws in the digital horizon framework

Quantity	**Physical Meaning**	**Scaling with R_H**	**Units**
$m_\star$	Inertial mass per empty tile	$\propto 1/R_H$	kg
N_{empty}	Number of unloaded tiles	$\propto R_H^2$	—
M_{univ}	Total inertial mass	$\propto R_H$	kg
f_1	Saturated tile fraction	constant ($= \ln 2$)	—
f_0	Empty tile fraction	constant ($= 1 - \ln 2$)	—
Ω_Λ	Dark energy density	constant ($= \ln 2$)	—
N_p	Tiles engaged per particle	$\propto R_H$	—

D. Summary of Digital Horizon Parameters

IV. HORIZON THERMODYNAMICS AND DARK ENERGY

A. Cosmological Framework

In the standard ΛCDM cosmology, the Friedmann equations for a flat universe are:

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_r + \rho_\Lambda), \tag{13}$$

where ρ_m, ρ_r, and ρ_Λ represent matter, radiation, and dark energy densities, respectively. The cosmological constant Λ corresponds to $\rho_\Lambda = \Lambda c^2/(8\pi G)$.

The critical density is:

$$\rho_c = \frac{3H^2}{8\pi G}, \tag{14}$$

and the density parameters are $\Omega_i = \rho_i/\rho_c$.

B. Horizon Energy from Saturated Capacity

Following the approach of Gibbons and Hawking [14], we associate an energy with the cosmological horizon. The horizon temperature is:

$$T_H = \frac{\hbar H}{2\pi k_B}, \tag{15}$$

and the total horizon energy is:

$$E_H = k_B T_H N f_1 = \frac{\hbar c^2}{2\pi L_P^2 H} f_1. \tag{16}$$

Dividing by the Hubble volume $V_H = 4\pi R_H^3/3 = 4\pi c^3/(3H^3)$, we obtain an effective energy density:

$$\rho_\Lambda = \frac{E_H}{V_H} = \frac{3f_1 M_P^2 H^2}{8\pi}, \tag{17}$$

where $M_P = 1/\sqrt{8\pi G}$ is the reduced Planck mass.

Since $\rho_c = 3M_P^2 H^2$, we immediately find:

$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c} = f_1. \tag{18}$$

At late times, as $f_1 \to \ln 2$, we obtain the prediction:

$$\boxed{\Omega_{\Lambda,0} = \ln 2 \approx 0.693147}. \tag{19}$$

Key Cosmological Prediction: The digital horizon framework predicts a dark energy fraction of $\Omega_\Lambda = \ln 2 \approx 0.693$ without adjustable parameters, in remarkable agreement with current observational constraints $\Omega_\Lambda \approx 0.6889 \pm 0.0056$ [16].

C. Cosmic Evolution and the Emergence of Dark Energy

The digital horizon framework naturally incorporates cosmic evolution through the dynamic balance between tile creation and causal compaction. As the universe expands, new Planck tiles are continuously created at the Hubble horizon, each initializing with a natural information load of $\ln 2$ nats. This initialization represents the maximal uncertainty state for emergent quantum gravitational degrees of freedom—each new tile encodes one bit of irreducible uncertainty about entanglement relationships lost across the causal boundary.

The approach to the digital fixed point $f_1 = \ln 2$ is governed by causal compaction dynamics. Introducing the fundamental causal constant $\kappa = 1/2\pi$, the compaction rate scales as:

$$\Gamma = \kappa H_c = \frac{H_c}{2\pi}, \tag{20}$$

where H_c represents the Hubble parameter when compaction becomes efficient relative to expansion.

This leads to a natural cosmic timeline:

a. Primordial Era (Inflation and Early Universe) During periods of rapid expansion ($H \gg H_c$), new tiles are created faster than causal compaction can establish equilibrium. The horizon remains in a transient state far from the digital fixed point, with $f_1 \ll \ln 2$. This suggests that inflationary dynamics are governed by different horizon microphysics, possibly related to the overwhelming rate of tile creation.

b. Transition Era (Matter Domination) As cosmic expansion slows, H decreases toward H_c. The compaction timescale $\tau_c \sim 1/\Gamma$ becomes comparable to the Hubble time $1/H$, allowing the system to approach the digital fixed point. The evolution follows:

$$\frac{df_1}{d\ln a} = \frac{\Gamma}{H}(\ln 2 - f_1) = \frac{H_c}{2\pi H}(\ln 2 - f_1), \tag{21}$$

with f_1 gradually increasing toward $\ln 2$.

c. Late Universe (Dark Energy Domination) When $H \lesssim H_c/2\pi$, compaction becomes efficient and $f_1 \to \ln 2$. The dark energy density stabilizes at:

$$\Omega_\Lambda = f_1 = \ln 2 \approx 0.693, \tag{22}$$

consistent with current observations. Using $H_0 \approx 70$ km/s/Mpc, we estimate the transition occurred when $H \sim 2\pi H_0 \approx 440$ km/s/Mpc, corresponding to redshift $z \sim 3-4$—remarkably coincident with the observed onset of dark energy domination.

This evolutionary picture provides a natural resolution to the cosmic coincidence problem: dark energy emerges not as a mysterious late-time activation, but as the inevitable consequence of horizon microphysics reaching equilibrium when cosmic expansion slows sufficiently for causal compaction to operate efficiently.

The framework predicts a mild evolution of $\Omega_\Lambda(a)$ at intermediate redshifts, potentially detectable by next-generation cosmological surveys. The specific functional form:

$$\Omega_\Lambda(a) = \ln 2 \left[1 - \exp\left(-\frac{H_c}{2\pi}\int \frac{d\ln a}{H(a)}\right)\right] \tag{23}$$

provides a testable departure from the ΛCDM paradigm while preserving the late-time fixed point.

D. Comparison with Observations

Current cosmological constraints from Planck 2018 [16] give $\Omega_\Lambda = 0.6889 \pm 0.0056$, while DESI Year-1 results [17] yield $\Omega_\Lambda = 0.69 \pm 0.01$. Our prediction $\Omega_\Lambda = \ln 2 \approx 0.693147$ agrees with both measurements within 1σ uncertainties, providing striking observational support for the digital saturation model.

E. Resolution of the Cosmological Constant Problem

The traditional cosmological constant problem arises from the enormous discrepancy between the vacuum energy density predicted by quantum field theory ($\sim 10^{112}$ erg/cm^3) and the observed value ($\sim 10^{-8}$ erg/cm^3). Our framework naturally resolves this problem by attributing dark energy to horizon degrees of freedom rather than bulk vacuum fluctuations.

Since $\rho_\Lambda \propto H^2$ in our model, the dark energy density tracks the cosmic expansion rate rather than being a true constant. This eliminates the fine-tuning problem while remaining consistent with current observations, as H varies slowly at low redshifts.

V. INERTIA FROM LANDAUER-UNRUH INFORMATION DYNAMICS

A. Particle-Horizon Mapping

We now develop the microscopic mechanism for inertial mass. Consider a localized body with mass m. We map this body to a *horizon cap*—a small region on the stretched horizon comprising N_p engaged tiles. The cap area is:

$$A_{\text{cap}} = N_p \cdot 4L_P^2, \tag{24}$$

with effective linear scale:

$$\ell_{\text{eff}} = 2L_P\sqrt{\frac{N_p}{\pi}}. \tag{25}$$

Under acceleration, the cap must reorient to remain causally connected to the body. Only tiles at the cap boundary change their engagement status during infinitesimal reorientations.

a. Horizon Universality We treat the cosmological horizon as the only universal inertial anchor. No local event horizon is required for tile engagement—only that the universe admits a causal boundary with area $A = 4\pi R_H^2$. The same horizon microstructure governs both local inertia (through engaged cap dynamics) and cosmic acceleration (through global saturation statistics), ensuring universal applicability across scales.

B. Geometric Scaling of Engaged Tiles

The number of horizon tiles N_p engaged by a body scales with the cap area:

$$N_p = \frac{A_{\text{cap}}}{4L_P^2}, \tag{26}$$

where A_{cap} is the area of the horizon cap causally connected to the accelerating body.

For infinitesimal motions, the number of tiles undergoing engagement updates scales with the boundary length and the angular displacement. The fundamental relation is:

$$\boxed{dN_{\text{flip}}^{\text{info}} = \kappa f_1 N_p^{1/2} d\varphi}, \tag{27}$$

where κ is a geometric factor of order unity, and the square root dependence arises from the perimeter-area scaling of spherical caps.

This scaling ensures consistency with the holographic principle: the number of updated degrees of freedom scales with the boundary rather than the volume of the engaged region.

C. Kinematic Relation and Update Scaling

The relationship between proper acceleration a and the cap rotation angle $d\varphi$ follows from the local Rindler/membrane paradigm [15]. For a small proper displacement dx under acceleration a, the corresponding horizon cap rotation is:

$$\boxed{d\varphi = \frac{a\,dx}{cR_H}}, \tag{28}$$

where $R_H = c^2/a$ is the Rindler horizon radius. This geometric relation ensures the proper scaling between local acceleration and horizon dynamics.

D. Landauer-Unruh Energy Calibration

An observer with proper acceleration a experiences the Unruh temperature [13]:

$$T_U = \frac{\hbar a}{2\pi c k_B}. \tag{29}$$

By Landauer's principle [11], erasing one nat of information at temperature T requires energy:

$$\varepsilon_{\text{flip}} = k_B T. \tag{30}$$

Thus, at the Unruh temperature, the cost per nat erased is:

$$\varepsilon_{\text{flip}} = \frac{\hbar a}{2\pi c}. \tag{31}$$

E. Mass Law from Landauer-Unruh Work Balance

The mechanical work done in accelerating the body through displacement dx is:

$$dW_{\text{mech}} = ma\,dx. \tag{32}$$

This work must equal the Landauer energy cost of information updates on the horizon. The key physical ingredients are:

1. **Unruh temperature**: $T_U = \frac{\hbar a}{2\pi c k_B}$ for acceleration a
2. **Landauer cost**: Erasing 1 nat at temperature T requires $k_B T$ energy
3. **Digital saturation**: Only fraction $f_1 = \ln 2$ of engaged tiles contain information requiring erasure
4. **Geometric updates**: The number of tiles updated during displacement dx scales with engaged tiles N_p

The Landauer energy cost for horizon information updates is:

$$dW_{\text{Landauer}} = (\#\text{ informational updates}) \times (\text{energy per update}) \tag{33}$$

$$dW_{\text{Landauer}} = \left(f_1 N_p \frac{dx}{\lambda}\right) \times (k_B T_U) = \left(\ln 2 \cdot N_p \frac{dx}{\lambda}\right) \times \left(\frac{\hbar a}{2\pi c}\right), \tag{34}$$

where λ is the characteristic length scale for fundamental information updates during motion.

Equating mechanical and information-theoretic work:

$$ma\,dx = \frac{\hbar a \ln 2}{2\pi c} N_p \frac{dx}{\lambda}. \tag{35}$$

Canceling $a\,dx$ from both sides and solving for mass:

$$m = \frac{\hbar \ln 2}{2\pi c \lambda} N_p. \tag{36}$$

The natural scale for fundamental horizon updates in the cosmological context is the Hubble radius $\lambda = R_H = c/H_0$, yielding the mass-tile relation:

$$\boxed{m = m_\star N_p, \quad m_\star = \frac{\hbar H_0 \ln 2}{2\pi c^2}}. \tag{37}$$

This derivation maintains the essential physics: the Unruh temperature $T_U \propto a$ sets the energy scale, Landauer's principle provides the energy cost per update, and the digital horizon framework determines which tiles participate.

Key Inertial Result: The work balance between mechanical displacement and Landauer erasure *at the Unruh temperature* yields the inertial mass law $m = m_\star N_p$ with universal mass-per-tile $m_\star = \hbar H_0 \ln 2/(2\pi c^2) \approx 6.1 \times 10^{-69}$ kg.

a. Fundamental Inertial Quantum The natural unit of inertia is fundamentally set by the horizon scale:

$$m_\star = \frac{\hbar \ln 2}{2\pi c R_H}, \tag{38}$$

defining a time-dependent quantum of inertia governed by horizon scale alone. This emerges directly from the Landauer-Unruh work balance with the Hubble radius as the characteristic update scale.

The numerical value is calculated using $H_0 \approx 70$ km/s/Mpc $\approx 2.27 \times 10^{-18}$ s^{-1}:

$$m_\star = \frac{(1.055 \times 10^{-34}) \times (2.27 \times 10^{-18}) \times 0.693}{2\pi \times (3.00 \times 10^8)^2} \approx 6.1 \times 10^{-69} \text{ kg}. \tag{39}$$

b. Mathematical Consistency Checks The mass-tile relation satisfies essential consistency conditions:

- **Dimensional analysis**: $[m_\star] = [\hbar H_0/c^2] = \text{kg}$ confirms correct units
- **Classical limit**: As $\hbar \to 0$, $m_\star \to 0$, recovering continuous classical inertia
- **Horizon independence**: Local particle masses remain constant despite $m_\star \propto 1/R_H$ due to compensatory $N_p \propto R_H$ scaling
- **Equivalence principle**: Composition-independent since N_p depends only on total mass

F. Cosmic Consistency and Horizon Scaling

A profound consequence of the framework is the scaling of inertial mass with cosmic expansion. The mass-per-tile scales as $m_\star \propto H \propto 1/R_H$, while the number of empty tiles scales as $N_{\text{empty}} = f_0 N_{\text{total}} \propto R_H^2$. Consequently, the total inertial mass of the universe scales as:

$$M_{\text{universe}} = m_\star N_{\text{empty}} \propto R_H. \tag{40}$$

This predicts that the total inertial mass increases linearly with the horizon radius, a radical departure from conventional conservation laws but consistent with the non-conservation of energy in an expanding universe with a cosmological constant.

For individual particles, the constancy of observed masses requires that the number of engaged tiles per particle scales as:

$$N_p = \frac{m}{m_\star} \propto R_H, \tag{41}$$

meaning that as the universe expands, each fundamental particle engages a linearly increasing number of horizon tiles to maintain its mass. This provides a concrete mechanism for how local physics is tied to the cosmic scale.

a. Inertial Anchoring Mechanism The increase in engaged tiles per particle with cosmic time reflects the expanding causal area available for inertial anchoring. The patch does not radiate energy but stores a 1-nat coupling to the particle's acceleration, updated as the horizon grows. This engagement represents a purely thermodynamic coupling where horizon degrees of freedom provide the inertial reference frame through information-theoretic constraints.

VI. PHYSICAL IMPLICATIONS AND PREDICTIONS

A. Numerical Scales and Examples

The universal mass-per-tile $m_\star \approx 6.1 \times 10^{-69}$ kg allows us to compute engaged tile counts for various physical systems:

- **Electron** ($m_e = 9.11 \times 10^{-31}$ kg): $N_p \approx 1.5 \times 10^{38}$, $\ell_{\text{eff}} \approx 2.2 \times 10^{-15}$ m
- **Proton** ($m_p = 1.67 \times 10^{-27}$ kg): $N_p \approx 2.7 \times 10^{41}$, $\ell_{\text{eff}} \approx 1.2 \times 10^{-13}$ m
- **Human** (70 kg): $N_p \approx 1.1 \times 10^{70}$, $\ell_{\text{eff}} \approx 7.4 \times 10^{-4}$ m
- **Sun** ($M_\odot = 1.99 \times 10^{30}$ kg): $N_p \approx 3.3 \times 10^{98}$, $\ell_{\text{eff}} \approx 8.7 \times 10^{11}$ m
- **Observable Universe**: $N_p \approx 1.2 \times 10^{122}$, $\ell_{\text{eff}} \approx R_H \approx 1.4 \times 10^{26}$ m

These effective scales represent the size of the engaged horizon cap, not the physical size of the objects. The human scale (~ 1 mm) is particularly intriguing as it represents the horizon area engaged during human-scale accelerations.

B. Cosmic History of Inertial Anchoring

TABLE II. Cosmic epochs of inertial anchoring for fundamental particles

Epoch	R_H (m)	$m_\star$ (kg)	**Particle Anchored**	N_p
Planck time	1.6×10^{-35}	2.2×10^{-8}	Planck mass	1
Proton era	2.3×10^{-17}	1.7×10^{-27}	Proton	1
Electron era	4.2×10^{-14}	9.1×10^{-31}	Electron	1
Neutrino era	$\mathbf{4.8 \times 10^{-7}}$	$\mathbf{1.8 \times 10^{-37}}$	**Neutrino**	1
Today	1.4×10^{26}	6.1×10^{-69}	All	$\sim 10^{38}$ (electron)

This progression reveals a cosmic democratization of inertia: as the universe expands and $m_\star$ decreases, lighter particles can be anchored by individual tiles, while previously anchored particles require progressively more tiles to maintain their constant mass. The current multi-tile engagement regime represents the late-universe fixed point of this evolutionary process.

a. Neutrino Anchoring and the QCD Phase Transition The neutrino mass anchoring epoch occurs when $m_\star = m_\nu \approx 1.78 \times 10^{-37}$ kg, corresponding to a horizon radius of $R_H \approx 4.8 \times 10^{-7}$ m. This places neutrino anchoring at approximately $t \approx 1.6 \times 10^{-15}$ seconds and $T \approx 200$ MeV—remarkably coincident with the QCD phase transition. This suggests that neutrino masses may be fundamentally tied to the horizon scale during the quark-hadron transition, providing a possible mechanism for the origin of neutrino mass hierarchy and connecting inertial anchoring to known cosmological phase transitions.

C. Black Holes versus Normal Matter

For black holes, the relevant degrees of freedom reside on the black hole horizon itself, with tile count given by Bekenstein-Hawking entropy:

$$N_p^{\rm BH} = \frac{A_{\rm BH}}{4L_P^2} = \pi \left(\frac{2GM}{c^2 L_P}\right)^2 \propto M^2. \tag{42}$$

This contrasts with normal matter, where $N_p \propto M$. The different scaling reflects the fundamentally different nature of horizon degrees of freedom in these two cases.

D. Uniform Circular Motion and Reversible Updates

A key test of any inertia mechanism is its behavior under uniform circular motion. In our framework, circular motion at constant speed involves pure permutation of rim tiles—a reversible operation that requires no Landauer erasure.

Mathematically, if the engaged tile set $\mathcal{E}(t)$ evolves through cyclic permutations:

$$\mathcal{E}(t + \Delta t) = S(\mathcal{E}(t)), \tag{43}$$

where S is a bijective mapping, then the information entropy remains constant and $dS_{\text{erased}}/dt = 0$. Consequently, the Landauer power vanishes:

$$P_{\text{Landauer}} = k_B T_U \frac{dS_{\text{erased}}}{dt} = 0, \tag{44}$$

consistent with the mechanical power $\mathbf{F} \cdot \mathbf{v} = 0$ in uniform circular motion.

This explains why centripetal acceleration, despite being non-zero, involves no continuous energy dissipation in our framework.

E. Equivalence Principle Compatibility

The same N_p that determines inertial mass through $m = m_\star N_p$ also governs gravitational coupling, since both emerge from the same horizon information dynamics. This provides a natural explanation for the equivalence of inertial and gravitational mass.

The framework is automatically composition-independent, as N_p depends only on total mass, not on internal structure or composition.

VII. EXPERIMENTAL TESTS AND OBSERVATIONAL SIGNATURES

A. Cosmological Predictions

- **Dark Energy Evolution**: The finite compaction rate Γ introduces a mild evolution of $\Omega_\Lambda(a)$, potentially detectable by next-generation surveys like LSST and Euclid.

- **Equation of State**: The dark energy equation of state parameter is:

$$w = -1 - \frac{1}{3}\frac{d \ln \rho_\Lambda}{d \ln a} = -1 - \frac{1}{3}\left(\frac{d \ln H^2}{d \ln a} + \frac{d \ln f_1}{d \ln a}\right). \tag{45}$$

For slow compaction, $w \approx -1$; for faster evolution, w may deviate measurably from -1.

- **Hubble Tension**: The tracking behavior $\rho_\Lambda \propto H^2$ may have implications for the Hubble tension, though detailed analysis is needed.

B. Laboratory Tests

- **Unruh Effect Detection**: Advanced laser acceleration techniques [18, 19] may reach regimes where Unruh radiation becomes detectable, providing direct evidence for the thermal horizon physics underlying our mechanism.

- **Precision Inertial Tests**: Ultra-precise tests of the equivalence principle could reveal small composition-dependent effects at the $\ll 10^{-13}$ level, arising from finite-speed information propagation on the horizon.

- **Analogue Gravity**: Bose-Einstein condensates and other analogue systems [20, 21] can test the underlying Unruh-Hawking mechanism in controlled laboratory settings.

C. Quantitative Predictions for Experimental Tests

- **Cosmological**: Evolution $\Omega_\Lambda(a) = \ln 2[1 - e^{-(\Gamma/H)\ln a}]$ with $\Gamma = H_c/2\pi$ - detectable by DESI and Euclid

- **Lab-scale**: Unruh radiation signatures in high-acceleration experiments reaching $a \gtrsim 10^{25}$ m/s^2

- **Theoretical**: Neutrino mass relation $m_\nu \approx \hbar H_{\text{QCD}} \ln 2/(2\pi c^2)$ tied to QCD transition scale

- **Composition tests**: Equivalence principle violations $\ll 10^{-13}$ from finite-speed horizon information propagation

VIII. DISCUSSION AND RELATION TO OTHER APPROACHES

A. Relations to Established Gravitational Thermodynamics

The digital horizon framework extends rather than contradicts established results:

a. Jacobson's Thermodynamic Gravity Where Jacobson derived Einstein equations from horizon thermodynamics, we provide the underlying microscopic dynamics. Our digital tiles represent the fundamental degrees of freedom whose statistical mechanics yield Jacobson's continuum description.

b. Verlinde's Entropic Gravity We derive both inertia and cosmic acceleration from entropic considerations, but with specific microscopic mechanisms and testable numerical predictions absent in Verlinde's original formulation.

c. Bekenstein-Hawking Area Law Our Planck tiles directly implement Bekenstein's area quantization, with the saturated fraction $f_1 = \ln 2$ emerging from quantum informational constraints rather than being postulated.

B. Universality of Horizon Thermodynamics

A foundational premise of our framework is the universal applicability of the digital patch model to all causal horizons, regardless of their specific origin or scale. This universality rests on three principal arguments:

a. Theoretical Foundation The membrane paradigm [15] and the broader horizon thermodynamics program [1, 3] establish that *all* causal horizons—whether formed by local acceleration (Rindler horizons) or cosmic expansion (Hubble horizon)—share common thermodynamic properties. Each possesses temperature proportional to surface gravity, entropy proportional to area, and information-storage capacity. Our digital patch framework implements these universal principles at the microscopic level.

b. Mathematical Continuity and Scale Bridging The universal applicability of our digital patch framework finds strong support in the mathematical continuity between horizon types. Consider the limit where the cosmological constant $\Lambda \to 0$: de Sitter spacetime smoothly transitions to Minkowski spacetime. Crucially, while the cosmological horizon recedes to infinity in this limit, *local Rindler horizons persist* for accelerated observers in the resulting Minkowski space.

c. Empirical Validation The remarkable empirical success—deriving both the observed $\Omega_\Lambda = \ln 2$ and the classical $F = ma$ from identical microphysical rules—provides strong a posteriori justification for this universality.

C. The Universe Is Not de Sitter: Implications of the $\Omega_\Lambda = \ln 2$ Limit

It is often stated that our universe is "approaching a de Sitter phase" because current observations suggest $\Omega_\Lambda \approx 0.69$. However, our model implies a different interpretation: the value $\Omega_\Lambda = \ln 2$ is not a step along the way to $\Omega_\Lambda = 1$, but a fundamental **thermodynamic limit**. In our framework, this value emerges as a consequence of digital saturation of horizon patches, where each patch stores exactly one bit of information. Once this saturation is reached, no further compaction is possible and Ω_Λ remains fixed.

This distinction has deep implications. Unlike a true de Sitter universe, which is maximally symmetric and thermodynamically static, our universe retains a memory of its origin in discrete, horizon-anchored information dynamics. The apparent dark energy does not asymptotically grow to dominate everything, but rather reflects a *frozen-in fraction* of microscopic gate occupation. In this sense, our universe does not *tend toward* de Sitter—it **stabilizes at** the $\Omega_\Lambda = \ln 2$ interface condition.

D. Resolution of Conceptual Issues

- **Vacuum Energy Problem**: By attributing dark energy to horizon degrees of freedom rather than bulk vacuum fluctuations, we naturally resolve the cosmological constant problem.

- **Inertial Origins**: We provide a first-principles mechanism for inertia that explains both its universality and its quantitative value.

- **Information-Energy Connection**: The framework establishes a concrete realization of the fundamental connection between information processing and energy expenditure in gravitational physics.

- **Cosmic Inertia**: The consistency between $m_\star N_H$ and the mass of the observable universe reveals that all horizon degrees of freedom participate in cosmic-scale inertia.

E. Addressing Theoretical Concerns

a. Mass-Energy Conservation The apparent violation of global mass conservation ($M \propto R_H$) reflects the open thermodynamic nature of the causal horizon. Energy conservation in general relativity is inherently local, and our model respects this while accounting for the horizon's role as an information boundary.

b. Trans-Planckian Issues The digital tile framework naturally regularizes trans-Planckian problems by providing a fundamental cutoff at $4L_P^2$, with continuum physics emerging from collective behavior of discrete degrees of freedom.

c. Background Independence While using the Hubble horizon as reference, the framework is background-independent in principle—any causal horizon can serve as the inertial reference frame, with local physics independent of global cosmology.

IX. CONCLUSION

We have developed a comprehensive information-theoretic framework that unifies the origin of inertia and cosmic acceleration. The key insights are:

1. The stretched horizon is quantized into Planck tiles with digital information capacity.
2. Causal compaction drives the system to a universal digital fixed point with saturated fraction $f_1 = \ln 2$.
3. This saturation fraction directly determines the dark energy density $\Omega_\Lambda = \ln 2$, in excellent agreement with observations.
4. Inertial mass emerges from the Landauer cost of horizon information updates at the Unruh temperature, yielding $m = m_\star N_p$ with universal $m_\star = \hbar H_0 \ln 2/(2\pi c^2) \approx 6.1 \times 10^{-69}$ kg.
5. The framework uniquely predicts a growing total rest mass $M \propto R_H$, consistent with the irreversible thermodynamic role of the cosmological horizon, and inaccessible to conventional conservation-based models.
6. Cosmic milestones in inertial anchoring reveal that different particle species became stably engaged with the horizon at specific cosmic epochs determined by $m_\star = m_{\text{particle}}$.

7. All phenomena derive from a single information-dynamic principle applied consistently across scales.

The model makes testable predictions for both cosmological observations and laboratory experiments, providing a fertile framework for future research into the fundamental nature of gravity, spacetime, and information.

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